Ivan Mutis · Timo Hartmann *Editors*

Advances in Informatics and Computing in Civil and Construction Engineering

Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management

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Letter from the Editors

The 35th CIB W78 conference took place in Chicago in 2018, with a theme focused on fostering, encouraging, and promoting research and development in the application of integrated information technology (IT) throughout the life cycle of the design, construction, and occupancy of buildings and related facilities. Organized by Professors David Arditi and Ivan Mutis (Illinois Institute of Technology, Chicago), Timo Hartmann (Technische Universität Berlin), Robert Amor (University of Auckland), and with special and valuable support from Bill East (Prairie Sky Consulting, USA), it brought together more than 200 scholars from 40 countries, who presented the innovative and unique concepts and methods featured in this collection of papers.

With the publication of these contributions, we expect to scaffold scholars' motivations to inspire and discover the pressing research questions that need to be answered in the coming decade. Framed under topic clusters as described in the introductory section, the Editors organized the responses of the 2018 worldwide, open call for submissions. Taking the number of submissions in each focus area as an indicator of research potential, the open call elicited the lowest response in the area of Systems of Integrated Computer and Physical Components (Cyber-Physical-Systems), which suggests underdevelopment of initiatives for scientific questions in this area. We look forward to seeing greater response to this area in the future.

Ultimately, the success of this event and its contribution to the field of informatics and computing in civil and construction engineering is the result of countless hours of investigation, development, and work from scholars across the globe. The Editors and organizing committee thank all who have supported the effort. We thank in particular the paper reviewers.

The research and approaches that have been developed and presented at this conference can immediately deliver extraordinary innovations to construction practices with benefits attributable to individuals, organizations, and the industry, as a whole. Looking forward, the legacy of this conference will be carried not only through its influence on the construction practice but also on research for years to come.

Ivan Mutis
Timo Hartmann

About CIB and CIB W78

CIB, officially named International Council for Research and Innovation in Building Construction, was established in 1953 under the name Conseil International du Bâtiment. The foundational objectives of CIB were to stimulate and facilitate the international cooperation and exchange of information between governmental research institutes in the building and construction sector, with an emphasis on those engaged in technical fields of research. Since its inception, the association has developed into a worldwide network that connects more than 5000 experts. These specialists represent the research institutes, university, and industry- and government-related entities that constitute the approximate 500-member organizations of CIB. Though the size and strength of the organization today has grown compared to the past, the focus of CIB and its members remains the same: the active collection of research and innovation information for all aspects of building and construction.

CIB W78, or work group 78, is one of the largest and most active working commissions of CIB. The scope of W78's work is broad, but its primary mission is to proactively encourage the integration of Information and Communication Technologies (ICT) into a facility's life cycle. It achieves this goal by disseminating research and knowledge among an international community of scholars and practitioners in a variety of means, most notably the annual international conference.

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Part VI Computing and Innovations for Design Sustainable Buildings and Infrastructure

Introduction

A Vision for Research and Innovation in Informatics and Computing in Civil and Construction Engineering

While we move into the first quarter of the twenty-first century, the practice of civil, construction, and building engineering embraces an incommensurable transformation in the way we deliver products, process data, and interact with agents and technology. New paradigms focused on sustainable practices, and the effective use of data and information and computing technologies, and automation have framed the trends we see in research initiatives and fundamental problems in civil and construction engineering disciplines. The continuous expansion of interdisciplinary work among computing, informatics, and construction and civil engineering merges perspectives to create integrated or hybrid methods of observing, dissecting and solving central problems and of integrating relevant theories. The 2018 conference and this related publication is an effort to register diversity of thinking to understand a phenomenon, problem, dataset, or methods that enable value creation in practice and expand the frontiers of new, integrated knowledge.

We view the worldwide, open call for research initiatives as a survey of innovations and novel approaches to phenomena and problems in computing and informatics in civil and construction engineering. The compilation is organized under seven concept clusters to align the contributions to the forefront of trends on investment for scientific research. The selection in clusters was decided to better capture new advancements of knowledge within the focus areas. The conceptualization and focus were based mainly on reflections from visionary documents [1–3]. The focus areas cover the spectrum of aims of scientific questions and the fundamental aspects that advance understanding or solve problems. Within each area, evolving technology may transform activities and subsequently shape research practices in the coming decade (Fig. 1).

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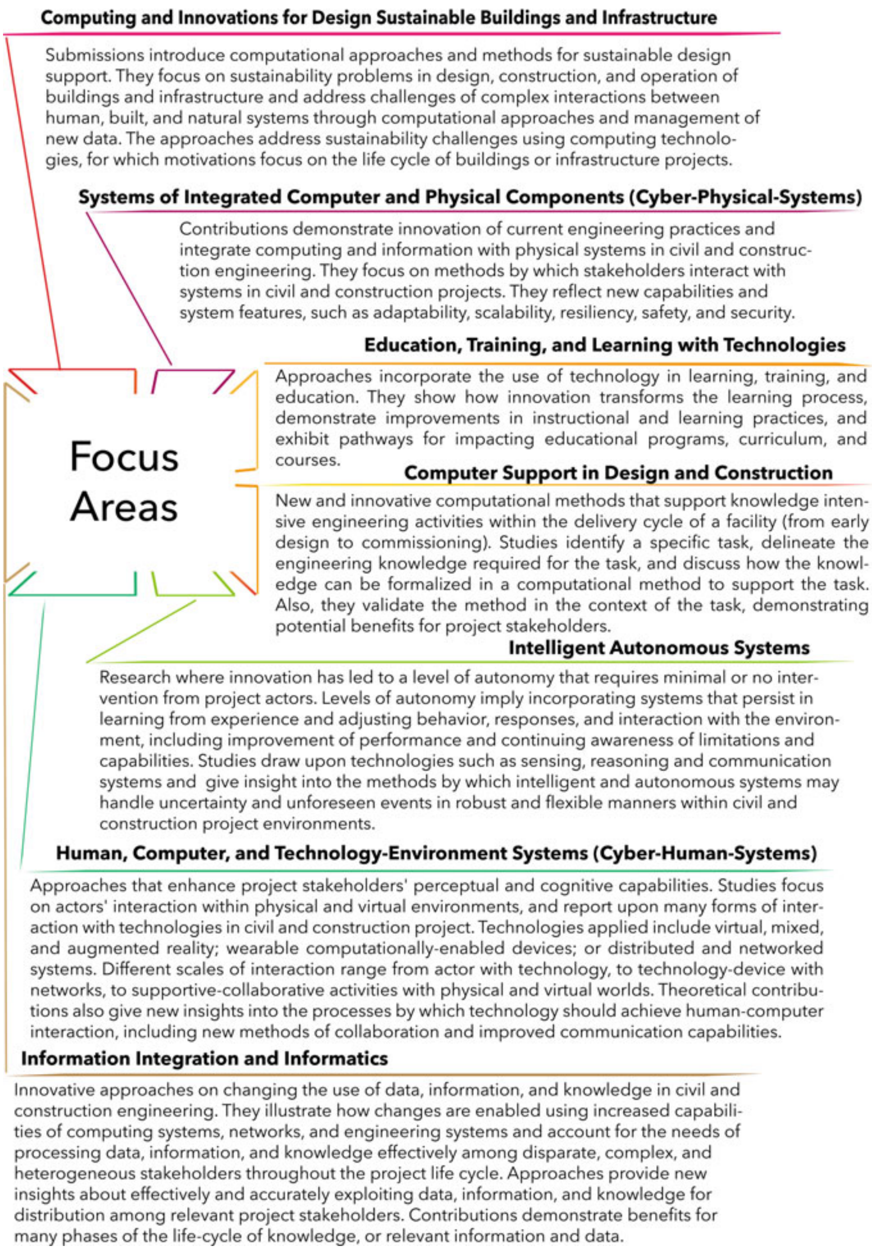

Fig. 1 Conference topics clustered in focus areas

References

1. National Science Foundation (NSF).: NSF's 10 Big Ideas. (2018) Available: https://www.nsf.gov/news/special_reports/big_ideas/
2. National Science Foundation (NSF).: Building the future investing in discovery and innovation. In: National Science Board, National Science Foundation (NSF), vol. NSF-18-45, Arlington, Virginia (2018)
3. Rajkumar, R., Lee, I., Sha, L., Stankovic, J.: Cyber-physical systems: The next computing revolution. In: Design Automation Conference, pp. 731–736. (2010)

Part I

Information Integration and Informatics

1 Barriers of Automated BIM Use: Examining Factors of Project Delivery

Jason Lucas and Sai Sri Neeharika Vijayarao

Abstract

The use of Building Information Models (BIM) for design and construction processes are growing as a whole, especially in terms of mobility platforms that help with managing the construction process. One area, however, that is lagging in the use of BIM for automated or semi-automated processes such as estimating. Literature has explored some reasons for this lack of adoption of BIM for estimating as issues with the user trusting the model's accuracy when that model is created by someone else when using a federated model approach. In order to enhance user confidence of BIM results with automated processes two areas were examined: (1) the use of historic data to create a reliability model based on risk and financial impact of systems and (2) examining factors of project delivery that influence the use of BIM. This paper discusses a two part survey that examined the project delivery system and various other factors as to how they relate to the user's confidence in the accuracy of a model. Results indicate that personal relationships are more influential than contractual obligations. Finally, findings of the survey that identify common trends of respondents in terms of setting up a project delivery to maximize the utilization of BIM are included.

Keywords

Building information modeling • Estimating • Integrated project delivery

1.1 Introduction

Building Information Modeling (BIM) has grown over the past decades as a process for creating a computer-generated model of a building containing geometry and data for designing, planning, constructing, and managing the building [1]. BIM has been proven to lead to cost savings during the design and construction processes, which has influenced its overall rate of adoption [2].

Automating processes like material take-off and cost estimation with BIM can allow contractors to spend less time on material take-offs and more time reviewing and planning the project. Automated measurement is one method to speed up the material take-off process [3]. When it comes to trusting automated BIM processes, however, many contractors are cautious about how much they use BIM, especially if the use of BIM has high risk associated with it (e.g. estimating a job). Because the accuracy of the model is often not contractually binding, there is a degree of ambiguity about who is responsible for the accuracy of the data [4].

Common obstacles that have limited the use of BIM for automated processes include: ownership licensing, control, and responsibility of data entry into the model. Typically, a federation of sub-models from different authors is used for the purposes of creating a model for construction planning. These models are often created for different purposes and can have varying levels of development, making it complicated to understand the accuracy of data they contain once these models are integrated together [5, 6]. Specifically with estimating, estimators lack confidence in automatically producing something that

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was previously controlled manually because the automation process removes some of the manual interpretation required to create an accuracy estimate [7, 8].

The main objective of this research is to identify methods to increase the user's trust in the model's accuracy and the results of automated or semi-automated processes when the model authored by someone else is used. The research has been broken into two focus areas. The first was to develop a reliability model based on historic modelling accuracy data, financial impact to the project (level of risk of a building system), and other user inputs. The second area of research addresses user confidence in a model stemming from how a project is contractually set up to promote or inhibit a more complete BIM workflow. This area looks into how various factors of different project delivery methods can influence a user's confidence in the general accuracy of a BIM authored by a third party and in utilizing that BIM for automated processes. The study results can then influence the way projects are set up, contracts are written, and relationships are developed to support a more trusting BIM workflow.

1.2 Phase 1: Reliability Model

The first phase of the research developed a reliability model for quantitative assessment of automated BIM processes [9]. The reliability model was proposed as a tool for contractors to assess the accuracy of results from automated BIM processes.

The reliability model was organized by UniFormat [10] classification and used inputs of historically accuracy for each major system of construction, a total project cost and percentage cost for each major system, and the acceptable rate of error that the user would accept from the model and each of the systems. These inputs then allowed for the identification of a "confidence in accuracy" rating to be calculated through the statistical analysis described in Lucas et al. [9].

The workflow for the proposed tool (Fig. 1.1) was to take a federated model and input the features of that model (e.g. type of structure, type of cladding, etc.) into the reliability model. Based upon the systems identified within the federated model the algorithms within the reliability model calculates a confidence in accuracy of the model and the criticality of each system to influence the overall accuracy. Each system's criticality is based on the systems financial risk and historical likelihood of its accuracy. Based on the confidence of accuracy, the user can determine if it high enough to utilize the model for automated processes. If not, the user could manually check a defined amount of the most critical system identified. If errors were found, they can determine that edits would need to be made before the model could be used. If no errors were found in the model the reliability model would be re-run with "0" errors for the critical system. This would allow a new confidence of accuracy to be calculated. The process would complete until the level of confidence was high enough for the user to accept the model as accurate. The process of checking the critical system for errors would be accompanied by a list of common issues that have been identified as potential errors throughout the data collection process (e.g. concrete slabs may be notated as 4″ but drawn as 6″, wall types drawn at the wrong thickness could affect volume). This will allow a user some insight as to what might need to be checked.

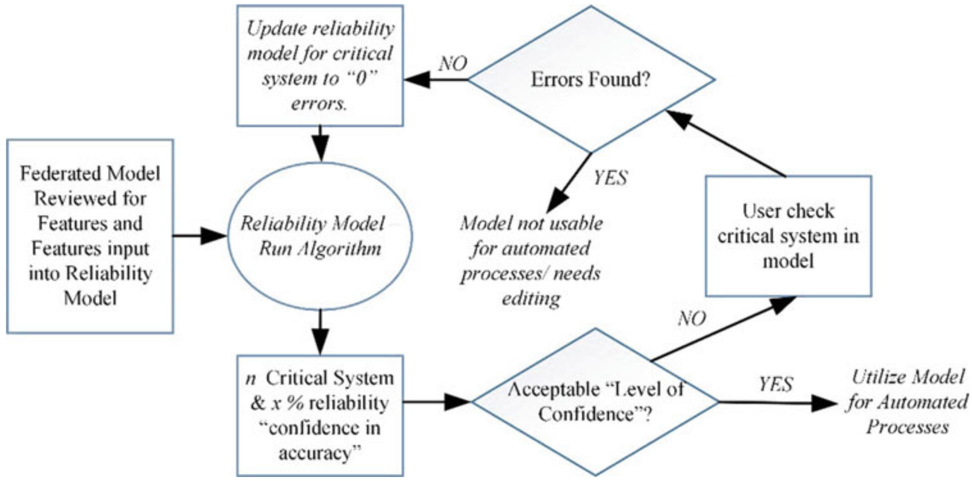
1.2.1 Findings from Phase 1

A proof-of-concept model was developed with sample project data input into a database for plumbing, HVAC, Fire Protection, and Electrical systems. Six participating firms participated in follow-up conversations and showed interest in the use of the reliability model should it be fully developed with a large enough dataset. A common theme among all firms was the amount of risk that they would place on the result of an automated process when they did not have direct and total control over the creation of the model. In open responses they also listed anecdotal evidence that they tend to rely on models more when they are more comfortable with the author who created the model. These types of comments led to the development of the second phase of the research.

1.3 Phase 2: Project Delivery and Trust

The second phase of the research was to further examine the challenges identified as to why construction personnel utilizing BIM were resistant to utilize BIM to its full capacity. The research began to look into how changes in the project delivery process may promote BIM in ways that can lead to project efficiencies. Areas considered within the second phase of the

Fig. 1.1 Reliability model Workflow



research and are discussed in this paper include: cross-disciplinary teams, strength of interpersonal relationship, contractual obligations, formal BIM execution plans, and modeler/modeler's organization reputation and experience.

1.3.1 Research Design

Phase two of the research utilized a literature review and multiple surveys to identify consensus of influence among BIM users. The steps are depicted in Fig. 1.2.

1.3.2 Identifying Project Delivery Variables that Impact BIM Use

A thorough literature review and comments received through the first phase of the research created 29 variables that were organized into 9 categories of potential influence on user confidence in a model's accuracy. Three models of influence for affecting trust were highly influential in the categorization of the variables [11–13]. The categories and descriptions of variables are shown in Table 1.1.

1.3.3 Survey 1

In the first survey thirteen broad range questions were asked about the influence of each of the nine categories that were identified. A 7-Point Likert scale was used to allow for greater granularity of results. Convenience sampling techniques were used for the study based on contacts available to the research team from past experience and from those on the organization's Industry Advisory Board for a total of 50 companies invited to participate. Chain referral sampling was also suggested to try and enlarge the respondent pool. In total 29 responses were collected. Of those responses, 21 reached the experience threshold set at 4 years of using BIM for project planning. The experience level of the qualified respondents ranged from 4 to 14 years (mean average of 7.4 years).

The results of the survey were analyzed through descriptive analysis. Results were tested for statistical significance using t-test (p) calculations. Results with a $p < 0.05$ were identified as statistically significant. These categories are included in Table 1.2 below. From the seven categories identified as having statistically significant results, the Relational category had the highest level of agreement (6.238/7) and Intuition Question 2, Contractual, and Integrity had the lowest level of agreement (5.095/7). Other categories that suggest a higher level of influence include Competence (6.00/7) and Deterrence (5.762) All had an overall positive impact over the median of a 4 out 7 on the Likert scale where 1 was absolutely not likely or influential and 7 was extremely likely or influenced.

Other open response responses were coded for themes and included: BIM author's technical experience, depth of author's construction knowledge, authoring organization's culture on modeling, nomenclature and technical structure of model, verifiability of component accuracy, buy-in of project-specific participants, and phase of LOD of the model.

Responses were also examined by age range. The two groups were broken into those with 4–6 years of experience (10 respondents) and those with 7 or more years of experience (11 respondents). Those with more years of experience only ranked Contractual Agreement and Institutional Based—Question 1 (Documentation Culture) higher than those with fewer years of experience. Though when looking at a regression analysis, even with statistical indication of a correlation, the subsequent scatter plot does not indicate a linear relationship.

1.3.4 Survey 2

The second survey took the categories that showed influence on someone's perception of the model delivery and created more specific questions to check the influence of specific variables. The survey consisted of twenty-nine (29) questions. 14 responses were received from the original 24 who were qualified to respond in the first survey. Since the second survey was to dig deeper and identify consensus about the influence of the test group, the same respondents were asked to further clarify their earlier responses.

After completing descriptive statistical analysis the top individual variables were identified (see Table 1.3). Five out of the top variables were from the top two categories from the first survey.

On the opposite end, three of the bottom five came from the 8th ranked category while the other two came from the top 3 (Table 1.4).

1.4 Findings and Observations

Based on the findings of the study, there is an indication that developing a relationship with the author (or authors) of a BIM is more influential to the confidence a user has in the overall accuracy of the model created by a third party than the contractual structure of the agreement to use BIM. Large scale validation of the findings need to be conducted with a larger response population and over a larger geometric area as most of the respondents were within the south-eastern United States. However, the study's findings suggesting that developing a relationship between the author and user of BIM as the most influential variable examined does coincide with previous literature. One study argues that in order to implement successful inter-organizational BIM and develop transparent technology use a team must create a social and organizational foundation to support collaboration [14]. Another study identified human-related factors (e.g. training, leadership, and experience) as essential for successful BIM implementation [15].

With the current study showing that user confidence in the accuracy of information within a BIM is higher with a developed relationship and other literature linking good social and organizational foundations to better collaboration and successful BIM implementation future studies on user confidence to project success are proposed to help understand if there is an actual link.

Another observation linked to the findings is to ensure project teams are not just spending time on technical specifications in terms of creating plans for using BIM. The industry commonly uses published methods for developing plans for BIM utilization. One of those documented methods is the *Building Information Modeling Execution Planning Guide* [16]. Within that guide, the authors place some emphasis on having the team members' work on setting up the execution plan to help clarify common goals, communicate strategy, and understand roles and responsibilities. This study enforces the importance of the team approach. Not only it is necessary to establish common goals and set up a project for success, but spending time to develop a relationship with the authors of the model was identify as a significant influence on a BIM user's confidence in the accuracy of the model they are receiving. Moving forward, it is recommended that project success in terms of BIM use and issues related to model accuracy be examined and compared to the relationship that the author and final user have developed to gain a quantitative understanding.

1.5 Conclusion

This study set out to look at how various factors of project delivery affect user confidence in using BIM for automated or semi-automated processes when the model was authored by a third part. Literature review summary and findings from an earlier study were used to formulate a list of variables. A two part survey was then completed to gauge the influence that each variable had on the user's confidence in a model's accuracy when the model was developed by someone else.

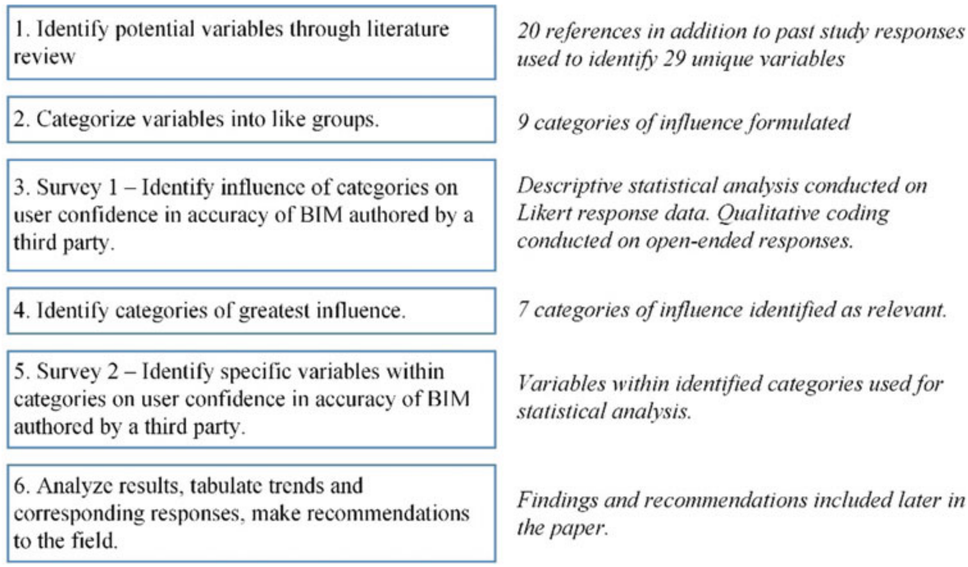


Fig. 1.2 Research steps

Table 1.1 Categories of potential influence

Category	Factors in category
Integrity	Integrity, fairness/transparency
Competence	Historic performance, reputation, apparent knowledge
Intuitive	Perceived risk involved, intuition (gut feeling)
Calculus-based	Economic self-interest, transaction cost analysis, perceived risk for self-interest
Relational trust	Personal experience with someone, historic interactions and past communications
Institutional-based	Inclusion of a boundary role person, legal systems in place, regulations, organizational policy and affiliations, comparison of institution to societal norms
Deterrence-based	Sanctions for breach of responsibilities
Knowledge-based	Fairness or transparency of interactions, knowledge of a person's or company's reputation/performance
Education	Certifications and formal education
Contractual agreement	Model level of detail, BIM execution plan, boundary role person/model coordinator

The first study looked at broad categories of variables and identified issues related to "Relational" aspects of project delivery ranked at the top and "Contractual" variables at the bottom. The second study examined the variables in more detail of those that proved to have a statistically significantly impact from the first survey.

The second study identified that personal experience with the person and company ranked highly among individual variables. The more technical aspects of project delivery that included defined contract addendums, owner-specified requirements for BIM execution plans, and level of detail specified for the BIM model all fell within the five least influential variables.

Many companies put great effort into developing a detailed BIM execution and utilization plan to ensure that rolls, responsibilities, and requirements related to BIM are clearly outlined. The BIM execution plans often include agreed upon strategic goals for the project team. The results of this study would caution against solely focusing on defining these aspects of the plan and not developing a relationship that can formulate a higher level of confidence in the models that inter-organizational team members are creating.

Table 1.2 Statistically significant categories ranked by mean

Category	Question	Mean	SD
Relational	How much of an affect does repeated interactions with the BIM models and its author(s) have on your level of trust in the accuracy of information?	6.238	0.971
Competence	How much of an effect does previous interactions with the author(s), past experiences, reputation of the author(s) or their associates entities have on of your trust in the accuracy of the BIM model?	6.000	0.976
Deterrence	If the accuracy of a BIM model is a contractual obligation and any breach of trust (e.g. Errors in accuracy) is penalized through economic sanctions or other means to motivate the creation of a more accurate model, how likely is this to affect your confidence in the accuracy and use of said BIM model?	5.762	1.630
Institution	To what extend does the documentation culture at your organization to make BIM models along with AutoCAD drawings, architectural visualizations, etc. influence your confidence in BIM model accuracy?	5.667	1.084
Knowledge	To what extent does your personal opinion of a BIM author influence your trust in their professional competence and ability to deliver an accurate model?	5.381	0.999
Education	To what extent does the formal post-secondary education of BIM techniques for the BIM's author influence your acceptance of the model as being accurate?	5.238	1.151
Institution	To what extent does the author's affiliation with a reputed organization/company affect your confidence in the BIM model's accuracy?	5.095	1.231
Contractual	To what extent does the inclusion of contractual obligations of BIM use (such as an owner required BIM execution plan, formal deliverables) affect your confidence in the accuracy of a model developed by another party?	5.095	1.444
Integrity	To what extent would you say that your level of confidence in model accuracy is fueled by the author's integrity? Meaning you believe that the author(s) will look out for your best interests in addition to their own	5.095	1.630

Table 1.3 Survey 2—top variables by mean

Category	Prior rank	Variable	Mean
Relational	1	Personal experience	6.45
Relational	1	Personal history with the author	6.45
Competence	2	Repeated interactions with the author	6.08
Knowledge-based	5	Integrity of the BIM author	5.90
Institution	4	Author's organization's policies on BIM	5.82
Relational	1	Personal history with the organization	5.63
Knowledge-based	5	Reputation of the BIM author	5.63
Competence	2	Overall performance of the BIM author	5.58
Integrity	7	Forthcoming in identifying model changes	5.58
Integrity	7	Openness to share model	5.50

Table 1.4 Survey 2—lowest variable by mean

Category	Prior rank	Variable	Mean
Contractual	8	Owner required BIM execution plan	3.42
Relational	1	Restricted nature of information sharing	3.82
Contractual	8	Inclusion of formal contract addendum	4.07
Deterrence	3	Promise of future business with the BIM author influencing severity of sanctions	4.25
Contractual	8	Level of development of the BIM model being specified in the contract	4.28

References

1. Eastman, C.M., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors. Wiley, Hoboken, NJ (2008)
2. Azhar, S.: Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. Leadersh. Manag. Eng. **11**(3), 241–252 (2001)
3. Tulke, J., Nour, M., Beucke, K.: A dynamic framework for construction scheduling based on BIM using IFC. IABSE Congress Report. 17. https://doi.org/10.2749/222137908796292119
4. Singh, V., Gu, N., Wang, X.: A theoretical framework of a BIM-based multi-disciplinary collaboration platform. Autom. Constr. **20**(2), 134–144 (2011)
5. Reinhardt, J., Klancnik, D.: The Contractor's Guide to BIM—Edition 2, Associated General Contractors of America (AGC) & BIMForum (2009)
6. Azhar, S., Hein, M., Sketo, B.: Building information modeling (BIM): benefits, risks, and challenges. In: Proceedings of the 44th Annual Conference on Associated Schools of Construction, Auburn University (2008)
7. McCuen, T.L.: Scheduling, Estimating, and BIM: a Profitable Combination. AACE International, Toronto, Canada (2008)
8. Shen, Z., Issa, R.R.A.: Quantitative evaluation of the BIM-assisted construction detailed cost estimates. J. Inf. Technol. Constr. **15**, 234–257 (2010)
9. Lucas, J., Khademi, A., Ross, B., Fulaytar, G.: A reliability model for BIM-related automated processes. In: Proceedings of the 32nd International Conference of CIB W78, Eindhoven, The Netherlands, pp. 497–505 (2015)
10. Construction Specifications Institute (CSI): Uniformat, https://csiresources.org/practice/standards/uniformat. Last accessed 2018/4/5
11. Hartman, F.T., Blakeney, D., DeMaere, R., Krahn, J., Skulmoski, G.J., Ren, L.S.: Update on trust: a collection of trust-based research findings. Paper presented at PMI® Research Conference 2002: Frontiers of Project Management Research and Applications, Seattle, Washington. Project Management Institute, Newtown Square, PA (2002)
12. Rousseau, D.M., Sitkin, S.B., Burt, R.S., Camerer, C.: Not so different after all: a cross-discipline view of trust. Acad. Manage. Rev. **23**(3), 393–404 (1998)
13. Lewicki, R.J., Bunker, B.B.: Developing and maintaining trust in work relationships. In: Kramer, R.M., Tyler, T.R. (eds) Trust in Organizations: Frontiers of Theory and Research, pp. 114–139. Sage Publications (1996)
14. Homayouni, H., Neff, G., Dossick, C.: Theoretical categories of successful collaboration and BIM implementation within the AEC industry. Construction Research Congress 2010: Innovation for Reshaping Construction Practice. ASCE Reston, VA (2010)
15. Ozorhon, B., Karahan, U.: Critical success factors of building information modeling implementation. J. Manag. Eng. **33**(3), 04016054 (2017)
16. Computer Integrated Construction Research Program (CICRP).: BIM Project Execution Planning Guide—Version 2.0. The Pennsylvania State University, University Park, PA, USA (2010)

2 Simulation of Construction Processes as a Link Between BIM Models and Construction Progression On-site

Ector Oliveira, Cláudio Ferreira Júnior, and Fabiano Correa

Abstract

Among Information and Communication Technologies (ICT) developed in the past decades—and successfully applied to Construction—is Building Information Modeling (BIM). One possible use of BIM models is Phase Planning (4D modeling), i.e., the integration of schedule with 3D building components of the BIM model. In addition, there is the growth in the use of: (1) technologies, such as augmented-reality equipment, to bring BIM models to the field; (2) sensor networks to feedback data about the daily progress of construction work on-site. However, the connection between 4D models, and real-world data from sensors on the construction site, to promote integration between design and construction (among other possible applications) is still in its infancy. The question addressed by this research is: how to use simulation as a link between 4D BIM models and a network of sensors on-site (off-site)? Simulation would be considered as a set of interlinked models of different construction processes, which should evolve in time based on (partial) data received from sensors. In that context, the objective of this preliminary work is to study and validate the level of detail in one construction process model, necessary to incorporate one specific type of sensor, and to quantify, even if indirectly, the amount of progression in construction work on the field. Given the availability of the ProModel software, the present research aimed to develop different models of the same construction process, with different levels of details, to draw conclusion that could be extrapolated to other processes.

Keywords

4D BIM • Simulation • Construction process modeling

2.1 Introduction

Among Information and Communication Technologies (ICT) developed in the past decades—and successfully applied to Construction—is Building Information Modeling (BIM). BIM should not be just a set of computer tools to produce, communicate and manage construction information, but entirely new processes inside Architecture, Engineering, and Construction (AEC) industry around information models [1]. Some authors refers to these processes using BIM as Virtual Design and Construction (VDC) [2]. VDC processes emphasize the integration between design and construction through an information (BIM) model, and explicitly represents construction processes [3]—other researchers had emphasized the necessity to have construction processes models, beyond the current and common product data model natural to BIM [4].

One possible use of BIM models is Phase Planning or 4D modeling [5], i.e., the integration of schedule with 3D building components of the BIM model. When "comparing traditional project scheduling tools like CPM networks and bar charts

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with 4D modeling" [6], among the benefits of using the latter is the visual details that are possible based on a different representation.

In addition to this context, there is the growth in the use of technologies, such as augmented-reality equipment, like Microsoft Hololens and Daqri smart helmet, to bring BIM models to construction site. Also, the use of drones, video cameras, and laser scanner equipment are starting to bring more data about the daily progress of construction work on-site, which could be feedback, for example, for comparing real versus planned 4D models. Clearly, there is the possibility to stablish a bi-directional link between BIM model platforms and construction progress on-site [7].

However, as BIM processes around the world is increasingly being implemented, one point that is still in its infancy is, in fact, the connection between the 4D models, and real-world data from sensors on the construction site. Moreover, what would be the benefits in committing to more detailed or even discrete-event models for construction processes simulation, to enable such link?

The possibility to simulate on-site (and off-site) construction processes on computer systems could generate tools to better plan, monitor and manage construction work [8]. As the complexity of one single model to represent all construction processes needed to erect a building is paramount, such simulation should be considered as a set of interlinked models of different construction processes, which would evolve in time based on (partial) data received from sensors.

The level of detail in modeling those construction processes would depends on:

(1) the kind of data from sensors on the field (partially observable system);
(2) the pre-processing and integration among heterogeneous systems of information acquisition, for example, images and temporal series of spatial positions;
(3) the predictability of the productivity of construction workers [9], when they are involved (which is frequently).

Probably, for each set of construction processes, sensor network, and different inputs or variables (work force, equipment, raw materials), one would have to choose a different level of detail in the model for use in the simulation.

The questions addressed by this research are: how to use simulation as a link between 4D BIM models and a network of sensors on-site (off-site)? How to develop such models of construction processes, and how to measure the adequacy of a chosen level of detail for each one?

Until now, there is not a formalization in how to integrate and connect the virtual world of BIM models, and the data gathered in the field. Some research has been done in the development of cyber-physical systems to be that link [10].

In that context, the objective of this preliminary work is to study and validate the level of detail necessary to incorporate one specific type of sensor, an ultrawide band (UWB) localization system, and try to figure out the right amount of detail necessary to capture the movement of work force, materials, and equipment.

The adopted methodology was to create and validate the model in an existent simulation platform to streamline the modelling and analysis of different details of a construction process. There are a few commercial platforms (like Arena, ProModel) that allow the modelling of construction processes. The present work is not focused in exploring the advantages and disadvantages of each one; given its availability, ProModel was the choice.

The focus of the present work is in the activity of structural masonry. A database of manually collected productivity measures was used to setup the parameters of the model, and to create post-processed data from UWB sensor.

2.2 Background

Manufacturing industries, in the context of Industry 4.0 concept, are using simulation not only to optimize shop floor layout, but as a digital twin of the real factory producing its own products. Referred as a cyber-physical system, it is a way to integrate horizontally and vertically one enterprise, to reduce costs and time-to-market, and to increase customization of its products, among other potential benefits.

Simulation for Construction industry is not a widespread application. Some issues with regard to simulation of processes in construction are: (1) difficult to model and to code with a simulation language [11]; (2) ideal models, and results do not agree with practice [9].

In specific construction processes, like in pre-fabrication of building components, simulation, being similar to manufacturing, are better developed [12, 13], because it provides a more controlled environment to predict work progress. Such simulation also counts with processes monitored sensors, like RFID technology [14].

There are also discussions of simulation being represented by dynamic systems [15], or just a logical sequence of actions.

In recent years, discussions involving 4D BIM models, with planned construction work, and real-time monitoring current work on the field, using different sensors started to appear [16]. One interest work [10] advocated the bi-directional link between BIM and sensors for monitoring construction progress using cyber-physical systems.

The framework in which the present work is developed follows some ideas from [7], but try to expand its uses. The simulation approach in this work is focused in the "logical sequence among the operation process or tasks", trying to manage resource's use [9].

2.3 Methodology

Based on manually collected data of productivity on-site for the masonry construction process, two types of simulation were elaborated: a model inside Microsoft Excel spreadsheets (as a tool to decide the right amount of workforce needed for the job), and another model in ProModel.

It was decided to implement the "same model" with a different level of detail inside ProModel system to compare how the difference in information could render different outputs, and how it could help in plan, monitor, and manage construction work. The representation detail was determined having in mind that data from position in real-time of construction work forced would be given by a UWB localization system.

2.4 Proposed Framework for Integration of 4D BIM Models and Sensor Data of Construction Activity Progress

The proposed framework allows virtual models of construction processes to work as the integration between 4D BIM models, or more specifically, certain activities of the work schedule, and data processed from sensors on-site (or off-site).

Considering that:

(1) there will be a model for each construction process, for example, one for foundation work, another for structural masonry, and so on;
(2) the combination of the execution of those models, sometimes in parallel, sometimes in sequence, should provide a real versus planned 4D BIM model;

Petri Nets should be a natural choice as the bi-directional link because there are many formalisms based on it, which allows stochastic transitions, transitions based on the reception of signals (data) from outside the system, and so on.

Figure 2.1 gives an overview of the proposed framework. Productivity measure database could be used to setup parameters of an initial model, and to real-time monitoring construction progress. The latter would be used directly to activate transitions in the Petri Net simulation.

Previous works were done in trying to stablish a methodology to facilitate the elaboration of the virtual construction process. It was addressed in [17], with the proposition to derive a Petri Net discrete-event simulation model from IDM (Information Delivery Manual) in BPMN language (following general mapping proposed by [18]). As professionals from AEC industry are already using BPMN language to specify IDM, to be later used to derive specific Model View Definition (MVD), it could be considered a promising starting point. Also, as a matter of future research, the use of EXPRESS (IFC) as a modular language to specify an object-oriented simulation of construction processes should be considered.

2.5 Case Study: Masonry

The construction work process analyzed in this paper is structural masonry. The simulation presents work in the construction of four tower, where two of them were dealt in parallel work to optimize the use of workforce.

The base parameters used to create the simulation were derived from historic data collected on the field. Some criteria were adopted to create standards for data collection:

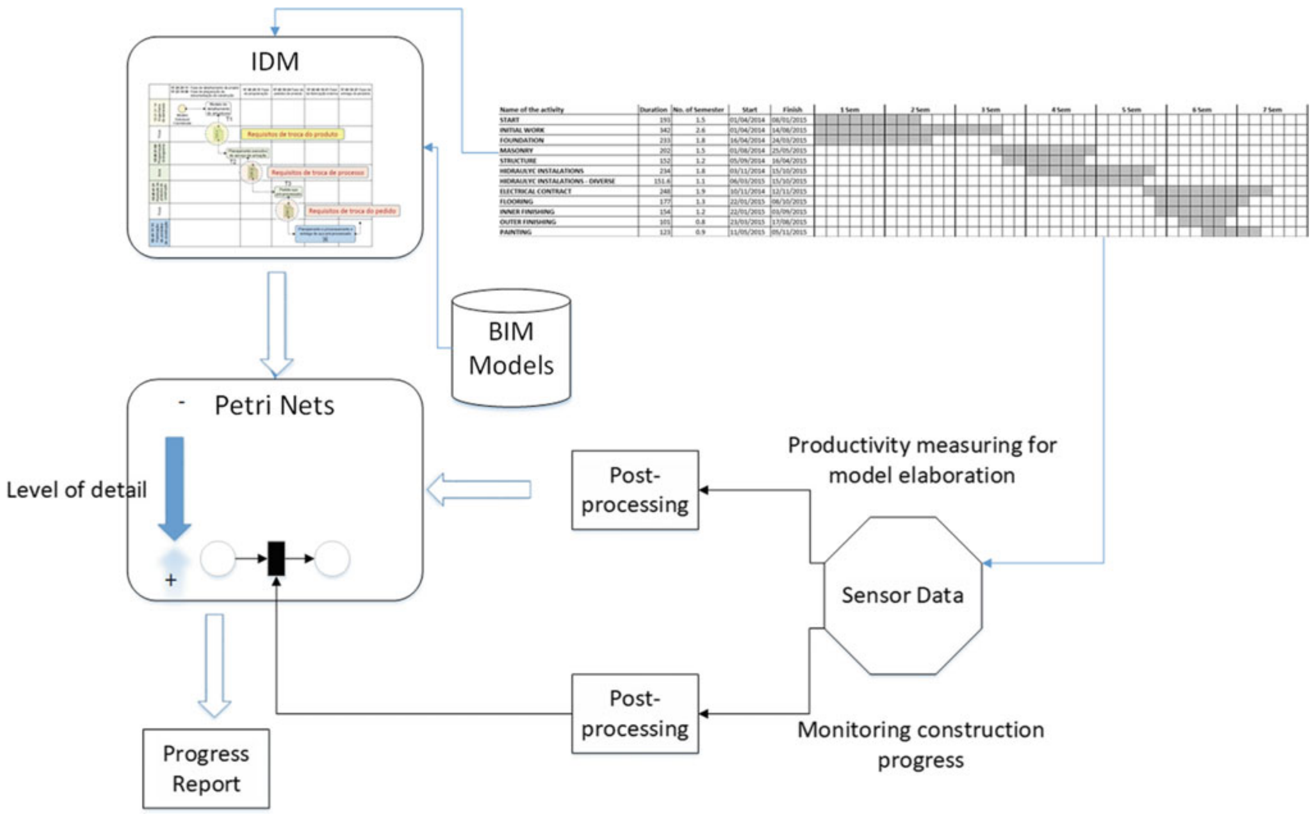

Fig. 2.1 Proposed framework for integration of 4D BIM models and sensor data for automatic construction report

Fig. 2.2 Image from the construction work in which the case study was developed

- In time measurement registration, stop periods smaller than 30 min has been deduct;
- Collecting plans, divided by sectors, were used, considering previously collected quantities;
- The amount of the workforce has been daily collected, identifying only those which were selected explicitly to the work being monitored;

Characterization of the working site: residential buildings for low-income people, 4 towers in total, 8 reference floor plans for each building, 8 apartments by floor and 2 different layout areas: 51 and 62 m^2 (Fig. 2.2).

Fig. 2.3 Skytrack

On each floor, there are 531.12 m^2 of slab area and 889.84 m^2 of structural masonry area, right foot of 2.60 m with 0.010 m of slab thickness (pre-slab) coated by pumped concrete.

Vertical transport had been implanted with Skytrack (Fig. 2.3), for the displacement of bricks and mortars pallets, until sixth floor was reached. A pinion elevator was used for the remaining floors.

Future work will be done in monitoring masonry construction workers on-site with a UWB system. The main objective is to study dimensioning of the work force, and non-added value displacement of resources to increase productivity on-site.

2.5.1 Simulation on Excel Spreadsheets

Based on productivity indicators, a "simulator" was developed and implemented on Microsoft Excel spreadsheets (Fig. 2.4). The quantitative data collected, have been tabulated following the productivity methodology developed by [19] of RUP (Unitary Rate of Production): daily RUP, cumulative RUP and potential RUP.

Based on these indicators, the "simulator" interpolates the most proper RUP for each project and search for the best productivity value. From those values, it identifies quantity and cost of workforce, and quantity of materials by step/floor required to attend the productivity goals (Fig. 2.4).

However, the "simulation" with Excel is restricted to show which resources, and in which place they must be applied, without allowing to deal with organizational and logistical optimization.

In trying to solve these variations, the ProModel, a software for simulation available to the research team, has been used.

2.5.2 ProModel Simulation

ProModel uses concepts such as entities, resources, locations, processing and arrivals, as basic building blocks of its simulation.

Entities are anything that will be processed in the simulation, and resources are agents in the transformation processes of entities. Both will generate, in general, the points looked after for analysis of the modeling details. In this simulation, entities are: raw material that end up being the structural masonry. And resources are the moving machinery and the pallets supplied.

Locations are fixed places which entities pass through: can be the place of arrival, processing or output. In the simulation made, the locations are: stock and sub stocks of supplies, each building tower and pinion elevators.

Processing are the logic of how entities travels from one location to another. Processing in this simulation are: transportation machinery with consideration for loading and unloading wait time, including supplies of pallets to specific building floors.

Arrivals are the moments in which the entities are inputted in some location in specific times of the simulation. In this simulation, the arrivals are: the input of machinery of transportation and the input of pallets of supplies.

	1º DIA			2º DIA			3º DIA			4º DIA			5º DIA		
Horário	7 às 17	17 às 17		7 às 17			7 às 17			7 às 17			7 às 9	9 às 17	
Serviços	Marcação	Elevação		Elevação			Elevação			Elevação			Elevação	1º Graute	
Duração	8.65 h	0.35 h		9.00 h			9.00 h			9.00 h			1.34 h	7.66 h	
Produção	91.07 m³	7.74 m³		200.00 m³			200.00 m³			200.00 m³			29.77 m³		
Produção %	100%	1%		33%			64%			95%			100%	85%	
Profissionais	6 Of	6 Of		6 Of			6 Of			6 Of			6 Of	6 Aj	
Blocos	12 pallets	1 pallets		26 pallets			26 pallets			26 pallets			4 pallets		
Argamassa	53 sacos	4 sacos		116 sacos			116 sacos			116 sacos			17 sacos		
Aço													430 kg		
Graute														7.7 m³	
Num. Viagens	12 viagens	1 viagens		26 viagens			26 viagens			26 viagens			5 viagens		
Tempo (min)	120 min	10 min		260 min			260 min			260 min			50 min		
Tempo Total	130 min			260 min			260 min			260 min			50 min		

Pavimento Selecionado	6º
Tipo de Transporte	Cremalheira
Tempo min de Espera 2º Graute	6 h

Selection of the type of transportation

Fig. 2.4 Production programming of the simulator inside Microsoft Excel

2.5.3 Results

In the ProModel simulation, it was possible to represent the site layout, and visualize horizontal and vertical transportation. It is also possible to identify some points that were impossible to identify in the Excel simulator. The programming and visual results of the simulator make it easier to understand many issues related to productive process.

Material stocks have been divided in locations: main (localized behind of tower 3) and temporary (in front of each tower according to productivity schedule). Figure 2.5 shows the construction site, and the horizontal transport logistic (the dashed line), which has been done by two Bobcats.

The ProModel simulation showed that, even with full capacity of all available equipment to produce, it would never reach the goals pre-established due to restrictions of layout and poorly studied choice of equipment. The test provided the perception that the equipment had a significant idle capability; however, it would not be possible to use it more often due to layout issues. For example, the Skytrack blocked a big area to be operated, thus paralyzing the zone around it (Fig. 2.3). It is possible to see the rear of the equipment during the movement to lift the pallets, blocking the access to any other equipment. In other words, while the material is lifted, it becomes impossible to do the horizontal transport of another material and vice versa.

Once identified the Skytrack problem using the ProModel simulation, it became possible to try other options to do the vertical transport. The solution tested has been to implement the pinion elevator, due to its load capability, cycle time and costs.

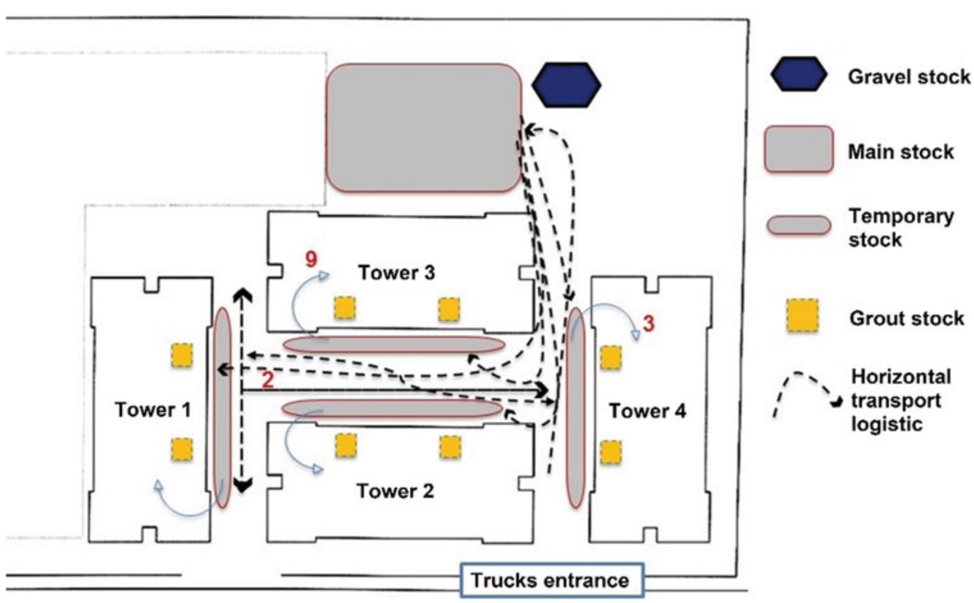

Fig. 2.5 On-site layout

Although it is a major investment (compared to the Skytrack), it produces better results to attend the production demand, and it would result in lower cost of the idle workforce, production delays, etc. Through the simulation, it is possible to identify these points, what brings the idea that there are many ways to predict a lot of Improvements and implement solutions on a short period of time.

Also, it is possible to see that between towers 3 and 4, there is a significant material flux, which afterwards has been identified as one of the logistic bottlenecks.

Some trials were also done in modeling with more detail each building tower. In these tests, the representation of each wall in each pavement was considered, as the localization system (UWB) could give the exact location of each individual of the workforce personnel. The main problem with this approach is that the order inputted in the simulation of work in each wall could not be predicted as decision still are made on site, of where to begin work of the present day.

2.6 Conclusions

In the context of evaluating construction processes simulation as a link between 4D BIM models, and data automatically collected on-site, primarily for automatic report of construction progress, two different initiatives were tested: an Excel spreadsheet, and a ProModel simulation. For the latter, different levels of details were trialed to adequate the model to future data collection situation in which workforce personnel will be tracked by a UWB system.

Results obtained from ProModel simulation (the potential of its use) were compared to a Excel spreadsheet simulation (worksheet calculus automation for the dimensioning of the workforce). Based on results of the simulations, it was possible to see a large improvement potential in using ProModel simulation when compared to traditional productivity system analysis. However, it is still necessary to develop strategies to information collection in real time (by means of sensors) to the promote corrective actions and strategy changes (through productivity failure) so it could be applied in a shorter period of time.

Although the ProModel choice has been linked to software availability, just a simple simulation result exposed problems that, in real life, were only realized after months of production as the cause of inefficiency in the workforce.

The amount of detail initially considered did not represented on-site layout and the movement of the workforce personnel (Excel). The initial model was further detailed to expose a rough movement of people in specific pavement, so it could be correlated to the data acquired by the UWB sensor system (ProModel). With the implementation of UWB system, it is expected the collection of real time of the flow of materials and people, the spent time on each workplace and with this every necessary information to the productivity simulation in real time.

However, the proposed implementation in ProModel does not allow to further development of a practical link with BIM models and construction progress on-site. Parallel work is being done in the simulation based on Petri Nets, which are largely used in the elaboration of controllers and the incorporation of observation of states of the system. To cope with conditions on-site such as weather, equipment fail, and so on, the use of stochastic transitions and transitions activated by external signals (from sensor on the field) are being incorporated in the model. Considerations are being made to provide choices made onsite by the workforce (for example, which wall to build first, each day) as a stochastic processes inside a new platform of simulation (Petri Nets), and to obtain through sensing, which walls are being constructed in real-time.

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References

1. Eastman, C.M., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: a Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors. Wiley (2011)
2. Andersson, L., Farrell, K., Moshkovich, O., Cranbourne, C., Farrell, K., Moshkovich, O., Cranbourne, C.: Implementing Virtual Design and Construction using BIM. Routledge (2016)
3. Kunz, J., Fischer, M.: Virtual design and construction: themes, case studies and implementation suggestions (2012)
4. Pan, W., Langosch, K., Bock, T.: Development of the process information modelling in the construction project: a case study of the ZERO-PLUS project. In: Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC) (2017)
5. Research Program, C.: BIM—Project Execution Planning Guide (2010)
6. Koo, B., Fischer, M.: Feasibility study of 4D CAD in commercial construction. J. Constr. Eng. Manag. **126**, 251–260 (2000)
7. Akanmu, A., Anumba, C., Messner, J.: Scenarios for cyber-physical systems integration in construction. ITcon (2013)

8. olde Scholtenhuis, L.L., Hartmann, T.: Changing scheduling purposes and evolving 4D-CAD models: a study of planning and realization in a utility project. In: Computing in Civil and Building Engineering, pp. 299–306. American Society of Civil Engineers, Reston, VA (2014)
9. Alzraiee, H., Zayed, T., Moselhi, O.: Assessment of Construction Operations Productivity Rate as Computed by Simulation Models. In: Proceedings of the Winter Simulation Conference (2013)
10. Akanmu, A., Anumba, C.J.: Cyber-physical systems integration of building information models and the physical construction. Eng. Constr. Archit. Manag. **22**, 516–535 (2015)
11. Oloufa, A.A.: Visual simulation programming for construction operations. In: The 9th International Symposium on Automation and Robotics in Construction (ISARC) (1992)
12. Arashpour, M., Bai, Y., Aranda-mena, G., Bab-Hadiashar, A., Hosseini, R., Kalutara, P.: Optimizing decisions in advanced manufacturing of prefabricated products: theorizing supply chain configurations in off-site construction. Autom. Constr. **84**, 146–153 (2017)
13. Li, C.Z., Shen, G.Q., Xue, F., Luo, L., Xu, X., Sommer, L.: Schedule risk modeling in prefabrication housing production. J. Clean. Prod. **153**, 692–706 (2017)
14. Altaf, M.S., Bouferguene, A., Liu, H., Al-Hussein, M., Yu, H.: Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. Autom. Constr. **85**, 369–383 (2018)
15. Jia, S., Yan, G., Shen, A., Zheng, J.: Dynamic simulation analysis of a construction and demolition waste management model under penalty and subsidy mechanisms. J. Clean. Prod. **147**, 531–545 (2017)
16. Alsafouri, S., Ayer, S.K.: Review of ICT implementations for facilitating information flow between virtual models and construction project sites. Autom. Constr. **86**, 176–189 (2018)
17. Correa, F.R., Maciel, A.R.: A methodology for the development of interoperable BIM-based cyber-physical systems. In: The 35th International Symposium on Automation and Robotics in Construction (ISARC) (2018)
18. Dijkman, R.M., Dumas, M., Ouyang, C.: Formal semantics and analysis of BPMN process models using Petri nets. Language (Baltim). **50**, 1–30 (2007)
19. Souza, U.L.E.: de: Como Aumentar a Eficiência da Mão-de-obra. (2006)

3 In Search of Sustainable Design Patterns: Combining Data Mining and Semantic Data Modelling on Disparate Building Data

Ekaterina Petrova, Pieter Pauwels, Kjeld Svidt, and Rasmus Lund Jensen

Abstract

Cross-domain analytical techniques have made the prediction of outcomes in building design more accurate. Yet, many decisions are based on rules of thumb and previous experiences, and not on documented evidence. That results in inaccurate predictions and a difference between predicted and actual building performance. This article aims to reduce the occurrence of such errors using a combination of data mining and semantic modelling techniques, by deploying these technologies in a use case, for which sensor data is collected. The results present a semantic building data graph enriched with discovered motifs and association rules in observed properties. We conclude that the combination of semantic modelling and data mining techniques can contribute to creating a repository of building data for design decision support.

Keywords

BIM • Semantics • Data mining • Pattern recognition • Knowledge discovery

3.1 Introduction

Cross-domain analytical techniques such as Big Data analytics, machine learning, semantic query techniques and inference machines have made the prediction of outcomes in building design possible and much more accurate. Research has shown promising advances within the use of machine learning and data mining techniques for model predictive control, meta-modelling for design space exploration, grey box modelling and advanced control strategies related to building energy systems, etc. These approaches carry a powerful potential and can directly influence the decision-making process in the Architecture, Engineering and Construction (AEC) industry by infusing it with an evidence-based character. The latter is of direct relevance for high-performance building design, which employs strict performance criteria. Responding to these criteria ideally requires evidence-based multidisciplinary input. Nevertheless, many decisions are still based on rules of thumb and previous experiences, and not on documented evidence. This leads to inaccurate predictions and assumptions regarding input parameters (e.g. occupancy rate), rare revisiting of analytical and building models during operation, no modification of design assumptions based on actual performance and thus a difference between predicted and measured performance.

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If knowledge discovered in building operation would be accessible, a design professional should be able to match the ongoing design with meaningful performance patterns. This article aims to investigate how data from buildings in operation can enable knowledge discovery and provide patterns that can be useful to inform future design processes. In particular, we consider available operational building data related to indoor space use, thermal performance and indoor climate collected from a culture and sports center. This use case is particularly interesting, as the building hosts different spaces such as conference and exhibition halls, ice hockey arenas, training facilities, swimming and wellness facilities, etc. The case provides operational building data captured through a sensor network and existing CAD drawings. From the collected datasets, we distil patterns and represent these so that they can be reusable by deploying the latest technological advances within Knowledge Discovery in Databases (KDD) [1] and semantic data modelling. The considered techniques are not often easily combined, especially not to inform future design decisions, which is the fundamental purpose of this study.

In this article, we first look into the diverse existing computational approaches for data analytics and knowledge discovery (Sect. 3.2), and semantic representation of building data (Sect. 3.3). In Sect. 3.4, we indicate how these data can be combined for knowledge discovery. We thereby suggest a system architecture aimed specifically at that purpose. Section 3.5 presents the use case we relied on for knowledge discovery, including the results obtained from that use case.

3.2 Data Analytics and Knowledge Discovery in the AEC Industry

The AEC industry nowadays generates large volumes of data associated with all stages of the building life-cycle. However, the traditional analytics can generate informative reports, but fail when it comes to content analysis [2]. As a result, data mining, pattern recognition and KDD have received major attention, as they can provide reliable results and effectively assist in analysis of data and extraction of knowledge. One definition of data mining is "the analysis of large observational datasets to find unsuspected relationships and to summarize the data in novel ways so that data owners can fully understand and make use of the data" [3]. Furthermore, Bishop defines pattern recognition as "the automatic discovery of regularities in data through the use of computer algorithms and with the use of these regularities to take actions such as classifying the data into different categories" [4]. Finally, KDD represents the overall process of knowledge extraction, with knowledge being the end product of the data-driven discovery and data mining being the step in the process which employs specific algorithms to discover patterns in the given data [5]. Fayyad et al. [1] state that the fundamental objective is to discover high-level knowledge in low-level data and define the transformation steps of raw data into actionable knowledge, i.e. data selection, preprocessing, transformation, mining and interpretation/evaluation of the discovered knowledge.

Widely accepted data mining categories include classification, clustering, association rule mining, regression, summarization and anomaly detection, targeting either predictive (supervised, directed) or descriptive (unsupervised, undirected) analytics [1, 6]. Supervised approaches describe the qualitative or quantitative relationships between the input and output variables and rely on domain expertise and significant amounts of training data. As a result, discovery of novel knowledge is unlikely, due to the predefined inputs and outputs. Unsupervised approaches (e.g. clustering, association rule mining, etc.), however, excel in discovering the intrinsic structure, correlations and associations in data and do not rely on training data, as inputs and outputs are not predefined. While predictive techniques are backward oriented due to their predefined target, descriptive ones are forward oriented (no explicitly defined target) and make it possible to discover interesting patterns and relationships in the data [7].

Within the high-performance and sustainable building design domain, the use of predictive approaches is usually related to prediction of building energy use and demand [8–10]; prediction of building occupancy and occupant behaviour [11, 12]; and fault detection diagnostics [13, 14]. Unsupervised tasks usually complement and target framework development [15–17]; discovery of patterns in occupant behaviour for improvement of operational performance [18]; and extraction of energy use patterns [19, 20]. Of course, KDD applications in the AEC industry span over a much broader area than the main categories defined above. For instance, Jun and Cheng [21] target high-performance with classification models for sustainability certification evaluation and Peng et al. [22] propose the use of BIM-based data mining approaches for improvement of facility management, etc.

These studies all show promising results when it comes to improvement of the building operation and occupant comfort. However, using knowledge discovery in data to support future design decision-making is an area that is not explored in detail. Studies have explored pattern recognition in simulation data and information extraction from BIM design log files [23], data-driven approaches for energy-efficient design by BIM data mining [24], as well as use of data mining for extracting and recommending architectural concepts [25]. Even though these studies demonstrate promising results within the use of KDD for design decision support, they rely on patterns only in design data. The data analysis results coming from existing buildings can rarely be linked to an early stage design, mainly because the data representations do not match. Thus, this study attempts to explore knowledge discovery in operational building data as a means to improve the decision-making in the performance oriented design process.

3.3 BIM and Semantic Representations of Building Data

The representation of building information nowadays typically happens using a BIM model, most commonly exchanged using the Industry Foundation Classes (IFC) data model, which captures building geometry, object properties, as well as semantics. The IFC schema is represented in the EXPRESS information modelling language. Any file exported to IFC is then typically an IFC STEP Physical File (IFC-SPF). Alternative formats for the IFC data model are available in XML, RDF and JSON. In all cases, however, the data model itself is derived directly from the EXPRESS or IFC-SPF format, making it the absolute reference.

Recent research and development initiatives have showed promising results using graph-based data modelling techniques, which are more common in a web environment (e.g. Neo4J, GraphDB). Such approaches are the preferred solution especially when a link needs to be made to outside data that is not typically captured in an EXPRESS-based format (e.g. sensor data, geospatial data). Typically, graph-based approaches focus entirely on the semantics and less on other specific data, such as geometry, large amounts of tabular data, etc. In such case, the semantic graph contains a direct link to the relevant information, which is kept in its original format. Both practice and research thus suggests the use of a graph-based format to capture building data, nevertheless keeping numeric data explicitly out of the semantic graph for computational performance reasons.

Representing semantic building data in a graph format can be done with the available ontologies by the W3C Linked Building Data (LBD) Community Group.[1] This includes a Building Topology Ontology (BOT) [26], a PRODUCT ontology, a PROPS ontology (properties), and an Ontology for Property Management (OPM). Using linked data technologies, links can then be maintained with other data [27], including operational data. For instance, device data can be captured using SAREF,[2] and sensor data can be represented using SSN[3] and/or SOSA.[4] For the building performance data, these ontologies do not serve well in case all operational data are targeted. In such case, a tabular format is still a lot more effective. The mentioned semantic ontologies can be used to capture static characteristics, such as averages, min-max values, features of interest, devices, and so forth.

3.4 Combining Semantics and KDD to Enhance High-performance Design: Proposed System Architecture

In this article, we consider the combination of KDD (Sect. 3.2) and building semantics (Sect. 3.3) for the purpose of design decision support. Most importantly, design decision support tools need to re-use the knowledge discovered in the available data through KDD and semantic data modelling. In this section, we focus entirely on discovering patterns using KDD and semantic data modelling, so that a repository of queryable design patterns can be built. Considering that the available data originate from multiple heterogeneous sources, a decentralized structure is preferred, which is most commonly realized using graph database approaches. Using these technologies, one can construct a web of semantic information in a decentralized manner, thereby allowing links between datasets, while respecting their original data structures. Transforming all data to a semantic format is possible and allows direct queries and applying semantic data mining techniques [28]. However, this approach may disallow many highly efficient data mining algorithms that can be used for retrieving useful knowledge. Instead, we propose to store the different kinds of data separately, thereby distinguishing between semantic data, geometric data and operational data (Fig. 3.1).

We additionally suggest a semantic data integration layer for linking the semantic data model of a building with its numeric representations and dynamic performance parameters. This layer serves as a reference model for the semantics of

[1]https://www.w3.org/community/lbd/.
[2]https://w3id.org/saref.
[3]https://www.w3.org/TR/vocab-ssn/.
[4]https://www.w3.org/ns/sosa/.

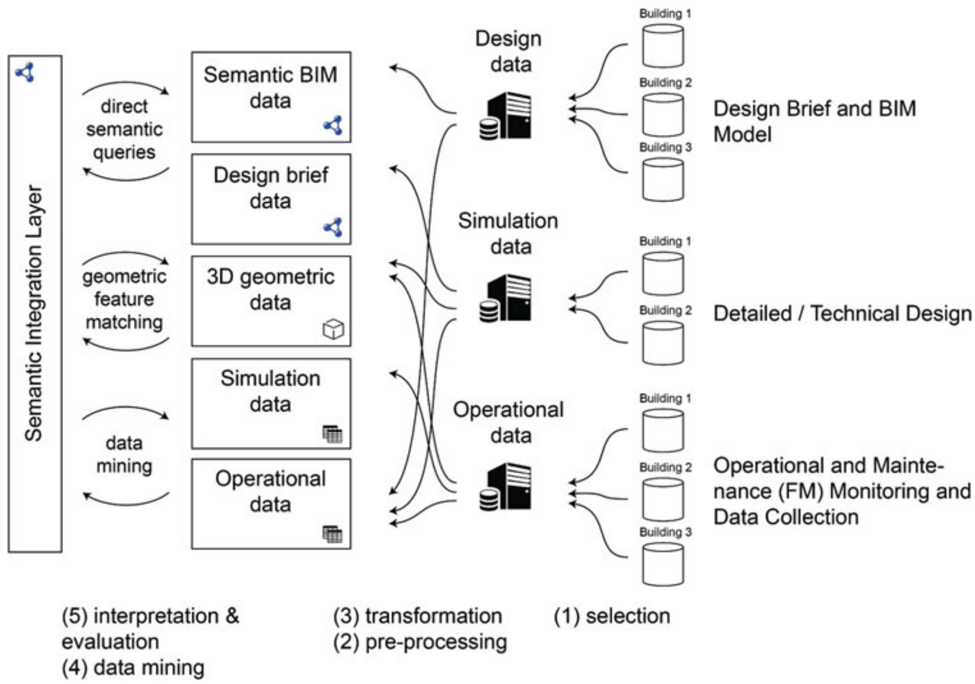

Fig. 3.1 Proposed system architecture for the combination of semantics and KDD

the different data sources and makes integration possible by pointing from within the semantic graph to web server addresses for operational data streams and geometric data files. As a result, systems accessing this data can recognize the relevant associations.

3.5 Use Case: Gigantium Cultural and Sports Center

Gigantium is a large cultural and sports center in Aalborg, Denmark, which opened to the public in 1999. Initially, it housed a hall with indoor football and handball courts, a sports hall and meeting facilities. In 2007, two ice skating halls were added, followed by swimming facilities in 2011. Today, Gigantium hosts an ice skating arena and training facility, sports halls, a concert and exhibition hall, swimming and wellness facilities, athletics hall, meeting rooms, a conference room, a cafe, and a lobby. The total area of the center is about 34,000 m^2. The ice skating arena can host 5000 spectators and the main hall capacity during concerts is 8500.

Operational building data is being collected through a sensor network consisting of 35 nodes, divided in all spaces [29]. The nodes monitor Temperature (°C), Relative Humidity (%), Air Pressure (hPa), Indoor Air Quality [Total Volatile Organic Compounds ((TVOC), ppb) and CO_2 (ppm)], illuminance (lux) and motion. The purpose of the data collection spans from monitoring indoor climate and thermal comfort, to providing information on space use for maintenance of the facilities. Clearly, the diversity of facilities and activities will be reflected in the collected data. For instance, temperature and relative humidity for meeting rooms, ice hockey arenas, and swimming pool will clearly be different. As a result, this use case provides an ideal dataset that can be used to test the proposed knowledge discovery approach in diverse environments within the same building. Most importantly, the discovered patterns can then inform design decisions related to thermal comfort and indoor climate. For example, persisting issues have been experienced with overheating in the conference room, which has led to a decision to renovate the mechanical ventilation system. The discovered insights would be invaluable to the decision-making related to the system design, by preventing uninformed decisions or use of design parameters that previously led to these issues.

3.5.1 Capturing the Building Semantics Using a Semantic Graph

As the use case building was built in 1998, there was no BIM model or 3D geometry available as project data. Instead, access was only available to 2D CAD data in PDF format. In this research, we generated a semantic graph from the available data. The spaces are represented using the BOT ontology as *bot:Space* instances. Each of the spaces is linked to its corresponding sensor nodes. These are defined as *bot:Element* and *gig:SensorNode* class instances. The *gig:SensorNode* class is a direct subClass of the *sosa:Platform* class, which is defined by the SOSA ontology to "carry at least one Sensor, Actuator, or sampling device to produce observations, actuations, or samples". Each sensor node hosts sensors, tracking different observable properties (Sect. 3.5). The information is described in a graph, following a combination of the BOT and SOSA ontologies, including custom classes and properties (namespace "gig:").

Important to note is that the data values are not directly stored in the semantic graph. Instead, a custom *gig:values* datatype property points to a web address that returns the data values as requested using the HTTP protocol. One is able to add attributes to an HTTP request, thereby setting query parameters such as time frame and refresh rate (e.g. *from = now-30d&to = now&refresh = 30*s). The result includes the pointer to the data stream for a *sosa:Result* of a *sosa:Observation*. A full data sample is available[5], yet, access to the sensor data streams is obviously restricted.

```
inst:room_1
        rdf:type bot:Space ;
        rdfs:label "Main hall" ;
        bot:hasSpace inst:room_2 ;
        gig:hasSensorNode inst:sensorNode_00000097, inst:sensorNode_000000B0,
                inst:sensorNode_00000077 ;
        geom:hasGeometry "2000, 3000, 4000, 6000"^^wkt:linestring.

inst:sensorNode_00000097 rdf:type gig:SensorNode, bot:Element ;
        rdfs:label "00000097" ;
        gig:observation "Space use" ;
        sosa:hosts inst:sensor_00000097_1 ;
        gig:placement "Placed in the middle of the hall, 8m above the floor. "

inst:result_1 rdf:type sosa:Result ;
        rdfs:label "Result of observation of Relative Humidity" ;
        gig:values "https://gigantium.dk/Gigantium2018instances?orgId=1&datastream=true"
```

Although not in direct focus for this paper, geometry of spaces is also stored in this semantic graph (*geom:hasGeometry*). This representation relies on a Well-Known Text (WKT) and can be used for simple visualization of the relevant spaces in a web-based floor plan layout visualization.

3.5.2 Knowledge Discovery in Operational Building Data

According to Fan et al. [30], operational building data is essentially multivariate time series data, where each observation is a vector of multiple measurements, and time intervals between subsequent observations are fixed. In that case, knowledge discovery can help capture relationships between variables over particular time periods (frequent repetitive patterns (motifs) and association rules [31]). This article demonstrates the implementation of these approaches on the diverse data streams from the cafe in the lobby. The location is chosen for its varying number of visitors both on a daily basis and during events, thereby minimising the likelihood of discovery of patterns due to regularly scheduled events. The data is collected in the period 12.03–16.05.2018, which constitutes the full available dataset so far. The hourly observations are exported as CSV files and preprocessed to enable motif discovery. Missing data fields are treated with five iterations of multiple imputation by running the Expectation Maximisation bootstrap algorithm in R. Symbolic Approximate Aggregation (SAX) [32] is further applied for dimensionality reduction and transformation of the input time series into strings. The univariate motifs in the

[5]http://users.ugent.be/~pipauwel/CIBW78_additionaldata.html.

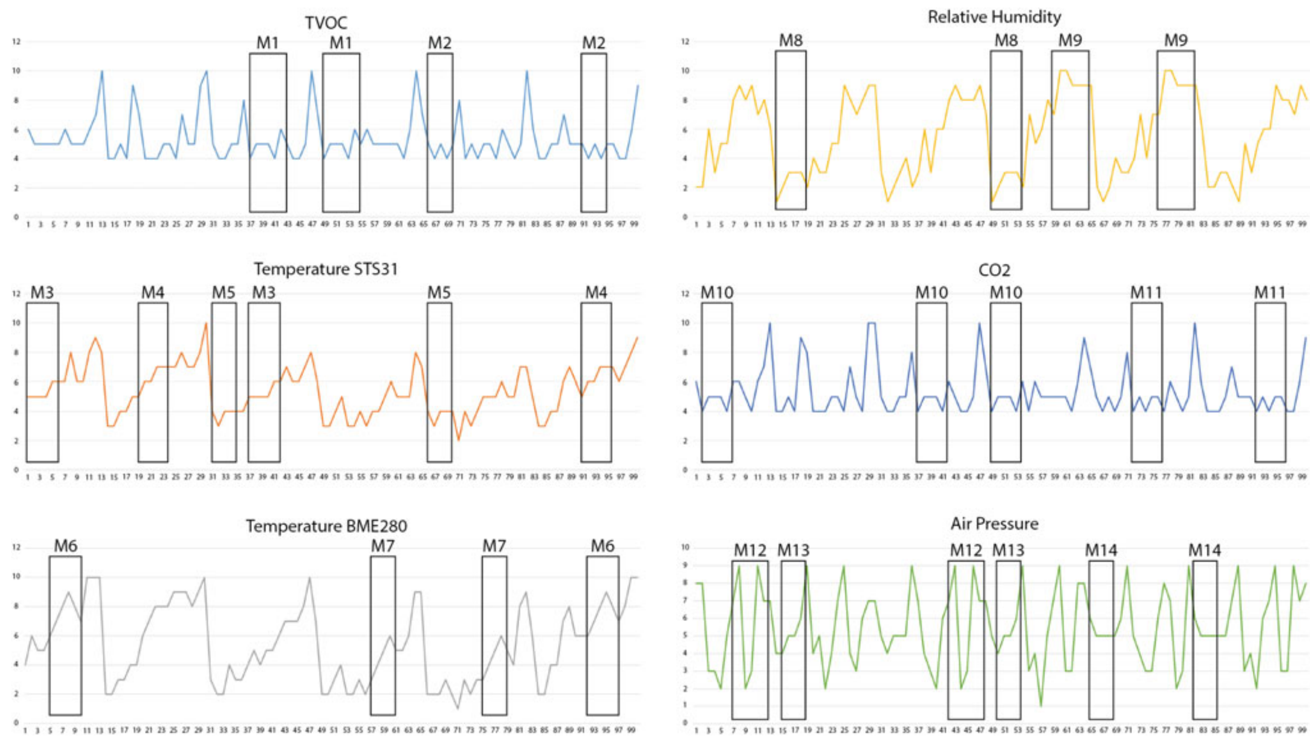

Fig. 3.2 Discovered univariate motifs (M1–M14) in the observed variables

multivariate time series data are discovered by identifying Longest Repeated Substrings with Suffix Tree implementation [33]. All repeated instances in the symbolic representation of the time series were identified, as for this effort only disjoint and non-overlapping motifs were considered. Figure 3.2 shows a graphical representation of the labelled discovered motifs (M1, M2,…, M14) in the sequence of the six variables. Overlapping motifs, as well as motifs contained within other motifs were excluded from observation.

To enable association rule mining, the discovered motifs are further used to construct a co-occurrence matrix. The columns of the matrix correspond to the motif number and the values for each row (1 or 0) indicate whether an univariate motif occurs or not. For example, M3 co-occurs with M10 and M6. Using the co-occurrence matrix, we obtained 10 sets of co-occurring items for the considered space. Associations between the items of these 10 sets have then been identified by using the association rule mining algorithm defined in [34]. Setting the minimum support and confidence as 0.2 and 0.8 respectively, this results in 13 association rules with support equal to 0.2 and confidence 1. Nine association rules are related to the co-occurrence of M7, M9 and M14. Other association rules are M1 => M10, M3 => M10, M12 => M10, M13 => M8, the last of them being a bidirectional association rule. This means that, for instance, when M12 occurs, the probability of M10 co-occurring is 100%. In this case, the rule indicates an association between observation patterns related to air pressure and CO_2. Naturally, the meaning of the discovered rules needs to be interpreted relatively to the design purpose. To be able to use the discovered knowledge, it also has to be connected to the semantic graph in Sect. 3.5.1. This can be done by representing the rules in a semantic graph, and linking this graph to the representation of sensor node 00000014, to create a single motif-enriched graph.

3.6 Conclusion

Knowledge discovered in operational data can be linked directly to a semantic representation of the building and can also be used for retrieving and re-using patterns. In this work, we aimed at making high-performance design rely more explicitly on tangible evidence from operational building data. In order to untap as much knowledge as possible from available sources, data mining and semantic data modelling are used. The combination of these techniques is not often intensively deployed in an AEC context. Yet, this combination provides great advantages, as formal semantic query can be combined with flexible and high-performing pattern recognition techniques. In this paper, we employ these techniques for the Gigantium Cultural and Sports Center in Aalborg. We hereby relied on the W3C ontologies for linked building data to model the building in direct connection to the available data streams. Furthermore, motif discovery and association rule mining were applied to the sensor data, thereby providing hidden knowledge through the semantic graph. This technique can in future work be used to build a repository that can inform any building designer of high-performing building design techniques.

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References

1. Fayyad, U., Piatetsky-Shapiro, G., Smyth, P.: From data mining to knowledge discovery in databases. AI Mag. **17**(3), 37–54 (1996)
2. Soibelman, L., Kim, H.: Data preparation process for construction knowledge generation through knowledge discovery in databases. J. Comput. Civil Eng. **16**(1), 39–48 (2002)
3. Hand, D., Mannila, H., Smyth, P.: Principles of Data Mining. MIT Press, Cambridge (2001)
4. Bishop, C.M.: Pattern Recognition and Machine Learning. Springer, NY (2006)
5. Piatetsky-Shapiro, G.: Knowledge discovery in real databases: a report on the IJCAI-89 workshop. AI Mag. **11**(5), 68–70 (1991)
6. Han, J.W., Kamber, M., Pei, J.: Data Mining Concepts and Techniques, 3rd edn. Morgan Kaufmann, Waltham, US (2012)
7. Fan, C., Xiao, F., Li, Z., Wang, J.: Unsupervised data analytics in mining big building operational data for energy efficiency enhancement: a review. Energy Build. **159**, 296–308 (2018)
8. Ahmed, A., Korres, N.E., Ploennigs, J., Elhadi, H., Menzel, K.: Mining building performance data for energy-efficient operation. Adv. Eng. Inform. **25**, 341–354 (2011)
9. Wang, Z., Srinivasan, R.S.: A review of artificial intelligence based building energy use prediction: contrasting the capabilities of single and ensemble prediction models. Renew. Sustain. Energy Rev. **75**, 796–808 (2017)
10. Zhao, H., Magoulès, F.: A review on the prediction of building energy consumption. Renew. Sustain. Energy Rev. **16**, 3586–3592 (2012)
11. D'Oca, S., Hong, T.: A data-mining approach to discover patterns of window opening and closing behavior in offices. Build. Environ. **82**, 726–739 (2014)
12. Zhao, J., Lasternas, B., Lam, K.P., Yun, R., Loftness, V.: Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining. Energy Build. **82**, 341–355 (2014)
13. Cheng, Z., Zhao, Q., Wang, F., Chen, Z., Jiang, Y., Li, Y.: Case studies of fault diagnosis and energy saving in buildings using data mining techniques. In: IEEE International Conference on Automation Science and Engineering, pp. 646–651 (2016)
14. Pena, M., Biscarri, F., Guerrero, J.I., Monedero, I., León, C.: Rule-based system to detect energy efficiency anomalies in smart buildings, a data mining approach. Expert Syst. Appl. **56**, 242–255 (2016)
15. D'Oca, S., Hong, T.: Occupancy schedules learning process through a data mining framework. Energy Build. **88**, 395–408 (2015)
16. Fan, C., Xiao, F., Yan, C.: A framework for knowledge discovery in massive building automation data and its application in building diagnostics. Autom. Constr. **50**, 81–90 (2015)
17. Yu, Z., Fung, B., Haghighat, F.: Extracting knowledge from building-related data—a data mining framework. Build. Simul. **6**(2), 207–222 (2013)
18. Xiao, F., Fan, C.: Data mining in building automation system for improving building operational performance. Energy Build. **75**, 109–118 (2014)
19. Miller, C., Nagy, Z., Schlueter, A.: Automated daily pattern filtering of measured building performance data. Autom. Constr. **49**, 1–17 (2015)
20. Wu, S., Clements-Croome, D.: Understanding the indoor environment through mining sensory data—a case study. Energy Build. **39**, 1183–1191 (2007)
21. Jun, M.A., Cheng, J.C.P.: Selection of target LEED credits based on project information and climatic factors using data mining techniques. Adv. Eng. Inform. **32**, 224–236 (2017)
22. Peng, Y., Lina, J.R., Zhang, J.P., Hu, Z.Z.: A hybrid data mining approach on BIM-based building operation and maintenance. Build. Environ. **126**, 483–495 (2017)
23. Yarmohammadi, S., Pourabolghasem, R., Shirazi, A., Ashuri, B.: A sequential pattern mining approach to extract information from BIM design log files. In: 33rd International Symposium on Automation and Robotics in Construction, pp. 174–181 (2016)
24. Liu, Y., Huang, Y.C., Stouffs, R.: Using a data-driven approach to support the design of energy-efficient buildings. ITCon **20**, 80–96 (2015)
25. Mirakhorli, M., Chen, H., Kazman, R.: Mining big data for detecting, extracting and recommending architectural design concepts. In: IEEE/ACM 1st International Workshop on Big Data Software Engineering, pp. 15–18 (2015)
26. Rasmussen, M.H., Pauwels, P., Hviid, C.A., Karlshøj, J.: Proposing a central AEC ontology that allows for domain specific extensions. In: Proceedings of the Joint Conference on Computing in Construction (JC3), pp. 237–244 (2017)
27. Pauwels, P., Zhang, S., Lee, Y.C.: Semantic web technologies in AEC industry: a literature overview. Autom. Constr. **73**, 145–165 (2017)
28. Ristoski, P., Paulheim, H.: Semantic web in data mining and knowledge discovery: a comprehensive survey. J. Web Semant. **36**, 1–22 (2016)
29. Rodriguez, I., Lauridsen, M., Vasluianu, G., Poulsen, A.N., Mogensen, P.: The Gigantium smart city living lab: a multi-arena LoRa-based testbed. In: 15th International Symposium on Wireless Communication Systems, Lisbon, Portugal (2018) (in press)

30. Fan, C., Xiao, F., Madsen, H., Wang, D.: Temporal knowledge discovery in big BAS data for building energy management. Energy Build. **109**, 75–89 (2015)
31. Fu, T.C.: A review on time series data mining. Eng. Appl. Artif. Intell. **17**, 164–181 (2011)
32. Patel, P., Keogh, E., Lin, J., Lonardi, S.: Mining motifs in massive time series databases. In: Proceedings of the 2002 IEEE International Conference on Data Mining. (2002)
33. Weiner, P.: Linear pattern matching algorithms. In: 14th Annual IEEE Symposium on Switching and Automata Theory, pp. 1–11 (1973)
34. Han, J., Pei, J., Yin, Y., Mao, R.: Mining frequent patterns without candidate generation: a frequent-pattern tree approach. Data Min. Knowl. Disc. **8** (2004)

The Role of Knowledge-Based Information on BIM for Built Heritage

4

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Abstract

Information about historic buildings is extensive and fundamental for maintenance, preservation, and restoration purposes. However, a common problem is lack of standardization and documentation updating. This work aims to gather 3D BIM model of historic buildings with their knowledge-base through a formal ontology. A terrestrial laser scanner was used to collect geometrical data. The resulted point cloud was delimited by Regions of Interest (ROI) then downsized and segmented. The selected case study is the Ballroom, part of the Pampulha Architectural Ensemble designed by the renowned architect Oscar Niemeyer. This building, located in Belo Horizonte, Brazil, has a unique, sinuous and irregular shape, recently listed as World Heritage site by UNESCO, rising its documentation importance both locally and worldwide. The CIDOC-CRM (International Committee for Documentation—Conceptual Reference Model) and FRBRoo (Functional Requirements for Bibliographic Records—object oriented) is the source for create the building ontology, later connected to the model. The proposed methodology shows that linking geometric and semantic database into a BIM environment can improve heritage documentation.

Keywords

Reality-based surveying • Ontology-based system • Computer vision

4.1 Introduction

The undergoing massive growth of digital technology is affecting all areas of Architecture, Engineering, and Construction (AEC), enabling unprecedented efficiency on all fronts, from design to construction. In recent years, there has been an increasing amount of research focused on the use of these technologies also in the stock of existing buildings, mainly in the maintenance and operation. The computational development in AEC, among them the Building Information modeling (BIM), allowed the integration of information about the whole system with the elements of the 3D model. According to [1],

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in addition to BIM, the semantic web technologies allow describing the information behind the artifact, namely all documentation about the complete context of the artifact, including all kinds of relations, types, properties, and links. For the heritage conservation purpose, linking BIM and semantic web technologies is valuable to gather and document all relevant information of the historic building, which is mandatory for renovation and maintenance works.

As demonstrated in other studies (e.g. [2–4]), the accurate data recording into BIM components allows the creation of a database where the interested party can filter specific information, providing an efficient documentation system able to memorize data for future interventions. Concerning BIM database, [5] pointed out the importance of the ontological model for built heritage representation. Ontology is described by [6] as "an explicit specification of a conceptualization" this means that when the universe of knowledge is precisely defined, a set of objects with relationships can represent it, creating a knowledge-base readable through programs. Therefore, an ontology-based system is based on the formalization of all knowledge related to each artifact through semantic networks, regarding entities, properties, and relationships. In order to support information management during the investigation and restoration activities, this paper presents an ongoing research that aims to develop a framework to integrate optical measuring surveys (material properties, geometrical data) and knowledge base (historical analysis, e.g. information models within its context) in a BIM Model. Our approach relies on an ontology-based system to represent the knowledge related to the historical events of each technological components of the building.

This paper is organized as follow: the state of art section addresses the scientific achievements in the field of BIM for heritage, integration of BIM and ontology by semantic web technologies, and computer vision applied to 3D data. Section 4.3 describes the methodological workflow applied to the case study. The results obtained and their potential application for the heritage conservation domain are discussed in Sect. 4.4. Section 4.5 outlines the limitations and future works offered by our approach.

4.2 State of Art

Some authors like [7] developed a conservation process model that aimed to be more than a data repository on existing architecture but also supporting heritage conservation process, which could be reached by means of ontologies. So, its approach is based on a double scope, capturing and representing the semantic contents of cultural heritage conservation process and suggesting a model that may achieve integration, mediation and interchange of information in the cultural heritage conservation field.

The International Committee for Documentation (CIDOC) developed a Conceptual Reference Model (CRM) to categorize and represent the semantic data of cultural heritage [8], the ISO 21127:2006 standard for cultural heritage documentation; it is an attempt by the Committee of the International Council of Museums (ICOM) to achieve semantic interoperability of cultural heritage data. CRM is an ontology which primary role is "to serve as a basis for mediation of cultural heritage information and thereby provide the semantic 'glue' needed to transform today's disparate, localized information sources into a coherent and valuable global resource" [9]. In addition, the CIDOC group has been working on documents to create specific ontologies such as FRBRoo, its objective is represent the bibliographic information and interchange it with museum data. Some works have explored this focused on cultural heritage [7, 10]; others for cultural information for tourism purposes [11]; software engineering [12]; compare bibliographic metadata [13]; and others.

Transpose geometric data to enriched models is not a direct operation demanding computational techniques able to convert early survey into workable information. Treatments like noise reduction through statistical tools or point cloud processing [14], filter outlier and small regions. Large point collections also compromise modeling tasks causing computational cost increment. A usual solution is point cloud downsizing [15] when recursive structures reduce cloud density. Additionally, segmentation provide easily convertible regions to models. A standard method to separate defined form is RANSAC common used to recognize regular elements such wall, ceil, floor, etc. [16].

4.3 Overview of the Approach

The methodological framework adopted for the proposed Knowledge-based BIM modeling consists in four steps as follow:

(1) Gathering Non-Geometrical Data: historical survey to track record of the different stages of the building (use changes, relocations, historical stratification, and degradations);

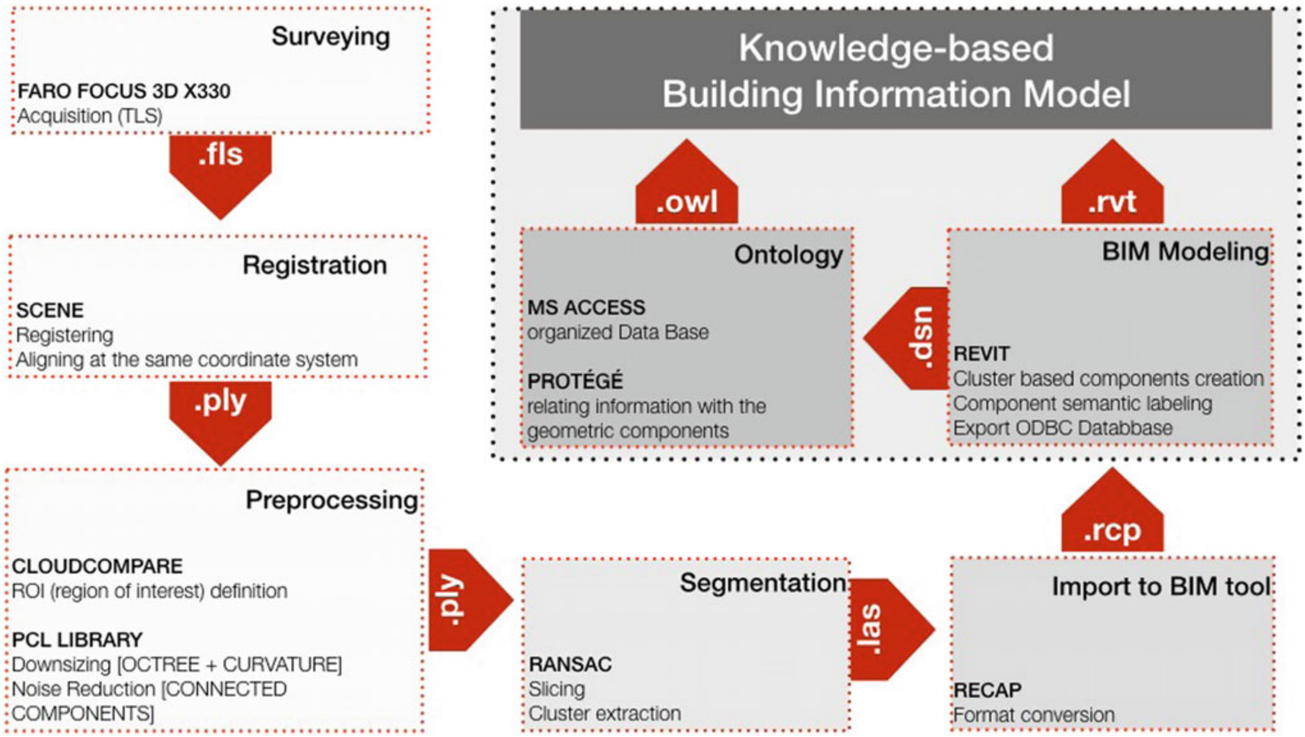

Fig. 4.1 Workflow for knowledge-based BIM

(2) Gathering Geometrical Data: measurement survey using laser scanning; point cloud registration; processing of the raw data and segmentation;
(3) Modeling building components in a BIM environment: defining identifiable classes in order to associate the non-geometrical data with them;
(4) Developing the Knowledge-based Information integrated with the BIM model. We adopted the CIDOC-CRM as the core ontology in this study to map heritage information in an extensible semantic framework.

Figure 4.1 summarizes these steps, starting from the laser scanner surveying, showing the software and format file for interoperability of each step.

4.4 Building the Knowledge-Based Information Model

4.4.1 Case Study: The Oscar Niemeyer's Ballroom in the Pampulha Modern Ensemble

A case study was selected to demonstrate the creation of a knowledge-based digital built heritage model. The presented case study is the Ballroom designed by Oscar Niemeyer in 1940 (Fig. 4.2). The Ballroom is one of the four buildings planned by Niemeyer surrounding an artificial urban lake that shapes the Pampulha Modern Ensemble (PME), located in the city of Belo Horizonte, in Brazil. The UNESCO's World Heritage Convention listed the PME for its outstanding universal value as a Cultural Landscape in 2016. Niemeyer's works in Pampulha establish a synthesis between local and regional practices and the principles of modern architecture language focused on new experiments in reinforced concrete.

The Ballroom is located in an artificial island and is composed of the main building, whose spatial organization is defined by two internally secant circles, with a free span exceeding the 19 m supported by a 40 cm high concrete grid. The horizontal interior roof plane flows on the outside to become a winding marquee supported by slender round columns, connecting the main building with the dressing room, a small outdoor stage, and a lily pond. In 2003, Niemeyer, at the age of 93 years, was responsible for the directives of intervention inside the building, constructing an auditorium and adapting the service rooms and sanitary, justified by the use change of the place. The modeling and comparison between the current state

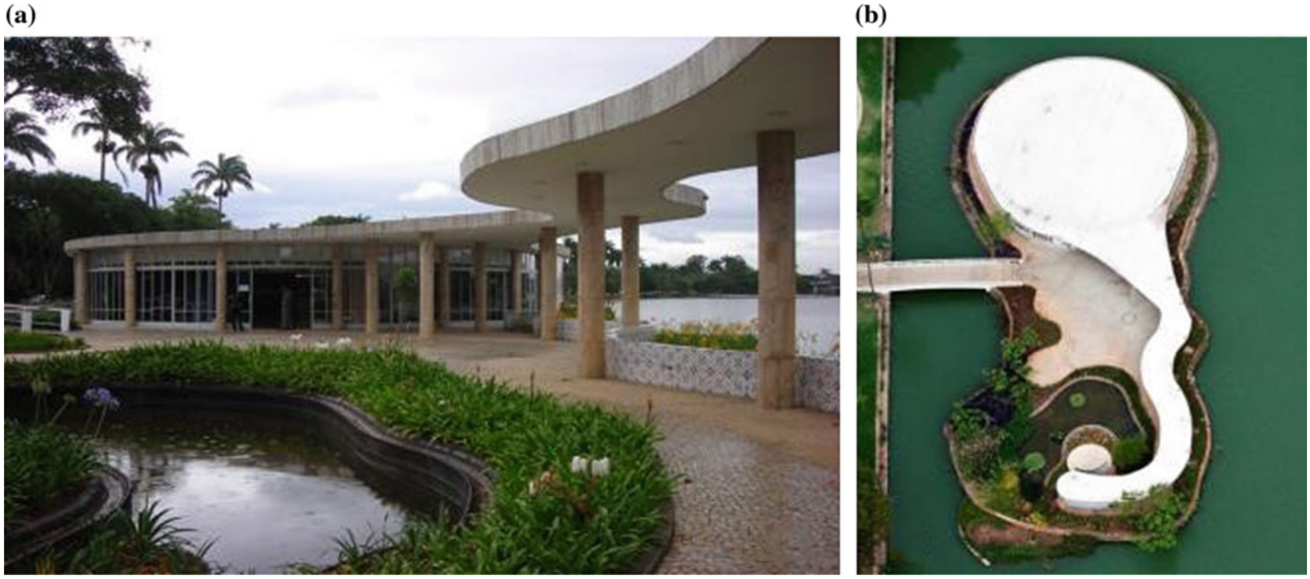

Fig. 4.2 Images of the Ballroom **a** view from the garden; **b** aerial view

of the building and its projected situation are fundamental to the understanding of the process of use change and documentation of these historical events. In the future, the building can undergo a new alteration if the use of the building changes again, but now as World Heritage any modifications must be strictly controlled to preserve its original features.

4.4.2 Non-geometric Data

A historical building, even with high quality data raised, still needs information related to its history to compose the model and make it semantically complete [17]. To do this, it is necessary to search in responsible public bodies official documents that bring important data such as their initial design, construction elements, materials, interventions suffered over time, their incorporated legal and social aspects and their impacts (environmental or anthropological).

For this work, the IPHAN (Institute of Historical and Artistic Heritage), a governmental institute responsible for preserving and disseminating the country's material and non-material assets, provided all documental information data. For this purpose, IPHAN produces an historic survey of each asset listed as cultural heritage, gathering documental information, photos, sketches, web references and other kind of media.

4.4.3 Geometric Data

The Ballroom location and its unique architecture reduces geometric data acquisition to few options. The building is inside a restricted air space due its proximity to Pampulha Regional Airport, excluding UAV survey. Another limitation is Ballroom position surround by Pampulha's Lake. Those factors associated with curved aspect on mainly construction elements demand a particular approach, described on next sections.

Data Acquisition. Due site restrictions, building singularity and accuracy required, TSL became the only alternative to geometry acquisition. Faro Focus 3D X330 was used covering both inside and outside areas of the building, including the roof (see Fig. 4.3). Ballroom rounded aspect and the lake were overcame positioning the scanner at different ranges. Point cloud density deteriorate as TSL and object surface distances increase. This and other issues are treated on preprocessing phase.

Preprocessing. Challenges imposed by the Ballroom architecture and the limited available areas for TLS arrange elevated the number of scanning position. Registration creates a dense point cloud containing around 370 million points. Although many points been required to represent a complex structure, the initial survey infeasible its analysis. Restrict the raw point cloud to region of interest (ROI) is primordial to exclude unnecessary data. Even been intuitive, this simple step

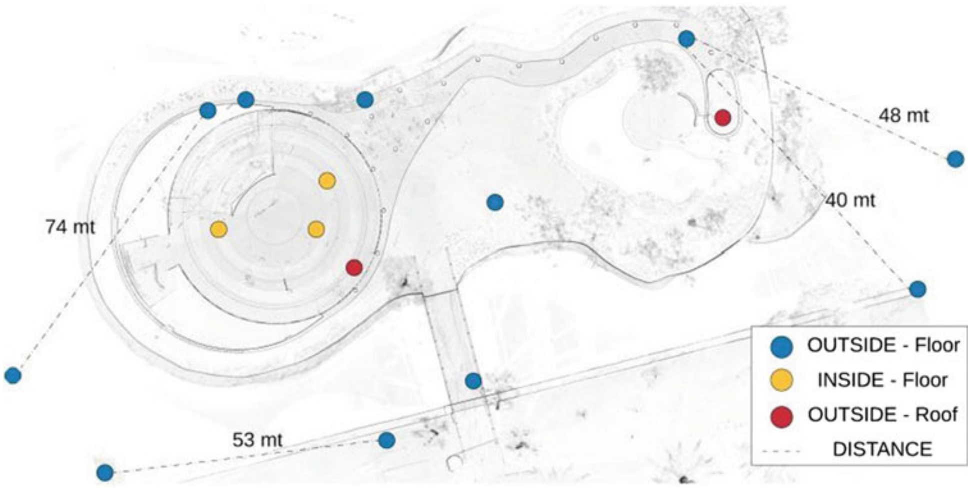

Fig. 4.3 Scanner position over Ballroom area (colors for distinct situations and measures in lines for distant positions)

lower the cloud to 90% of its original size. Density normalization is possible by octree downsizing, method able to recursively reduce point clouds defining a fix cubic structure and maintaining only center points [18]. At this stage, data decrease reaches 75% forcing even more withdrawing. Keep wiping out points after the previous methods probably compromises objects forms, invalidating the cloud for modeling. An appropriate policy to lower cloud avoiding impairments is point exclusion weighting by its curvature. Computing normal and estimating local curvature [19] enables choose regions better describable with few points. Maintaining higher density where curvature also increase is desirable (blue vs. red areas at Fig. 4.4) a simple algorithm minimize the cloud to 56 million points (15% of raw size).

Small clusters, usually noise, possibly remain but a well know method easily exclude those groups applying connected components strategies [20].

Segmentation. A wide spread technique for point cloud segmentation on as-built state of art is RANdom SAmple Consensus (RANSAC) [21]. In brief, its operation tries to find a defined form (e.g. planes, spheres, and cylinder) estimating how well random sets of points fits the model. Floor and roof are basically planes what makes RANSAC capable to recognize it precisely just adjusting inliers. The same applies to columns assuming cylinders as model for detection. For non-regular forms, a model is not possible turning hard to segment these structures. Alternatives for RANSAC are available but horizontally slicing the prepressing cloud was already enough for Ballroom case.

4.4.4 Modeling Through the Point Clouds

The Dense surface models resulted from the 3D point cloud has non-structured features as lack of topology and semantic discretization. This makes the building information modeling an essential step to provide intelligence for these data. Due to the rounded building shape, automatic feature extraction was not effective. We used EdgeWise Software for automation but it failed to deliver satisfactory results.

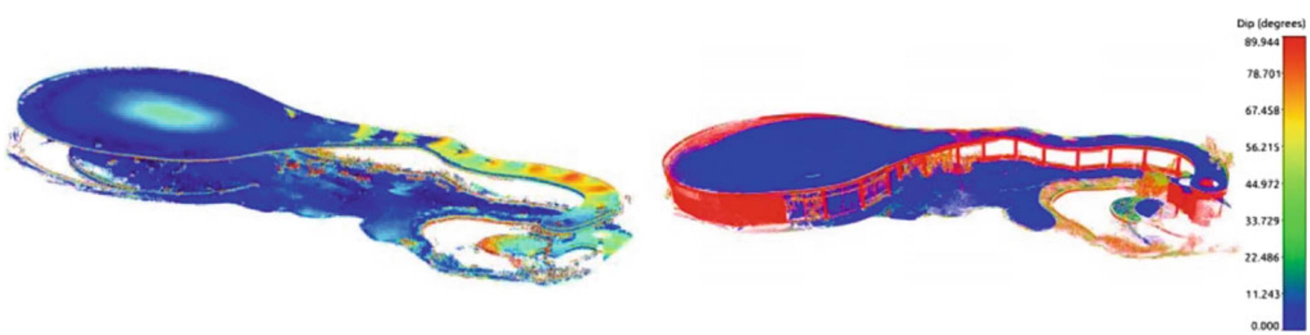

Fig. 4.4 Curvature analysis of downsized Ballroom scanning from lowest to highest [blue to red]

Fig. 4.5 Model of Ballroom: **a** point cloud section of interior; **b** rendered interior view of BIM model; **c** rendered exterior view of BIM model

The Ballroom was modeled in a BIM environment using Autodesk Revit 2018 tool. We performed the modeling approach directly on the imported point clouds from Autodesk ReCap tool, using the native systems families (walls, columns, floors, roofs, curtain walls), model in-place components (ceilings) and hosted in system elements (windows, doors).

In addition, the slices were used for the modeling of the other components in BIM environment. The greatest difficulty of this particular building is in its non-regular form, which requires more time to finish the job.

Each BIM component was labeled using the OminiClass element, which is primitive of Revit and shared parameters were used to the CIDOC_CRM ontological system. Figure 4.5 depicts the final model of The Ballroom and a section in the aligned point cloud.

4.4.5 Knowledge-Based

In the Historical Building conservation process thousands of facts and documents are collected to shed light on the past contextualizing the object in study, but nevertheless it is difficult to integrated and connect all evidential data in a relationship to the physical substance of the building.

The goal of connect all kind of documents, including digital measurements acquisition and 3D Models is to provide the means to the historical data in such a way that the following functionality is supported:

1. Maximize interpretation capability over the documents and facts contextualizing their spatiality;
2. Possibility of the knowledge revision in the building life cycle;
3. Comparing all intervention on the building;
4. All kinds of comprehensive material and historical studies.

Some software are being developed to sketch out this ontological process so that structure the information in classes and subclasses and connect them to the instances through relationships. In this way, it is possible to visualize all the non-geometric relations this artifact has. In this research, the Protégé software was used to create the ontological basis.

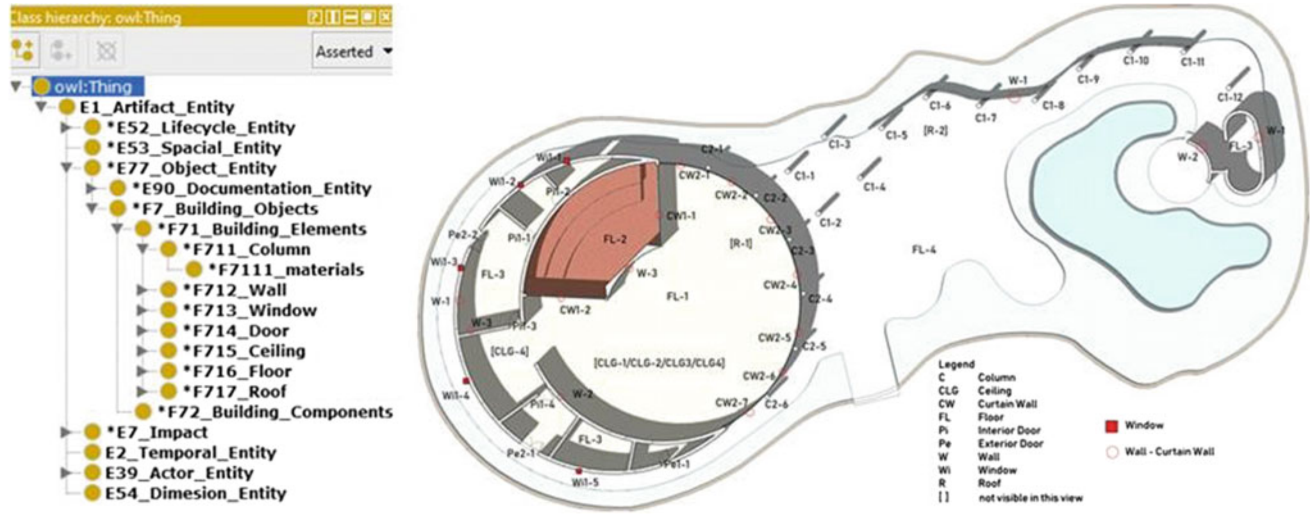

Fig. 4.6 Knowledge-base created in Protégé and element markings

The artifact was defined as the main class coded as E1 (CRM Entity), according to the CIDOC-CRM, being followed by entities (subclasses): temporal, spatial, object, impact, actors, dimension and life cycle. The subclasses with the letter F were taken from FRBRoo. In each of them was inserted the information, in subclasses and instances. Some ad hoc adjustments to the codes were necessary to follow a logical sequence and to detail the information; they are shown with an asterisk. The graph result is shown in Fig. 4.6.

After creating the ontology, this was connected with 3D model based on [22]. The elements were named according to the proposed ontology and DBLink Plugin formalized the integration between the BIM environment and knowledge base. The steps for integrating the ontology with the BIM model are described in four steps, according to [22]:

- Export the BIM model information in Access format, containing its properties and objects, throught DBLink plug-in;
- Conversion of the ontology file in MySQL format, for OWL connection of Protégé software;
- It is necessary to name the objects and properties in the ontological software according to the BIM model, and;
- Mapping and identification of the semantic structure in the two databases (Revit and Protégé).

4.5 Conclusions and Future Works

In this paper, we proposed and detailed a methodological framework to improve the BIM model for heritage, including non-graphical information. Contribution especially needed when the modeling environment is created for existing buildings starting from scratch.

This work aimed to collaborate to overcome the drawback the low level of semantics in use of BIM for heritage, as cited by [1]. Corroborating with said by [23], the exploitation of point cloud, the BIM environment could produce fully detailed graphics documentation, for the conservation of historic structure, in 2D and 3D representation. The aggregation of semantic information in the model enhances the digital documentation, as shown in our approach.

This study demonstrated the possibilities to linking non-structured data into BIM to create a comprehensive environment for built heritage knowledge management. Ontology-based Systems allows the integration of the building's components with knowledge representation and management, fostering a useful bundling of geometrical and non-geometrical data. BIM proved to be a tool capable of managing information collected and modeled, improving its availability and accessibility.

Working semantics into BIM is not trivial work. For this reason, we envisage for next research the development of a tool based on dataset for IFC model structure, enabling easily visualization of the BIM model components and their linked semantics.

References

1. Acierno, M., Cursi, S., Simeone, D., Fiorani, D.: Architectural heritage knowledge modelling: an ontology-based framework for conservation process. J. Cult. Heritage **24**, 124–133 (2017)
2. Pauwels, P., Bod, R., Di Mascio, D., De Meyer, R.: Integrating building information modelling and semantic web technologies for the management of built heritage information. In Digital Heritage International Congress (Digital Heritage), vol. 1, pp. 481–488. IEEE (2013)
3. Fai, S., Graham, K., Duckworth, T., Wood, N., Attar, R.: Building information modelling and heritage documentation. In: Proceedings of the 23rd International Symposium, International Scientific Committee for Documentation of Cultural Heritage (CIPA), Prague, Czech Republic. pp. 12–16 (2011)
4. Dore, C., Murphy, M.: Integration of historic building information modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. In: 18th International Conference on Virtual Systems and Multimedia (VSMM), pp. 369–376. IEEE (2012)
5. Garagnani, S., Manferdini, A.M.: Parametric accuracy: building information modeling process applied to the cultural heritage preservation. Int. Arch. Photogrammetry Remote Sens. Spat. Inf. Sci. **5**(1) (2013)
6. Gruber, T.R.: A translation approach to portable ontology specifications. Knowl. Acquisition **5**(2), 199–220. ISSN 1042-8143, https://doi.org/10.1006/knac.1993.1008 (1993)
7. Fiorani, D., Acierno, M.: Conservation process model (CPM): a twofold scientific research scope in the information modelling for cultural heritage. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. **XLII-5/W1**, 283–290. https://doi.org/10.5194/isprs-archives-XLII-5-W1-283-2017 (2017)
8. CIDOC CRM Homepage, http://www.cidoc-crm.org/. Last accessed 2018/05/02
9. Doerr, M et al.: Realizing lessons of the last 20 years: A manifesto for data provisioning & aggregation services for the digital humanities (a position paper). D-lib Mag. **20**(7/8) (2014)
10. Guillem, A., Bruseker, G., Ronzino, P.: Process, concept or thing? Some initial considerations in the ontological modelling of architecture. Int. J. Digit. Libr. **18**(4), 289–299 (2017)
11. Di Giorgio, S., Felicetti, A., Martini, P., & Masci, E.: Dati. Cultura Italia: a use case of publishing linked open data based on CIDOC-CRM. In EMF-CRM@TPDL, pp. 44–54 (2015)
12. Aalberg, T., Vennesland, A., Farrokhnia, M.: A pattern-based framework for best practice implementation of CRM/FRBRoo. In: East European Conference on Advances in Databases and Information Systems, pp. 438–447. Springer, Cham (2015)
13. Nurmikko-Fuller, T., Jett, J., Cole, T., Maden, C., Page, K.R., Downie, J.S.: A compara- tive analysis of bibliographic ontologies: implications for digital humanities. Digit. Humanit. 639–642 (2016)
14. Han, X.F., Jin, J.S., Wang, M.J., Jiang, W., Gao, L., Xiao, L.: A review of algorithms for filtering the 3D point cloud. Sig. Process. Image Commun. **57**, 103–112 (2017)
15. Wang, C., Yong, K.C., Changwan, K.: Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. Autom. Constr. **56**, 1–13 (2015)
16. Jaehoon, J., et al.: Productive modeling for development of as-built BIM of existing indoor structures. Autom. Constr. **42**, 68–77 (2014)
17. Simeone, D., Cursi, S., Toldo, I., Carrara, G.: BIM and knowledge management for building heritage. In Acadia, vol. 2014, pp. 681–690 (2014)
18. Trevor, A. J. B. et al.: Efficient organized point cloud segmentation with connected components. Semant. Percept. Mapp. Explor. (SPME) (2013)
19. Meek, D.S., Walton, D.J.: On surface normal and Gaussian curvature approximations given data sampled from a smooth surface. Comput. Aided Geom. Des. **17**(6), 521–543 (2000)
20. Elseberg, J., Borrmann, D., Nüchter, A.: Efficient processing of large 3d point clouds. In: XXIII International Symposium on Information, Communication and Automation Technologies (ICAT). IEEE 2011
21. Lu, Qiuchen, Lee, Sanghoon: Image-based technologies for constructing as-is building information models for existing buildings. J. Comput. Civil Eng. **31**(4), 04017005 (2017)
22. Cursi, S., Simeone, D., & Coraglia, U. M. An ontology-based platform for BIM semantic enrichment
23. Quattrini, R., Malinverni, E.S., Clini, P., Nespeca, R., Orlietti, E.: From TLS to HBIM. High quality semantically-aware 3D modeling of complex architecture. The international archives of photogrammetry. Remote Sens. Spat. Inf. Sci. **40**(5), 367 (2015)

5 Heritage Building Information Modelling (HBIM): A Review of Published Case Studies

Ian J. Ewart and Valentina Zuecco

Abstract

Building Information Modelling (BIM) is gaining popularity worldwide as a system of collaboration and data management for the AEC sectors. However, the usefulness of BIM has largely been seen in the design and construction phases, rather than in post-construction—for example in facilities management or occupancy. As the concept of BIM has matured, there has been increasing interest in applying these concepts and technologies to heritage buildings (HBIM), despite some fundamental differences: heritage buildings usually have a long history of use, re-use and alteration; their management is often related to conservation rather than occupancy; and they are often a social and community resource. Therefore, HBIM is faced with a different set of stakeholders to 'standard BIM', which leads us to question the optimistic perceptions of its usefulness when BIM is applied to a historic built environment context. We investigate this question by thinking about how we can characterise HBIM, and what sort of information will give us further insights. Using published case studies as a source of secondary data, we have collected information about specific characteristics, which we analyse and use to discuss the uptake of HBIM, the purpose of HBIM and the role of stakeholders. We conclude that there needs to be a significant change in perception of HBIM by academics and technicians, before it is likely to be adopted by practitioners in the heritage sector.

Keywords

HBIM • BIM • Heritage buildings • Case studies

5.1 Introduction: The Distinctive Nature of Heritage BIM

5.1.1 Perspectives on BIM

While long recognised as a significant influence on the architecture, engineering and construction (AEC) sectors, descriptions and definitions of Building Information Modelling (BIM) have grown to include aspects of the lifecycle of a building beyond its design and construction. Typical of these is the National BIM Standard as quoted in ISO 29481-1: "Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined

This research was carried out as part of an Erasmus+ Student Traineeship between the Universities of Reading, UK and Padova, Italy. This allowed VZ to work on her Master's thesis, which forms the basis of this paper [1].

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as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder."

Of note is the emphasis on collaborative working and the vision of BIM as a method that can be applied at all stages of the life of a building, as well as the lack of a specific mention of a 3D model as a pre-requisite of BIM. In particular, there is an important implication that the range of stakeholders is likely to be wide and varied, and that access to (and possibly also management of) digital data is a democratic process. Other definitions focus on the technologies of BIM (e.g. those of the US Government's GSA, Heritage Foundation Canada, and software suppliers such as Autodesk), especially the use of 3D models, often at the expense of downplaying the role of collaboration in the production and use of the system. Conversely, in a similar vein to the NBS quoted above, several authors and organisations have seen the collaborative aspects of BIM as the key tenet, and recognised some of the issues this exposes. In the UK, for example, the British Standards Institute is working to formulate and promote a set of standards to ensure digital data quality, and the American Institute of Architects aims to increase awareness of issues of interoperability through the BuildingSMART Alliance, for "the sharing and exchanging of information via integrated technological solutions, no matter what project phase, discipline or participant role in the built asset life cycle" [2].

So, while the benefits of BIM are generally held to include reduced costs and errors, increased efficiency in planning and construction, collaboration in design and understanding, and more efficient facilities management, the published literature is heavily biased towards the design and construction phases of the building's life cycle (e.g. all the case studies in 'the BIM handbook' [3]). Successful and widespread adoption of post-construction BIM is proving elusive, in part due to issues of interoperability and digital data standards, and how these clash with existing data and asset management systems, but also due to the different skillsets that are traditionally available to an FM manager, and the need for a cultural shift [4]. If applying BIM to finished buildings is proving difficult, then an extra layer of complexity becomes apparent when the same systems are applied retrospectively to older existing buildings, usually without native digital data, since much of the information is 'born analogue', or even basic information on structures and services that would be required to construct a comprehensive and useful dataset [5].

5.1.2 Understanding HBIM

'HBIM' (as Historic Building Information Modelling) was first mentioned in 2009 and defined as "a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements (including detail behind the scan surface) are accurately mapped onto a point cloud or image-based survey" [6: 311]. The term has since been broadened to include the heritage environment generally, recognising a more complex set of historic and aesthetic values and the involvement of multiple stakeholders and disciplines.

Heritage has a social value for individuals and communities but there are national and regional differences in evaluating heritage status and value. The north European concept of heritage is wider than for example in Italy, meaning a broad idea that records and expresses the long processes of historic development, as social reference point and a contribution to local identity. It is defined by English Heritage as "all inherited resources which people value for reasons beyond mere utility" [7: 71]. This definition includes more than just physical features, and even buildings which are architecturally irrelevant or even no longer standing can be recognized as heritage for having had an historic role within the community in the past.

Since a heritage building is a distinct type of existing construction that involves facility management activities, HBIM appears to have the same potential as the implementation of BIM for the whole building lifecycle but also the same unresolved issues. Over and above the issues described above for a typical new or recent construction, a heritage building lacks a complex set of data that takes account of the history of construction, maintenance and reconstruction of all or part of the structure and services. In many cases the available information is insufficient to provide the basis for such a dataset. Furthermore, the distinct nature of heritage buildings as cultural and community resources raises the question of what data is useful, relevant and important to the building, to satisfy the needs of a wide range of stakeholders, or which of those stakeholders should be omitted from consideration? As well as the owners, occupants and facilities managers of a typical building, there are other stakeholders such as visitors, historians, researchers, students, heritage organizations, local government and the local community. In cases of building intervention architects and engineers may cooperate with surveyors, archaeologists, conservationists and academics.

Applying BIM to heritage buildings seems to be an opportunity to mobilise a proactive approach to management and conservation of the construction and its community value. BIM can provide a set of information useful for FM tasks such as condition monitoring, preventive maintenance, repair and restoration, but also for the management of visitors and related security and safety planning. Moreover, the Information Model could be a resource for many or all of the stakeholders interested in the historic and social value of the building, as well as supporting further studies. However, this potential is largely illusory as "the effective use of BIM is far more complex than new build and the benefits less obvious" [8: 19]. To date, the majority of recent research has focused on the technical challenges of producing accurate 3D models, rather than investigating the wider application of HBIM and resolving some of the softer issues described above.

Currently there is no comprehensive overview of HBIM case studies in the published literature, but a review of BIM for existing buildings was carried out in 2014 including papers reporting on heritage buildings [9]. That study confirmed that the available literature tends to cover only a few topics, especially technical challenges such as automated data extraction, whereas issues beyond the modelling stage were largely unconsidered by academics at that time.

5.2 Methodology: A Case Study Database

To offer some insights into the application of BIM tools and techniques to the heritage sector, the authors carried out a systematic literature search to identify any published case studies and analyzed the content [1]. The aim was to understand what BIM for heritage currently means, so the research papers deemed eligible for the case study database were the ones that claimed to be examples of BIM for heritage, historic or existing buildings, regardless of whether they effectively used a BIM process or not. We did not include publications that discussed the application of BIM to heritage in an abstract way, but included only those that described an actual example of the application of BIM to a physical building. This was not restricted to the use of the term 'BIM' specifically, but also included any BIM-like methods of digital data management and control.

A comprehensive literature search of the main academic sources was conducted, using specific keywords that were adjusted according to the keywords used on each eligible publication. These were primarily: BIM, HBIM, heritage, historic, digital, archaeology, cultural, restoration, conservation, reconstruction, maintenance. During the search process it became clear that Italy is a prominent advocate of HBIM, so equivalent searches were carried out in Italian (one of the authors, VZ, is Italian). With very few exceptions, the publications reported on academic or research projects; the remainder were from industry, and usually the result of support from suppliers of hardware or software. This research ended in October 2017 at which time the database contained fifty-two case studies.

Data from each case study was extracted to examine both the object of study—the building or site studied—and the methods and results of the BIM process as reported by the authors. This resulted in 27 data variables in two sets (see Table 5.1), one relating to the building data and one relating to the publication data, for each of the 52 case study ID numbers. The variable data ranged from simple binary responses (e.g. was additional data attached to the model? Yes/No), to multiple responses (e.g. 12 different results to 'what was the purpose for creating the HBIM model?').

Table 5.1 Variables extracted from each case study

Building data variables		Publication data variables	
Object type	Listing status	Keywords	Plug-ins
Country	Conservation status	Purpose	Data added
City	Original use	Stakeholders	Data type
Size	Current use	Type of survey	Data exported
Area	Access to public	Survey software	Other software
Accessibility	Construction year	Modelling software	Publication year
Ownership		New component families required?	HBIM useful?

5.3 Analysis and Discussion

5.3.1 Introduction

A comprehensive presentation and discussion of the results of this analysis is in preparation, but we are able to offer some preliminary insights here. Considering the 27 variables for each of the 52 identified case studies, and with between 1 and 12 responses for each variable, the resulting database can be divided up, combined, and analyzed in a number of ways. As mentioned above, a more detailed analysis is in preparation, but after an initial review of the data we are able to present three points of discussion that offer some basic but interesting insights, which we will expand upon in the near future: uptake of HBIM; purpose of HBIM; and HBIM stakeholders.

5.3.2 Trends in the Uptake of HBIM

As discussed in the introduction, BIM has had a generally positive reception, especially among the academic and policy-making communities, and has been adopted with little resistance in the AEC sector. It has made fewer inroads as a technology into the post-construction phases of the life of a building, although in many ways the philosophy of BIM as collaborative and accessible data management is ingrained within the working practices of many FM professionals. It is this disconnect between existing philosophies of practice and suspicions about the need for digital tools and skills that is halting general acceptance. The specific requirements of the heritage sector exacerbate those issues: funding is even more limited, the skillsets of the stakeholders are less aligned with recent digital technologies, and the needs of the stakeholders are even wider. Therefore, it is no great surprise that the uptake of HBIM appears to be relatively slow.

If we are correct in assuming that our database is sufficiently comprehensive to be representative of the actual use of HBIM, then there has been a fairly gradual increase in the last decade, but by no means an exponential growth. Similarly, Figs. 5.1 and 5.2 show that the reported use of HBIM is not only increasing gently, but is also localized, particularly in Europe and especially in Italy. Furthermore, many of the non-European case studies have been carried out by European researchers, with the same individuals appearing repeatedly as authors.

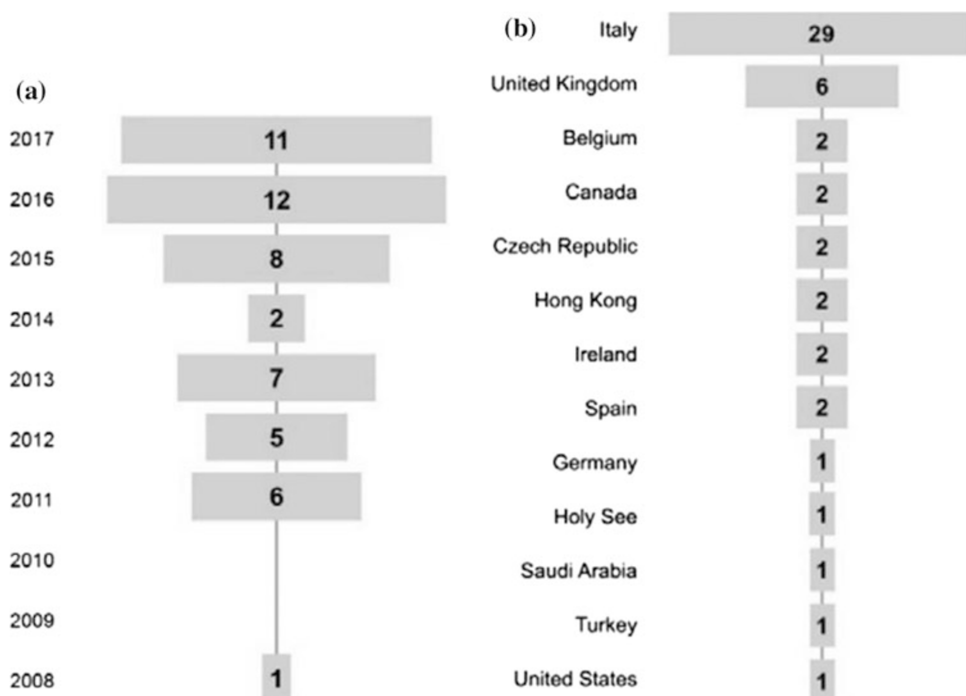

Fig. 5.1 **a**, **b** Number of case studies per year and per country

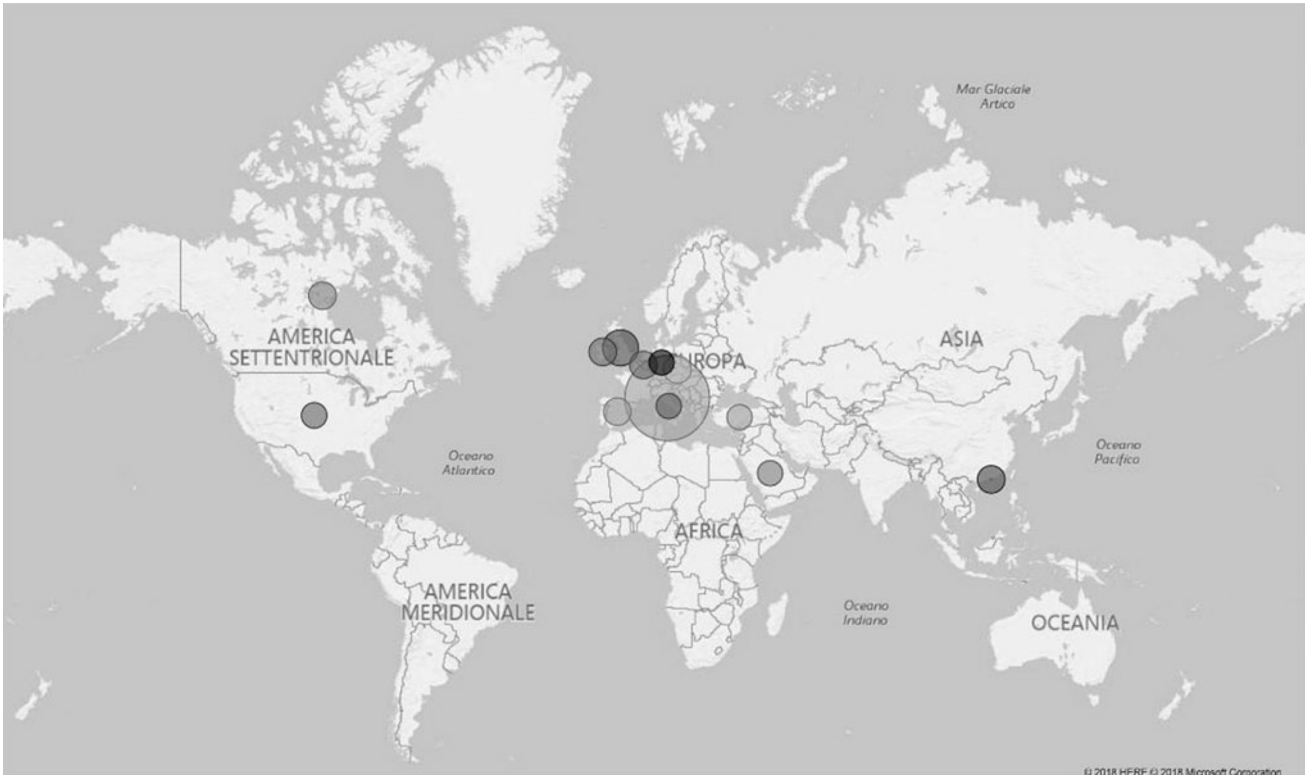

Fig. 5.2 Case study locations by country (circle size = no. of case studies)

5.3.3 The Stated Purpose of HBIM Systems

As a relatively new method and technology, BIM has been undergone something of an explosion in interest in the last decade—the so-called BIM-boom was widely reported and predicted in many construction industry journals. From the beginning the main point of BIM was the management of a comprehensive digital dataset in a way that allowed collaborative working. As tools and technologies developed, so did the possible uses including for example 3D, 4D and even 5D models, and everything from LEED to disaster planning (e.g. [10]).

However, while this demonstrates the *potential* for use, it does not reflect actual working practices. In fact, it may be seen as a consequence of the confusion that still surrounds the purpose of BIM, with different practitioners 'doing BIM' in very different

Table 2 Stated purpose of HBIM case study

Purpose	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Testing BIM for heritage	1				1	2		3	6	2	15
Planned conservation/FM				1	2	3	1	4	1	7	19
Archaeological/architectural studies				4	1	1	1	1	4		12
Restoration project				1		2	1	3	2	3	12
Representing historical stages				1	2	2		1	1	2	9
Valorization of heritage					1	3	1	1	5	3	14
Energy/wind/sunshine analysis					2	1		2		2	7
Degradation analysis					1			3	1	1	6
Structural analysis					1			2		3	6
Virtual reality					1					1	2
3D printing						1			1		2
Unknown											0

ways [11] To evaluate the perception of BIM when applied to heritage buildings, we extracted from the case studies a summary of the stated purpose for carrying out the work. While this is in some ways a subjective judgement, especially as almost none of the case studies explicitly defined their aim, we narrowed down the wide variety of implied purposes to a list of 12 (see Table 5.2).

From this we can see that there is no distinct purpose or trend that helps to answer the question 'why did you do this case study?' Of those that were most clear about their purpose, the three most common are the use of HBIM for conservation; an academic exercise to test the workflow; and as a tool to valorize, or ascribe value to the building studied. And, reflecting some of the enthusiasm for BIM, these case studies do not claim to have actually achieved their loosely stated purpose, they are instead describing the *potential* uses of HBIM.

5.3.4 Stakeholder Involvement and Responses

Of particular interest, and informed by the apparent confusion about the role of HBIM (and it could be argued, of BIM also), is the degree to which stakeholders are recognised as an important part of the technology and philosophy of BIM. As shown in Table 5.2 the published case studies imply that there are a number of potential purposes for HBIM, but they remain, at present, apparently unfulfilled. For the authors of the published case studies, their potential purposes are linked to imagined stakeholders, such as the claim that a HBIM system could "…serve as the basis for future conservation and rehabilitation of the structure [and] can benefit the restoration, conservation, and management of this important heritage building as well as contribute to an integrated record of the more intangible aspects of the construction process" [12: 119].

Invoking these imaginary target audiences gives HBIM a cloak of usefulness, but in truth there is little to suggest that the diversity of stakeholders inherent in a heritage site have been seriously considered as part of these case studies (see Table 5.3). The list of stakeholders we have produced, based on the content of the publications, is by no means exhaustive, and yet it still goes to show the diversity of uses that HBIM could serve. These are potential users of an HBIM system, each with their own requirements for data and means of access; a facilities manager for example would have very different needs to a local historian. It is worth noting that the largest proportion of all stakeholders identified in all case studies is 'unknown', that is, in more than half the case studies there is no mention of stakeholders.

Table 3 Stakeholders discussed in case studies

Stakeholder	Total	Stakeholder	Total
Unknown	28	Facility managers	4
Conservationist, architects	11	Heritage organisations	3
Students, researchers, historians	10	Local governments	3
Visitors	6	Occupants	0
Owner	4	Archaeologists	0

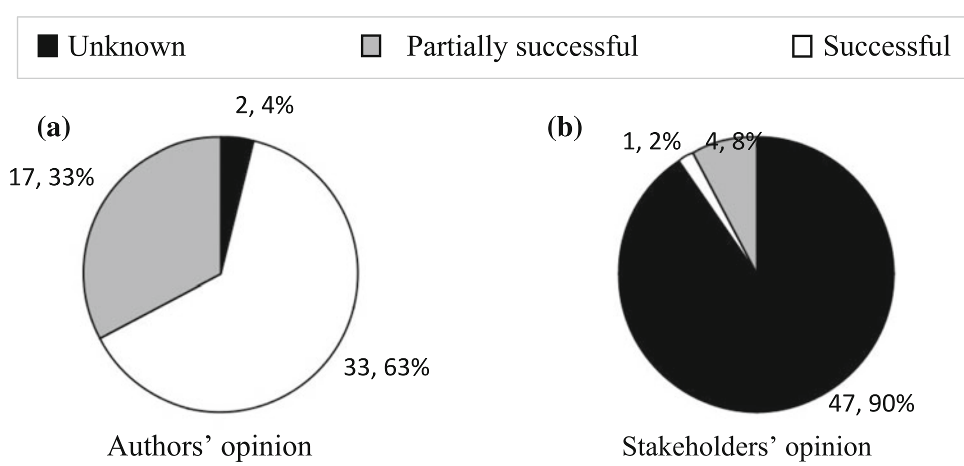

Fig. 5.3 **a**, **b** Opinions as to the success of the HBIM system produced

We can see a similar picture in a final piece of data from our analysis, which was an assessment of whether the HBIM system was deemed a success. Figures 5.3a, b show that the vast majority (96%) of the authors of the publications (and usually also the systems) viewed it favourably, in fact none of the studies reported negative feedback. On the other hand, the opinion of other stakeholders (apart from the authors) is unknown in the vast majority of cases (90%), and of those whose evaluation of the HBIM system was reported, in all cases the stakeholders were less enthusiastic than the authors.

5.4 Conclusions

Our study shows that there is a slowly growing suggestion that BIM could be usefully applied to heritage sites and buildings, especially in Europe. The cases we report on here all try to apply existing BIM workflows to their highly varied examples, and report a very high degree of satisfaction with their results. This is despite the widely reported distinctive requirements for a heritage site, in particular the extent and condition of standing buildings or remains of buildings, an expanded range of stakeholders to acknowledge the social importance of heritage sites, and the complexities of conservation and historic change. We can also note the lack of a clearly defined purpose or structure for a HBIM system, and the absence of any evidence that the reported potential uses for such a system have actually been realized. The majority of these cases are primarily interested in solving technical challenges, in particular ever more accurate 3D models of complex structures, without reflecting seriously on the needs of the presumed stakeholders.

It would therefore be perhaps somewhat harsh, but apparently true to say that this study suggests that we do not know what HBIM is, who it is for, or why it would be used, but it is gaining popularity among academics and industry technicians in the hope that resolving technical issues will make it a practical proposition to the heritage sector generally.

References

1. Zuecco, V.: Implementing Building Information Modelling for Heritage Buildings and Multiple Stakeholders: Literature Overview and Case Study. Unpublished thesis, Università degli Studi di Padova (2018)
2. American Institute of Architects: Document B141.: Standard Form of Agreement Between Owner and Architect with Standard Form of Architect's Services. AIA, Washington DC (1997)
3. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers and Contractors. Wiley, Hoboken (2011)
4. Davies, R., Harty, C.: Measurement and exploration of individual beliefs about the consequences of building information modelling use. Constr. Manag. Econ. **31**(11), 1110–1127 (2013)
5. Bryan, P., Antonopoulou, S.: BIM for Heritage: Developing a Historic Building Information Model. Historic England, Swindon (2017)
6. Murphy, M., McGovern, E., Pavia, S.: Historic building information modelling (HBIM). Struct. Surv. **27**(4), 311–327 (2009)
7. Drury, P., McPherson, A.: Conservation Principles, Policies and Guidance. For the Sustainable Management of the Historic Environment. English Heritage, London (2008)
8. Brookes, C.: The application of building information modelling (BIM) within a heritage science context. Discovery Innovation and Science in the Historic Environment. Historic England Research Project Report no. 7351 (2017). ISSN2398-3841
9. Volk, R., Stengel, J., Schultmann, F.: Building information models (BIM) for existing buildings—literature review and future needs. Autom. Constr. **38**, 109–127 (2014)
10. Shou, W., Wang, J., Wang, X., Chong, H.Y.: A comparative review of BIM implementation in building and infrastructure industries. Arch. Comput. Methods Eng. **22**, 291 (2015)
11. Dainty, A., Leiringer, R., Fernie, S., Harty, C.: BIM and the small construction firm: a critical perspective. Build. Res. Inf. **45**(6), 696–709 (2017). https://doi.org/10.1080/09613218.2017.1293940
12. Fai, S., Filippi, M., Paliaga, S.: Parametric modelling (BIM) for the documentation of vernacular construction methods: a BIM model for the commissariat building, Ottawa, Canada. In: ISPRS—Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 2 (5/W1), pp. 115–120 (2013)

6 Next Generation of Transportation Infrastructure Management: Fusion of Intelligent Transportation Systems (ITS) and Bridge Information Modeling (BrIM)

Alireza Adibfar and Aaron Costin

Abstract

Bridges are one of the most important elements of the sustainable transportation infrastructure network that require significant care and consideration. Aging and deterioration are two main complications in their operation and maintenance that require precise data and efficient technologies to improve the quality of their lifecycle management. Intelligent transportation systems (ITS) have been altering the infrastructure management process by converting it into an automated process to capture, store, analyze, and manage the data. While the data have helped the management process, the issues of heterogeneity of the data and non-interoperable databases are still challenges for fully integrated management of the infrastructure. Thus, there is a crucial need for an integrated database that can help in consolidation of data management. Building Information Modeling (BIM) is one of the recent technologies that its benefits have motivated its utilization in the transportation infrastructure, and their specific use for bridges is known as Bridge Information Modeling (BrIM). Currently bridges are being inspected biannually and only structural data are being recorded for their assessment. This paper suggests the inclusion of traffic data in lifecycle management of bridges and introduces ITS as a great source of data, and BrIM as a great visual database that can help in enhancing the integration and management of databases. Fusion of ITS data with BrIM can provide many benefits for efficient operation and management of bridges that eventually improves the quality of facility management and helps as a reliable tool for decision making and budget allocation. In this paper, BIM and ITS capabilities have been discussed and finally a framework has been suggested to illuminate the dataflow process.

Keywords

Intelligent transportation systems (ITS) • Bridge information modeling (BrIM) • Bridge inspection • Operation and maintenance • Data management

6.1 Introduction

Reliable, safe, and efficient ground transportation network is one of the most important pillars of every country. The key to superior operation and management of infrastructure, especially bridges, is having plenty of timely and reliable data accessible. Aging and deterioration are two main complications about bridges [1, 2]. Thus, they are needed to be inspected routinely and accurately to ensure the reliable flow of traffic stream over the network. Bridge inspections provide a comprehensive overview and data about the bridge health status that help in understating their need for repair or rehabilitation, which enables robust decision making about allocating the required budget and resources accordingly.

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However, the amount of manual inspection needed with the lack of funding is a major challenge [3]. The cost of data collection for evaluation of the transportation network is high, as it requires considerable amount of time and experienced technicians and inspectors. Inspections causes lane closures and traffic delays that can negatively affect the commuters and economic impact. Furthermore, inspectors and crews can be placed in unsafe situations that increase the risk for the whole process [4].

While the structural inspection information is beneficial for the maintenance and management of bridges, there are some deficiencies. From a structural aspect, McGuire et al. [5] stated that collected data is only reflecting the description of the fault and its position, but neither reflecting its effects on the load bearing capacity of the bridge, nor providing useful information for enhanced management of bridge operation. This presents a major need to ensure bridges are continually inspected to prevent disastrous failures or collapse. However, traditional bridge inspection methods are risky, difficult, and prone to error [6]. Inspections are conducted and based on the inspector's experience and expertise, and errors are likely to occur due to personal judgment [7]. Furthermore, rehabilitation takes a great amount of time, effort, and monetary investment [8]. Therefore, there is a great need for an efficient, cost effective, and reliable method for bridge inspection and management to ensure safe and reliable passage. Different technologies are now helping inspectors and state departments of transportation (DOT) to capture considerable amount of data with higher precision and degree of reliability. Shaghlil and Khalafallah [4] reviewed how new technologies can help in monitoring the condition of road, and analysis of the damage severity, and help in better determination of maintenance needs. For example, laser scanners mounted to truck and drones are now being used for monitoring road distress and defects, which have reduced the inspection costs, increased safety, and optimized the accuracy of the captured data.

While the structural and physical assessment of roads and bridges are vital for transportation network, this research hypothesizes that real-time traffic data can enhance the quality of assessment, judgement, and decision making. Supplement to structural data, traffic data could help in better assessment of the real status of dynamic stresses and strains and fatigues that are being imposed to the bridge, in which knowing the utilization of bridges can help with preventative maintenance. Miao and Chan [9] used Weigh in Motion (WIM) data for modeling live loads on a short span bridge and compared it with other common loading models that yielded satisfying results. Mahmoud Khan et al. [10] assessed the integration of Intelligent Transportation System (ITS) with Structural Health Monitoring (SHM) systems and concluded that their integration can improve the efficiency and reliability of bridge management system. Lan et al. [11] used SHM and traffic data to improve the predictive probabilistic models for estimation of fatigue damage on bridges that eventually helps in better management of bridge defections.

The inclusion of traffic could enhance the quality and accuracy of maintenance planning, which ultimately helps in optimization of resource and budget allocation for the preservation of bridges (e.g. high utilized bridges would get inspected more frequently than less utilized bridges). To test this hypothesis, this paper first presents Intelligent Transportation Systems (ITS) as a great source of traffic data and identifies Bridge Information Modeling (BrIM) to supply the structural and other bridge information. The integration and fusion of heterogeneous traffic and structural data in BrIM could potential assist in efficient and cost-effective decision making for bridge maintenance.

6.2 Methodology

One goal of this research is to identify different applications of ITS and BIM and develop a framework to promote the fusion of these technologies and support efficient and cost-effective bridge operation and maintenance. The research aims to find an efficient method for integration and centralization of ITS data, so the data could be effectively shared and used by different stakeholders. The paper contributes to the body of knowledge by providing a review of intelligent transportation systems (ITS) and Bridge Information Modeling (BrIM), including the various technologies, components, and data types. The review uses qualitative and quantitative methods for the assessment. Additionally, review provides a holistic view about the data, application, and extent of ITS. The paper also presents the novel framework of the ITS and BrIM integration. Potential applications, opportunities, and challenges of this integration are discussed. Although the current scope of this research is for bridges, results of this approach could potentially benefit and enhance the design, management, and maintenance process of other transportation infrastructure. The main objectives of this research can be categorized as follows:

1. Investigate the capabilities and applications of ITS as an automatic data collection system and the extent of information which could be achieved.
2. Determine proper automated data capture methods for better flow and storage of acquired data.

3. Design methods that can help in automation of database establishment and enrichment and increase the efficiency and comprehensiveness of collected data.
4. Evaluate the extents of the capabilities achieved by this approach and the potential benefits of the data produced for the stakeholders.

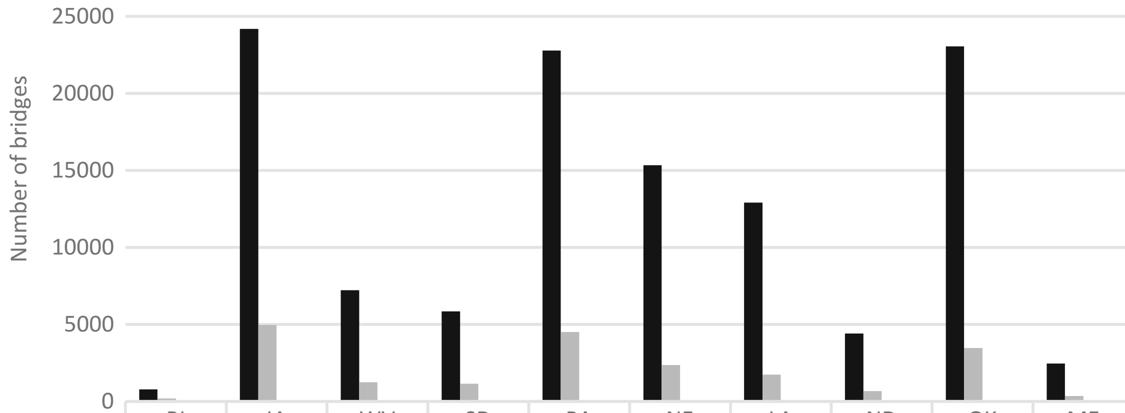
This research first conducted an exhaustive literature review about the use of BIM in the transportation infrastructure [12]. Using the same methods, this paper focuses on applications specifically relating to ITS. To obtain a comprehensive understanding about ITS and BrIM, a keyword-driven search was conducted in online databases with academic focus including Google Scholar, EBSCO and SCOPUS. The search has been conducted with the general keyword "Intelligent Transportation Systems" or "ITS" and has been narrowed down to the research that discuss various ITS systems and their application. The same process has been conducted using keywords "BIM," "Building Information Modeling," "Bridge Information Modeling," "bridge," "bridge inspection," "bridge maintenance," and "infrastructure maintenance." Then, each abstract and conclusion were reviewed to determine if the article contained the data about the ITS and their applications. Once it was determined that the paper was relevant to the review, it was fully reviewed and data was extracted and stored in an application and database. The reviewed papers contained information about (1) applications of technology, (2) benefits and potential research developments, (3) limitations and challenges. The reviewed articles consisted of 11 journal papers, 5 conference proceedings, and 2 reports. The reports that have been retrieved from Federal Highway Administration (FHWA) and State DOTs websites were used as the primary source for quantitative representation and analysis. ITS devices and systems have been introduced and the type of data that they can produce have been introduced. After gaining the understanding about ITS and BIM specifications, a framework has been proposed for their integration.

6.3 Overview of the Current Infrastructure

According to the recent ASCE infrastructure report, 9.1% of the more than 600,000 bridges across the United States are structurally deficient, while having an estimate of 188 million trips over them during 2016, showing the great concern of safety risks [13]. Currently, a considerable number of these bridges need maintenance and repair [14] and estimated cost for their rehabilitation and repair is roughly $123 billion [13]. Furthermore, the cost for the maintenance and repair of other civil infrastructure is even more staggering. Potholes, patching, cracking, and deformation of surface are the most common road surface defects. These problems damage the passing vehicles and impose costs to drivers and government [4]. From another perspective, the increase in the fleeting traffic may either meet or exceed the maximum design amount, which causes excessive deterioration that also leads to backups and delays that imposes great waste to national economy. This is crucial as Sweet [15] stated that the hourly value of travel delays is $16.01 for private vehicles and $105.67 for commercial vehicles, and it is evident that congestion exacerbates these costs. According to Texas Transportation Institute, traffic delays imposed a $160 billion loss to the U.S. economy in 2014 [16]. Thus, it is significant that the structure and fleeting traffic of bridges should be constantly monitored to minimize any failure that leads to congestion and its negative effects on the transportation infrastructure and national economy.

To establish an understanding about the current situation of states that have the most problem with deficient bridges, a sample of 10 states that have the highest ratio of deficient bridges to their total number of bridges have been selected using the data from ASCE Report Card [13]. Figure 6.1 visually compares this ratio and shows that an average of 17.5% of bridges in these states are deficient. Additionally, these ten states have spent a total $2.5 billion for their bridges during the year 2016 and may need increase the budget with the increasing need for operation and maintenance.

The states that have high ratio of defective bridges require considerable amount of budget for their maintenance. On the other hand, some states like Texas have very high number of bridges that are not considerably deficient, but they also require high amount of budget for keeping their bridges in standard condition. Therefore, deciding about the budget allocation in national scale is a complex and crucial problem for decision makers and government, that needs comprehensive data and efficient analytical approaches. Figure 6.2 compares these two group of states and shows that difference in geographical location of these states can add another condition to the problem and increases the complexity of robust decision making for budget allocation for their maintenance.



	RI	IA	WV	SD	PA	NE	LA	ND	OK	ME
■ Total Bridges	772	24184	7217	5849	22791	15334	12915	4400	23053	2450
■ Deficient Bridges	192	4968	1247	1147	4506	2361	1739	661	3460	352
Ratio of deficiency	24.90%	20.50%	17.30%	19.60%	19.80%	15.40%	13.50%	15.00%	15.00%	14.40%
Budget expenditure ($M)	93.87	633.04	154.88	17.85	974.54	61.77	203.73	15.30	341.10	3.16

Fig. 6.1 Comparison of ratio of deficient bridges to all bridges for states with highest ratio of bridge deficiency

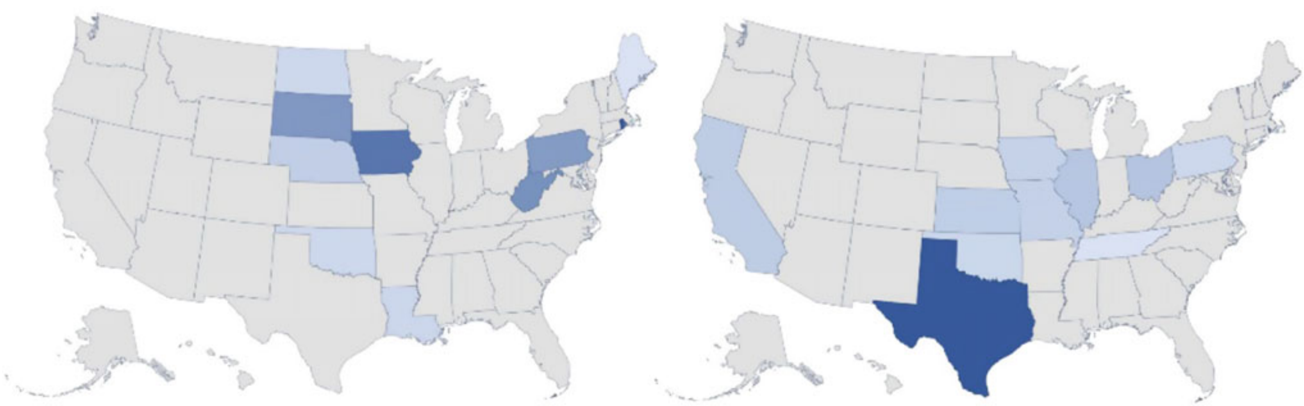


Fig. 6.2 Comparison of states with highest ratio of bridge defect (left) versus states with highest number of bridges (right)

6.4 Intelligent Transportation Systems (ITS)

ITS helps transportation infrastructure to be safer, more reliable, and more efficient [17], which is significant since the performance of transportation infrastructure has direct influence on economic growth of countries [18]. The following sections provide an overview about ITS and their extent.

6.4.1 Components of ITS

The focus of this paper is to identify the electronic devices and systems that capture and provide the real-time information to be used in BrIM. These devices could be generally categorized and discussed under mechanical sensor components and vision-based components. Other equipment including Variable Message Signs (VMS) and interactive interfaces are the devices that are being used for returning the results of processed data to the users for their information and direction.

Mechanical sensors are electronic devices that capture on-site traffic data. Mechanical sensors could be as simple as a closed loop sensor that count the number of passing vehicles, or as advanced as Weigh in Motion (WIM) stations that capture the complete properties of the commercial vehicles including speed, number of axles, weight, plate number, as well as their photo. Global Positioning System (GPS) is another good example of vehicle-based sensors that guide vehicles through their optimum routes while balancing the network congestion. With the development of sensing technologies, these sensors are now providing a considerable amount of real-time data which is known as Big Data [19].

Vision-based sensors use image processing technology to capture data. Cameras have been widely used for monitoring roads, automatic detection of congestion and accidents, speed enforcement, red light enforcement, and bus and high occupancy vehicle lane monitoring, etc. The captured data could later be used for statistical analysis and vehicle tracking and can also be analyzed through developing recognition models or rule-based reasoning logic [17]. These systems are easier and much cheaper to install, operate and maintain, and could be a proper replacement for human-operated tasks.

The result of captured and processed data needs to be relayed back to road users to update them with latest information about network. Different mobile applications are now using processed data to provide the live data for users. Variable Message Signs (VMS) are electronic signs installed across the highways and before the interchanges to inform drivers about driving conditions, such as emergencies, weather, and traffic conditions.

Table 6.1 shows a sample of data that could be captured by ITS devices and how different systems can provide various data to enhance the comprehensiveness. Significantly, amongst the suggested systems, Weigh in Motion Systems (WIM) are great components for capturing exhaustive information about fleeting traffic and their weight that could help in better assessment of bridges.

6.5 ITS-BrIM Fusion Data Framework

The current management of the captured data is a very intensive process, thus integrating the data with bridge information models (BrIM) could help inspectors and managers to have better control over the health of bridge. Database-enabled BrIM models could be a great platform for integration of these data as it can be connected to different databases and receive their information, while having the capability of storing and representing the summary of quantitative and qualitative data. The data could be retrieved and visualized through BrIM visual capabilities.

The ITS-BrIM fusion and data framework developed by this research is shown in Fig. 6.3. The data captured through different devices could be analyzed and used by different stakeholders, including structural designers, traffic engineers, transportation planners, operation and maintenance managers, project owners, state departments of transportations (DOTs), government authorities, and road users (e.g. commuters). The data can be captured through different ITS systems and stored in the database for analysis and record keeping. These data will be processed, and the pre-designed system will export different

Table 6.1 Sample of ITS captured data

Sensor type	System	Type of recorded data
Mechanical sensors	Weigh in motion (WIM)	Count Speed Weight Vehicle classification
	Inductive loops	Count Speed
	Electronic tolling	Count Charged amount
	Road Weather Information Systems (RWIS)	Wind speed Rain volume Humidity percentage
Video-based sensors	Video-based traffic count systems	Count Speed Traffic state Vehicle classification
	License plate readers	Vehicle plate information Origin-destination information

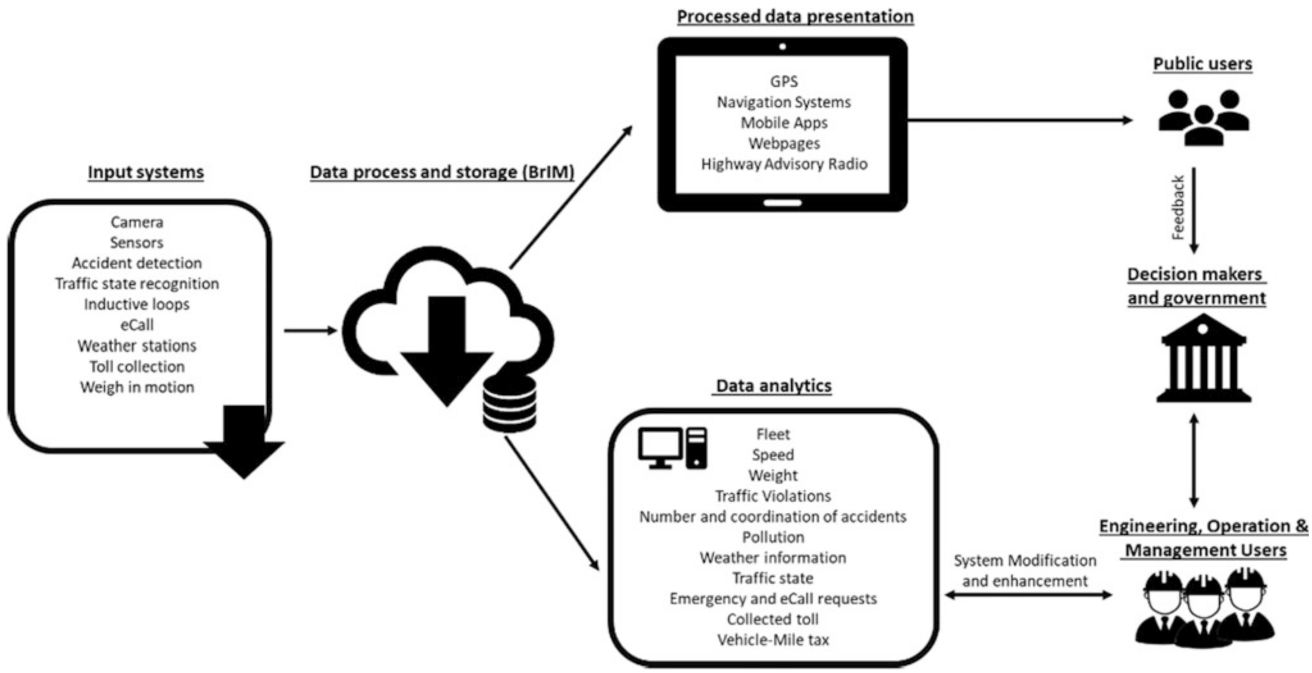


Fig. 6.3 ITS data framework

results. A portion of this result will be provided for public users (e.g. commuters) through interactive user interfaces including mobile apps or webpages. The system has real-time capabilities and will help users to fulfill their current need for real-time conditions about the road and infrastructure. This information may include the maximum allowable speed, height, and weight of the vehicle, as well as road congestion status, any possible accidents, tolling stations, etc. (refer to Table 6.1). Unlike the public users, the bulk of the data in the database will be available for the operation and management users, who are responsible for management, operation and maintenance of the infrastructure. State Departments of Transportation (DOTs) are examples of operation and management users.

The raw and processed data (e.g. speed, type and weight of passing vehicles, accidents, weather information, emergency requests, etc.) can be used for querying and data analytics. Managers, designers, and operators could use these data to evaluate the current traffic condition of the bridge and help the structural designers to have more parameters that may affect the bridge corrosion and deterioration and have better assessment and judgement over the structural health condition of the bridge. In higher administrative levels, this data could be evaluated and help in decision-makings about the best maintenance strategies for the bridge to maximize the efficiency and performance. As for any system, feedback is extremely important for system modification and data enhancement. This will help them in finding and modifying potential deficiencies and ensuring the operability of the infrastructure. This framework primarily shows the need for an integrated and centralized database, so all the stakeholders can benefit from the information. The individual BrIM models could later be developed on GIS-based platform to expand the BrIM capabilities into network scale.

6.6 Conclusion

Bridges are one of the critical components of road transportation network. Aging and deterioration affects commuter safety, while the fleeting traffic may exceed the design forecasts and exacerbate this deficiency. Real-time and reliable data can significantly enhance the bridge management, and ITS can automatically provide the required data. In this paper, different types of ITS and their obtainable data have been reviewed and a framework for better flow of data has been proposed. The review resulted in finding the following benefits:

– Current data that have been collected through different sensors could be associated and represented in a unified and visual database such as BrIM model that helps in their better understanding and utilization.
– The amount type of ITS equipment could be selected in accordance to the need and importance of the bridge.
– The ITS data utilization will be enhanced to satisfy the current expenditure on these devices and promotes future investments on these systems.
– The data could be visualized and presented through different media for operation and maintenance managers.
– Proposed system can provide data for the development of other research on bridges. Traffic analysis, structural analysis, sustainability analysis, maintenance cost analysis, and road deterioration analysis are a few examples of development of utilization of this approach for helping the transportation infrastructure.
– The maintenance and management strategies and budget allocations could be adjusted due to better understanding of the conditions that are harming the bridges.

Despite the benefits, the review found these challenges and gaps for implementation of this approach the require further research:

• Although the data produced by ITS are useful in their own right, their heterogeneity may be an obstacle in full implementation of the methodology.
• Independence, dispersion, and heterogeneity of the data make the integration of databases difficult that may require innovative approaches in database design.
• The amount of data that has been produced by ITS devices is large in volume and that require automated algorithms and methods for their analysis and assessment.
• The streaming data needs to be associated with the BrIM model through online platforms. Testing and finding a proper online platform with compatibility for its connection with different databases could be a challenge in this process.

Significantly, the fusion of ITS and BrIM can ultimately provide one method of reducing the funding gap needed to maintain the vast network of bridges. This research will continue to follow the further steps for implementation of the proposed methodology and associate the ITS data with BrIM model.

References

1. Catbas, F., Malekzadeh, M.: A machine learning-based algorithm for processing massive data collected from the mechanical components of movable bridges. Autom. Constr. **72**, 269–278 (2016) https://doi.org/10.1016/j.autcon.2016.02.008
2. Okasha, N., Frangopol, D.: Computational platform for the integrated life-cycle management of highway bridges. Eng. Struct. **33**, 2145–2153 (2011) https://doi.org/10.1016/j.engstruct.2011.03.005
3. Maeda, K., Takahashi, S., Ogawa, T., Haseyama, M.: Distress classification of class imbalanced data for maintenance inspection of road structures in express way. In: Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE), pp. 182–185, April 19–21, Taipei, Taiwan (2017)
4. Shaghlil, N., Khalafallah, A.: Automating highway infrastructure maintenance using unmanned aerial vehicles. In: Construction Research Congress 2018, April 2–4, 2018, New Orleans, Louisiana (2018) https://doi.org/10.1061/9780784481295.049
5. McGuire, B., Atadero, R., Clevenger, C., Ozbek, M.: Bridge information modeling for inspection and evaluation. J. Bridge Eng. **21**(4), 1–9 (2016) https://doi.org/10.1061/(ASCE)BE.1943-5592.0000850
6. Metni, N., Hamel, T.: A UAV for bridge inspection: visual servoing control law with orientation limits. Autom. Constr. **17**, 3–10 (2007) https://doi.org/10.1016/j.autcon.2006.12.010
7. Al-Shalabi, F.A., Turkan, Y., Laflamme, S. BrIM implementation for documentation of bridge condition for inspection. In: Proceedings of the 5th International/11th Construction Specialty Conference, June 8–10, Vancouver, British Columbia, vol. 262, pp. 1–8 (2015) https://doi.org/10.14288/1.0076437
8. Badrinath, A., Chang, Y., Lin, E., Hsien, S., Zhao, B.: A preliminary study on BIM enabled design warning analysis in T3A Terminal of Chongqing Jiangbei International Airport. In: Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE), pp. 485–491, July 6–8, Osaka, Japan (2016)
9. Miao, T.J., Chan T.H.T.: Bridge live load models from WIM data. Eng. Structures. **24**(8), 1071–1084 (2002)
10. Mahmoud Khan, S., Atamturktur, S., Chowdhury, M., Rahman, N.: Integration of structural health monitoring and intelligent transportation systems for bridge condition assessment: current status and future direction. IEEE Trans. Intell. Transp. Syst. **17**(8), 2107–2122 (2016)
11. Lan, C., Li, H., Ou, J.: Traffic load modeling based on structural health monitoring data. Struct. Infrastruct. Eng. **7**(5), 379–386 (2011)
12. Costin, A., Adibfar, A., Hu., H., Chen, S.: Building information modeling (BIM) for transportation infrastructure—literature review, applications, and challenges. Autom. Constr. 94, pp. 257–281 (2018). https://doi.org/10.1016/j.autcon.2018.07.001
13. American Society of Civil Engineers (ASCE) (2017).: Infrastructure report card. https://www.infrastructurereportcard.org (April 7, 2018)

14. Abdessemed, M., Kenai, S., Bali, A., Kibboua, A.: Dynamic analysis of a bridge repaired by CFRP: experimental and numerical modelling. Constr. Build. Mater. **25**, 1270–1276 (2011) https://doi.org/10.1016/j.conbuildmat.2010.09.025
15. Sweet, M.: Does traffic congestion slow the economy? J. Plann. Lit. **26**(4), 391–404 (2011)
16. Schrank, D., Eisele, B., Lomax, T., Bak, J.: “2015 Urban Mobility Score Card”. Texas A&M Transportation Research Institute and INRIX Inc., Texas, USA (2015)
17. Cheng, H., Gau, V., Huang, C., Hwang, J.: Advanced formation and delivery of traffic information in intelligent transportation systems. Expert Syst. Appl. **39**, 8356–8368 (2012)
18. Pradhan, R., Bagchi, T.: Effect of transportation infrastructure on economic growth in India: the VECM approach. Res. Transp. Econ. **38**(1), 139–148 (2013)
19. Zeyu, J., Shuiping, Y., Mingduan, Z., Yongqiang, C., Yi, L.: Model study for intelligent transportation systems with big data. In: International Congress of Information and Communication Technology, pp. 418–426, Sanya, China (2017)

7 Blockchain in the Construction Sector: A Socio-technical Systems Framework for the Construction Industry

Jennifer Li, David Greenwood, and Mohamad Kassem

Abstract

Distributed ledger technologies (DLTs) including blockchain are increasingly being investigated as a potential solution to address many of the challenges hindering the construction industry's performance such as collaboration, information sharing and intellectual property rights. Existing studies addressing blockchain applications within construction and the built environment have ignored the interrelation of social and technological dimensions. To address this gap, this paper proposes a multi-dimensional emergent framework for DLT adoption within the construction sector. The framework was developed following a focus group discussion and took a socio-technical systems approach that encompasses three dimensions: political, social and technical. The framework was overlaid with an extensive set of construction-related challenges and opportunities and identified a number of associated agents across the dimensions. The structured and inter-connected dimensions provided by the framework can be used by field researchers as a point of departure to investigate a range of research questions from political, social or technical perspectives.

Keywords

Blockchain • Distributed ledger technology • Construction industry • Built environment • Socio-technical systems

7.1 Introduction

Technological advancements in the construction industry have been less effective in comparison with other industries such as logistics, automotive and mechanical engineering [1–5]. In the next 10 years, £600 billion will be spent on construction in the UK to improve infrastructure with efficiencies and productivity becoming strategic priorities in the sector for the UK Government [6]. Building Information Modelling (BIM) is the current expression of digital innovation in construction [7–9]. Blockchain is a possible enabler for ameliorating the issues of trust that often hinder collaboration and information sharing [8], both key to successful BIM projects. Blockchain is "*a peer-to-peer distributed ledger technology which records transactions, agreements, contracts, and sales*" [10].

The Blockchain, the first distributed ledger technology (DLT) introduced in 2008 alongside Bitcoin [11], is a verification tool for cryptocurrencies with the potential to be applied to other applications [12] and industries including, but not limited to health care [13], information sharing [14], information management, insurance, automated dispute resolution, real estate [15], crowdfunding [16], big data analytics [17], and education [18]. It has the "potential to benefit the economic, political, humanitarian, and legal sectors by reconfiguring the workings of society and operations" [13].

This paper aims to build on previous work by Li et al. [19] that explored the current level of research on DLT applications in the built environment through further development of its proposed emergent framework for DLT implementation. First, the paper explains key concepts underpinning DLT; second, an emergent multi-dimensional framework for DLT implementation in construction is presented; and third, the methodology for developing the framework is discussed.

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7.2 Distributed Ledger Technology (DLT): Key Concepts

A distributed ledger is simply a database of transactions. However, unlike those of a bank, which are processed and stored by one trusted, centralised organisation, transactions on DLT are processed and stored across many different (hence, decentralised) computers, known as nodes, replacing *trust* with *proof* [20]. Trust is built into the technology through its decentralised nature and basis of consensus representing a paradigm shift from trust to a "trust-free" society in which the need for trusted third-party substantiation becomes redundant [21]. Trust is transferred from people or intermediaries to computational code [22].

In a public network, anyone can access the ledger; in a private network, participants are granted access [23]. DLT operates across a decentralised P2P network and is immutable once chained. An algorithm ensures all nodes have the same version of the ledger. It uses a Proof-of-Work mechanism to validate transactions; in the case of Bitcoin this is a mathematical and deterministic currency issuance mechanism [15, 24]. Each user has a unique public key made up of an alphanumeric string of characters making it almost impossible to identify the individual it belongs to [25]. Secure by design, its cryptography and distributed consensus mechanism offers anonymity, persistence, auditability, resilience and fault tolerance [23].

Upon creation of a new transaction, the details are broadcast to the network for validation and verification [26]. If consensus is reached, the transactions in the block are considered valid, the block is appended to the blockchain and each node's copy of the blockchain is updated accordingly [27]. In a public blockchain, it is very difficult to change an existing block as all blocks thereafter must also be changed due to each block containing a hash of the one before it [28]. Moreover, this must be done in the time it takes to mine one block to the blockchain [29]. For changes to a private blockchain, all nodes on the network must agree by consensus and then modify the data. All blocks are linked back to the genesis block ensuring the blockchain's integrity [30]. Data privacy is stronger in a private blockchain due to access rights [23]. The blockchain architecture is constructed such that malicious attacks are difficult to achieve requiring significant computational power and simultaneous access to each node to be successful [1].

7.3 Emergent Framework

In this section, an emergent framework is proposed to form the basis of implementing DLT in the context of the built environment and specifically, the construction industry. The framework was developed using a socio-technical systems approach to ensure both social and technical elements are considered. A *political* dimension is introduced to address the political and legal environment concerning the use of DLT in construction given that this is a key area of focus for any technological system to thrive. Justification for adding this dimension stems from the challenges highlighted by a number of authors [31–34], and discussed in the review by Li et al. [19], that underlines the need for regulation, laws and governance around DLT for it to be successful in all sectors and across all applications. Lack of these elements leaves the door open for challenges to the international economic order [35] and the potential to descend into an anarchic state [22].

One of the aims of the review by Li et al. [19] was to identify challenges and opportunities facing the built environment with regards implementation of DLT. The framework combines three interconnected dimensions—technical, social and political—with overlaps across dimensions that represent the real-world environment where one characteristic rarely sits within just one dimension. A number of agents have been identified such that, when considering a challenge or opportunity, the specific agents that have influence on (or should be involved in) the corresponding solutions will be highlighted. Laying the challenges and opportunities onto this framework will ensure that each relevant element and its associated group of users is considered when addressing each challenge and exploiting each opportunity. The framework is presented in Fig. 7.1 along with the identified agents for each dimension. Challenges and opportunities may sit within one dimension, across two, or at the point of convergence of all three in the centre. Figure 7.2 demonstrates how the framework can be overlaid with the challenges and opportunities facing DLT applications in construction. Each of the dimensions is detailed in the following paragraphs and is explained in the context of the socio-technical system.

The **technical** dimension deals with the implementation of the technical architecture of DLT. Many challenges highlighted at this stage in the technology's development (e.g. throughput, latency, interoperability) are likely to be addressed over time with either updates of existing technologies or the development of new products. For example, NEO [36] is one of the newest smart contract platforms in development proposing to provide solutions to throughput and latency, interoperability and resistance to quantum attacks. In this context, following Szabo [37], a smart contract is defined as a computerized

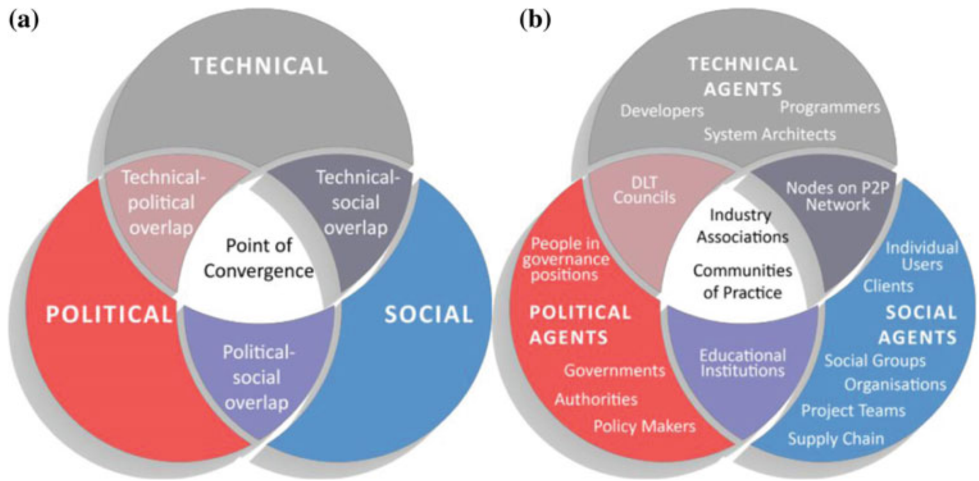

Fig. 7.1 **a** Emergent framework; **b** identified agents

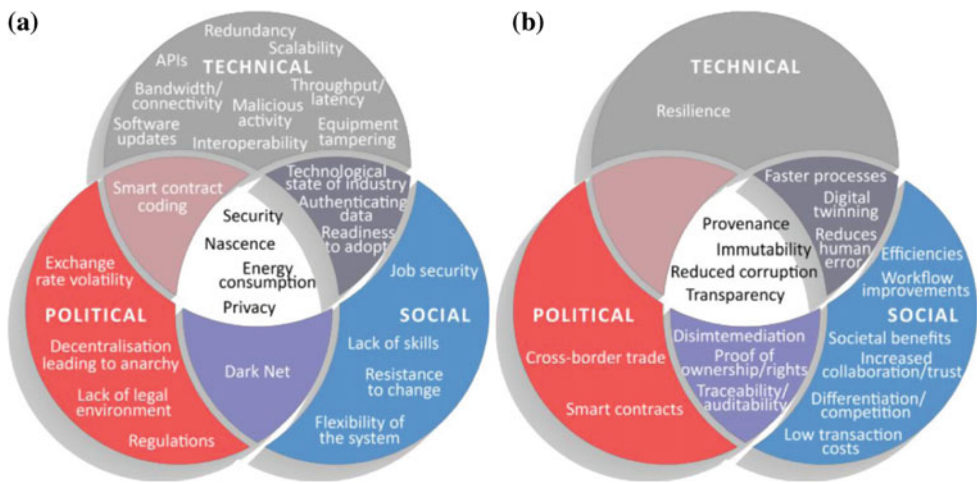

Fig. 7.2 **a** Framework overlaid with challenges; **b** framework overlaid with opportunities

transaction protocol that executes the terms of a contract. The agents involved in this dimension include, but are not limited to: developers, system architects and nodes (computers running the P2P Network). When developing blockchain-based systems for the construction sector, consideration needs to be given to whether public or private access is required. Once this decision has been made, consideration then needs to be given to scalability, data frequency requirements, security and integration with hardware (e.g. sensors) and software (e.g. BIM, interoperability, Application Programming Interfaces (APIs), networking).

The **social** dimension is associated with the impact DLT will have on society; it is broad-reaching in terms of the agents associated. These include, but are not limited to: individual users, social groups, educational institutions, industry associations, communities of practice, organisations operating within the built environment generally and construction projects specifically. This dimension addresses how the technology will integrate into the real world, represents the social system where benefits of DLT adoption will occur, and identifies the agents who will benefit from and influence its adoption. At this early stage of framework development, a holistic social dimension is adopted as the focus is on exploring the opportunities and challenges for the entire built environment and the construction sector. During technological development, attention should be given to how data is presented and stored on the blockchain, particularly where personally identifiable data is generated, to ensure privacy is maintained, especially in the wake of data scandals such as that involving Cambridge Analytica [38]. Consideration of environmental sustainability should be inherent in any new technology, particularly given the currently high levels of energy required to run blockchains.

Overlap with the technical dimension with regards usability (interoperability, appropriate APIs etc.) will ensure technical solutions also meet social requirements. Finally, any solution should be developed with a view to promote information sharing, without compromising on privacy, which will assist in promoting collaboration and development of DLT applications for good uses.

The **political** dimension represents the environment in which DLT will be established and the interactions/influences that agents from the political field exert on DLT adoption. This includes establishing robust regulations, laws and compliance for implementation of DLT in the built environment and the construction industry. Agents for this dimension include, but are not limited to: governments, authorities, policy makers, DLT councils (those with the power over how DLTs function) and other organisations/individuals in governance positions. For example, as smart cities are a goal for many governments, they have a responsibility to ensure appropriate infrastructure is put in place to support the development of DLT to allow it to thrive in the long-term and integrate fully with smart technologies. To promote the integration of services and overcome interoperability, robust regulations and a manageable system in which DLT applications can function without inhibiting innovation are needed. Government strategies should incorporate plans to educate the general public of the benefits and operation of DLT to be successful as the system relies on user-led data and are user-run. In addition, robust succession planning to train sufficiently skilled personnel to run the system is required such that resourcing does not become a barrier to implementation.

In light of the three dimensions and current stage of development, the attentive scoping of DLTs is key to ensure what is designed offers a solution to the construction industry that succeeds in solving its challenges and allows it to assimilate with technologies like BIM. In particular, the solution must be everlasting and tolerant of updates and future advancements as DLT provides an everlasting ledger of information.

The framework will help in answering a number of questions related to DLT that must be dealt with during development including: is the construction sector ready for DLT? What needs to be put in place to ensure it will be ready in the near future? Who bears the initial implementation costs? How can stakeholders from across the dimensions be encouraged to work together? What needs to be done to ensure integration with existing technologies (e.g. BIM, Internet of Things)? Addressing these questions along with the extensive challenges and opportunities identified in the earlier paper by Li et al. [19] will ensure the technology matures in line with the socio-technical environment.

In the next stage of development of this framework a fourth dimension will be proposed to encompass *processes* which, at present, are inherently embedded into the social dimension. This will allow the framework to take a more industry-specific and project-oriented approach for application to the construction industry.

7.4 Methodology

DLT is nascent technology and its coverage in the built environment literature is recent, with no prevalent theoretical considerations of its implementation. The research conducted for this paper was inductive in nature where theories are borne out of observations and/or findings, typically from qualitative research. Qualitative research is important for research of socio-technical systems [39]. This study encompassed a systematic literature review (SLR) informed by a socio-technical approach and a focus group session.

7.4.1 Socio-Technical Systems

Socio-technical systems design (STSD) methods are an approach to design that considers human, social and organisational factors, as well as technical factors in the design of organisational systems [40]. Neglecting to consider social and technical factors, particularly when developing new systems, will often result in failure of the system due to meeting technical requirements but missing social ones [40]. Geels [41] discusses three aspects of socio-technical systems as “production, diffusion and use of technology” highlighting the importance of looking at the relationship between innovation *and* users to ensure societal needs are fulfilled. Regulation sits at the centre as the element that produces trust and intercepts with each of the three aspects. Lack of regulation currently represents a significant gap in development of DLTs [42, 43].

7.4.2 Systematic Literature Review

A systematic literature review was used to identify where current research lies on blockchain applications in the built environment and to compile a list of challenges and opportunities with regards its implementation in the sector. More detailed results from the SLR can be seen in an earlier review providing an extensive description of current applications, challenges and opportunities regarding DLT in the built environment [19]. In summary, a review was made of 53 papers to discover the current body of research focused on seven applications of DLT: (i) smart energy; (ii) smart cities and the sharing economy; (iii) smart government; (iv) smart homes; (v) intelligent transport; (vi) BIM and construction management; and (vii) business models and organisational structures.

The most widely-researched application to date is *smart energy* focusing on microgrids and energy trading, where the blockchain is opening up markets and promoting prosumer behaviour. *Smart cities* and the *sharing economy* focuses on improving communication and data sharing between citizens and governments for mutual benefit, promoted by the IoT. *Smart government* is looking to move some services onto the blockchain such as land registries, tax collections, identity management, government records [31], voting, and patents [44]. *Smart homes* (and smart districts [45]) focuses on developing better places for people to live, work and interact day-to-day. There are overlaps with regards applications (ii)–(iv) where security and privacy of data are key concerns along with interoperability, longevity, accessibility and balance of power [22, 46]. Blockchain is transforming *intelligent transport* by allowing people to monetise their idle vehicles by offering rides to people travelling in the same direction [47] and providing alternatives for charging electric vehicles [48]. In (vi), many use cases are identified that benefit areas such as the supply chain, payments, equipment leasing, facilities management, data management, collaboration, information sharing and intellectual property rights [3, 8, 15, 49]. However, the research lacks empirical data to support the use cases and there is consensus that BIM needs to advance from its current level of implementation (i.e. BIM Level 2) before any benefits can be realised [9, 16, 50]. Finally, blockchain will introduce new business roles (e.g. smart contract mediator [51]), new organisational structures such as decentralised autonomous organisations [24, 31] and many tasks and activities will become semi- and fully automated [31].

7.4.3 Focus Group Discussion

A focus group was held on the premises of a UK university with eight participants: five academics, one industry practitioner and two Ph.D. students all involved in BIM and digital construction innovation. The purpose of the session was to canvas views on blockchain and its potential benefits for construction with a focus on potential benefits and challenges to implementation. The one-hour session consisted of a brief presentation of DLT and applications currently investigating its use followed by semi-structured questions.

Participant comments supported the framework development, particularly that DLT "*must be considered as a socio-technical system*". Another commented that, "*it has the potential to address one of the biggest challenges in the construction industry, which is trust*". Other considerations that emerged from the discussions centred on: whether a decentralised system is required or whether the industry, projects or organisations would still benefit from centralised blockchains; what are the transactions that take place throughout a construction project lifecycle, and whether blockchain can improve current practices; how the problem of data authenticity is solved as blockchain alone will not solve the problem (garbage in, garbage remains and is immutable); and how data and transaction frequency requirements will impact on choice of technology.

This initial focus group helped direct development of the framework presented in this paper. It was not intended to be an exhaustive session and will be followed up with further sessions and different agent groups as the research progresses. This paper does not intend to answer the concerns raised; they are highlighted to support other researchers' investigating the use of DLT in the built environment and the construction industry.

7.5 Conclusions

This paper aimed to further expand on an emergent framework [19] based on identified challenges and opportunities associated with the adoption of DLT in the built environment. Based on initial focus group discussions a socio-technical systems methodology has been proposed. An inductive research approach underpinned the inquiry process and culminated with the development of an emergent multi-dimensional framework.

The framework combines three interconnected dimensions—political, social and technical. It is overlaid with an extensive set of challenges and opportunities facing the implementation of DLT in the built environment and represents an important baseline for its adoption. Field researchers can utilize the framework as a point of departure for a wide range of investigations from political, social, and technical perspectives.

It is the authors' intention to add a fourth dimension to the framework to encompass *process* to improve its applicability to project environments, particularly those related to the construction industry. The revised framework will be validated with academics and industry practitioners and subsequently applied to a construction-related project to demonstrate Proof-of-Concept.

References

1. Barima, O.: Leveraging the blockchain technology to improve construction value delivery: the opportunities, benefits and challenges. In: Hall, K. (ed.) Construction Projects, pp. 93–112. Nova Science Publishers Inc, New York, USA (2017)
2. Cardeira, H.: Smart contracts and possible applications to the construction industry. In: New Perspectives in Construction Law Conference on New Perspectives in Construction Law Conference, Bucharest (2015)
3. Mason, J., Escott, H: Smart contracts in construction: views and perceptions of stakeholders. In Proceedings of FIG Conference, Istanbul May 2018. [In Press], Available from: http://eprints.uwe.ac.uk/35123 (2018)
4. Merschbrock, C.: Unorchestrated symphony: the case of inter-organizational collaboration in digital construction design. Electron. J. Inf. Technol. Constr. **17**, 333–350 (2012)
5. Oesterreich, T.D., Teuteberg, F.: Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. Comput. Ind. **83**, 121–139 (2016)
6. Neely, A.: Carrying the Torch for Digital Built Britain. http://www.bimplus.co.uk/people/carrying-torch-digital-built-britain/?utm_source=dlvr.it&utm_medium=twitter
7. Succar, B., Kassem, M.: Macro-BIM adoption: conceptual structures. Autom. Constr. **57**, 64–79 (2015)
8. Mathews, M., Robles, D., Bowe, B.: BIM + Blockchain: a solution to the trust problem in collaboration? In: CITA BIM Gathering 2017, Dublin, Ireland (2017)
9. Heiskanen, A.: The technology of trust: how the internet of things and blockchain could usher in a new era of construction productivity The technology of trust: how the internet of things and blockchain could. Constr. Res. Innov. **8**, 66–70 (2017)
10. Christidis, K., Devetsikiotis, M.: Blockchains and smart contracts for the internet of things. IEEE Access. **4**, 2292–2303 (2016)
11. Nakamoto, S.: Bitcoin: a peer-to-peer electronic cash system. Www.Bitcoin.Org. 9 (2008)
12. Mengelkamp, E., Gärttner, J., Rock, K., Kessler, S., Orsini, L., Weinhardt, C.: Designing microgrid energy markets: a case study: The Brooklyn Microgrid. Appl. Energy **210**, 870–880 (2018)
13. Azaria, A., Ekblaw, A., Vieira, T., Lippman, A.: MedRec: using blockchain for medical data access and permission management. In: Proceedings of the 2016 2nd International Conference on Open Big Data, OBD 2016, pp. 25–30 (2016)
14. Kogure, J., Kamakura, K., Shima, T., Kubo, T.: Blockchain technology for next generation ICT. Fujitsu Sci. Tech. J. **53**, 56–61 (2017)
15. Turk, Ž., Klinc, R.: Potentials of blockchain technology for construction management. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85030479533&doi=10.1016%2fj.proeng.2017.08.052&partnerID=40&md5=4878dacb604a1adffad4e389b518d155 (2017)
16. Mason, J.: Intelligent contracts and the construction industry. J. Leg. Aff. Dispute Resolut. Eng. Constr. **9**, 4517012 (2017)
17. Zheng, Z., Xie, S., Dai, H.N., Wang, H.: Blockchain challenges and opportunities: a survey. Work Pap.–2016 (2016)
18. Danilin, P.I., Lukin, A.A., Reshetova, E.N.: Assessment organization service based on Ethereum platform. In: Cavalli, A.R., Petrenko, A., Pozin, B. (eds) Proceedings of the 5th International Conference on Actual Problems of System and Software Engineering, pp. 291–294, Moscow, Russia (2017)
19. Li, J., Greenwood, D.J., Kassem, M.: Blockchain in the built environment: analysing current applications and developing an emergent framework. In: Creative Construction Conference 2018 (2018)
20. Catlow, R.: Artists Re: thinking the blockchain introduction. In: Catlow, R., Garrett, M., Jones, M., Skinner, S. (eds.) Artists Re: Thinking the Blockchain, pp. 21–37. Liverpool University Press, Liverpool (2017)
21. Kiviat, T.I.: Beyond bitcoin: issues in regulating blockchain transactions. Duke Law J. **65**, 569–608 (2015)
22. Atzori, M.: Blockchain technology and decentralized governance: is the state still necessary? SSRN Electron. J. (2015)
23. Hamida, E.B., Brousmiche, K.L., Levard, H., Thea, E.: Blockchain for enterprise: overview, opportunities and challenges. In: Thirteenth International Conference on Wireless and Mobile Communications (ICWMC 2017), pp. 83–88 (2017)
24. Kypriotaki, K.N., Zamani, E.D., Giaglis, G.M.: From bitcoin to decentralized autonomous corporations: extending the application scope of decentralized peer-to-peer networks and blockchains. Presented at the (2015)
25. Swan, M.: Blockchain: Blueprint for a New Economy. O'Reilly Media Inc, Sebastoplo, CA (2015)
26. Karafiloski, E., Mishev, A.: Blockchain solutions for big data challenges: a literature review. In: IEEE EUROCON 2017–17th International Conference on Smart Technologies, pp. 763–768, Ohrid, Macedonia (2017)
27. Biswas, K., Muthukkumarasamy, V.: Securing Smart Cities Using Blockchain Technology <Go to ISI>://WOS:000401700900187 (2016)
28. Tapscott, D., Tapscott, A.: Blockchain Revolution: How the Technology Behind Bitcoin is Changing Money, Business, and the World. Penguin, New York (2016)
29. Yermack, D.: Corporate governance and blockchains. Rev. Financ. **21**, 7–31 (2017)
30. Nofer, M., Gomber, P., Hinz, O., Schiereck, D.: Blockchain. Bus. Inf. Syst. Eng. **59**, 183–187 (2017)

31. Boucher, P., Nascimento, S., Kritikos, M.: How Blockchain Technology Could Change Our Lives: In-depth Analysis. European Parliament (2017)
32. Mylrea, M., Gourisetti, S.N.G.: Blockchain for smart grid resilience: exchanging distributed energy at speed, scale and security. Resilience Week (RWS). 18–23 (2017)
33. Ølnes, S., Ubacht, J., Janssen, M.: Blockchain in government: benefits and implications of distributed ledger technology for information sharing. Gov. Inf. Q. **34**, 355–364 (2017)
34. Sun, J., Yan, J., Zhang, K.Z.K.: Blockchain-based sharing services: what blockchain technology can contribute to smart cities. Financ. Innov. **26** (2016)
35. Maupin, J.: The G20 countries should engage with blockchain technologies to build an inclusive, transparent, and accountable digital economy for all. Economics Discussion Papers (2017)
36. NEO: NEO White paper: a distributed network for the smart economy. http://docs.neo.org/en-us/index.html
37. Szabo, N.: Smart Contracts. http://www.fon.hum.uva.nl/rob/Courses/InformationInSpeech/CDROM/Literature/LOTwinterschool2006/szabo.best.vwh.net/smart.contracts.html
38. The Economist: The Facebook scandal could change politics as well as the internet. https://www.economist.com/news/united-states/21739167-even-used-legitimately-it-powerful-intrusive-political-tool-facebook-scandal
39. Shin, D.: A socio-technical framework for internet-of-things design: a human-centered design for the internet of things. Telematics. Inform. **31**, 519–531 (2014)
40. Baxter, G., Sommerville, I.: Socio-technical systems: from design methods to systems engineering. Interact. Comput. **23**, 4–17 (2011)
41. Geels, F.W.: From sectoral systems of innovation to socio-technical systems. Res. Policy **33**, 897–920 (2004)
42. Kshetri, N.: Will blockchain emerge as a tool to break the poverty chain in the Global South? Third World Q. **38**, 1710–1732 (2017)
43. Ammous, S.H.: Blockchain technology: what is it good for? SSRN Electron. J (2016)
44. Kovic, M.: Blockchain for the people: blockchain technology as the basis for a secure and reliable e-voting system. Zurich, Switzerland (2017)
45. Pieroni, A., Scarpato, N., Di Nunzio, L., Fallucchi, F., Raso, M.: Smarter city: smart energy grid based on blockchain technology. Int. J. Adv. Sci. Eng. Inf. Technol. **8**, 298–306 (2018)
46. Hou, H.: The application of blockchain technology in e-government in China. In: 26th International Conference on Computer Communication and Networks (ICCCN), 2017, pp. 1–4. IEEE, Vancouver, BC, Canada (2017)
47. Yuan, Y., Wang, F.-Y.: Towards blockchain-based intelligent transportation systems. In: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), 2663–2668. Rio de Janeiro, Brazil. (2016)
48. Kang, J., Yu, R., Huang, X., Maharjan, S., Zhang, Y., Hossain, E.: Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains. IEEE Trans. Ind. Inform. **13**, 3154–3164 (2017)
49. Wang, J., Wu, P., Wang, X.Y., Shou, W.C.: The outlook of blockchain technology for construction engineering management. Front. Eng. Manag. **4**, 67–75 (2017)
50. Kinnaird, C., Geipel, M.: Blockchain technology: how the inventions behind bitcoin are enabling a network of trust for the built environment. https://www.arup.com/publications/research/section/blockchaintechnology (2018)
51. Tapscott, D., Tapscott, A.: How blockchain will change organizations. MIT Sloan Manag. Rev. **58**, 9–13 (2017)

8 Formalized Knowledge Representation to Support Integrated Planning of Highway Projects

Jojo France-Mensah and William J. O'Brien

Abstract

The objective of this paper is to propose an ontology capable of supporting a structured coordination of spatial-temporal conflicts in highway projects plans. For many highway agencies, there are different functional groups in charge of capital projects planning, safety, design and construction, maintenance and rehabilitation, and short-term operational tasks. However, many of these functional groups tend to have a "siloed" approach to planning. Integrated planning is therefore challenged by the existence of multiple incompatible legacy systems and the lack of a standardized knowledge representation format for planned highway projects information. Current literature and existing formal representations fail to address the level of information coverage and depth to support the integrated planning of highway projects. Accordingly, this study proposes an ontology-enabled knowledge representation which allows relevant planned projects information and inter-project conflicts to be processed in a standard computer interpretable manner. Ontology development was done through the analysis of project attributes of more than 30 highway agencies, review of existing ontologies, and interviews with team leads of different functional groups of highway agencies. The proposed representation was validated via logical consistency checks and competency questions evaluations in the Protégé environment. Future work will aim to employ this ontology to capture and implement tacit integrated projects planning knowledge for improved decision support.

Keywords

Knowledge representation • Ontology • Conflict analysis • Integrated planning • Maintenance and rehabilitation

8.1 Introduction

The planning process for the development and preservation of highway infrastructure is a multi-faceted problem which often involves different information needs for capital projects planning versus maintenance and rehabilitation (M&R) projects planning [1, 2]. Furthermore, different asset classes (like bridges, pavements, safety appurtenances, etc.) may also have different funding categories and project eligibility constraints which needs to be accounted for as part of the decision-making process [3]. Consequently, there are often multiple functional groups within the same agency working on different aspects of the same asset or multiple functions across different assets. This can lead to a "siloed" approach to planning which can have inefficiencies in the form of repetitive information generation, missed opportunities for synergistic projects, and a lack of coordinated decision-making across project information silos [3, 4].

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Additionally, there are often multiple independent legacy information systems being utilized by different functional groups within the same agency [5]. Hence, most State Highway Agencies (SHAs) often have to deal with disconnected databases which result in interoperability barriers and redundant data acquisition efforts [4, 5]. Hence, the data generated tends to have significant heterogeneity in their structure, syntax, and semantics [6]. This is especially the case for projects data that are generated by different functional groups working on the same asset. When it comes to projects data, many SHAs manage hundreds of projects in various phases of development and delivery at any given time. Potential changes in highway funding also mean that projects scheduled to take place within a specified plan period can be moved up or postponed for different reasons depending on funds availability. Furthermore, unpredicted natural and/or man-made (economic) activities in a region can lead to faster deterioration of existing roadways which necessitate new M&R projects that were not initially budgeted for. This can affect the priority list of projects and lead to changes in scope and costs of extant highway projects [4]. To address these issues with data systems, dynamic data updates, and inadequate synergy in what should be a more effective cross-functional process, an integrated planning process is essential. Salient to this process, is establishing a formal standard representation of highway projects data to support cross-functional projects planning.

However, while there have been a number of representations in the form of XML-based schema and other upper-level ontologies about the transportation domain, there is still a deficiency of representations that have the depth and coverage required to support cross-functional projects planning in the highway domain. More specifically, there is a need to represent inter-project (cross-functional project) conflicts knowledge in a computer-interpretable format to ensure timely conflict response and assigned responsibilities. This paper presents a 2-part ontology that formalizes planned highway projects information and inter-project conflicts in highway projects plans.

8.2 Background

Ontologies are a form of standardized knowledge representation which allow for human-readable language (vocabulary) in a structured, and standardized form. An ontology, as used in information science, is an explicit description of concepts in a domain and the relationships that exist between those concepts [7]. It enables complex fuzzy knowledge gained by domain experts to be captured in a standard computer interpretable manner to better support decision-making tasks that target domain experts have to make [6, 8]. There have been several ontologies and other forms of formalized representations proposed in the literature to support processes and concepts in the built environment. A strong theme that runs through several of these representations is the emphasis on data exchange standards in an effort to improve CAD-based software or streamline principal business processes [9]. Some of these studies on the development and application of ontologies are further discussed in the succeeding sub-sections.

8.2.1 AEC/FM

Traditionally, the Architectural, Engineering, and Construction (AEC) industry generates large amounts of data throughout the planning, design, construction, and operations phases of building projects. Accordingly, there have been several formal representations to capture project information via the Industry Foundation Classes (IFC) schema, aecXML, agcXML, E-COGNOS ontology, BIM Collaboration Format (BCF), and many other representations that have concentrated on providing a formal structure for data exchange and knowledge reasoning in the AEC domain [6, 10, 11]. The E-COGNOS ontology was developed to support knowledge representation of knowledge items in the construction domain. Additionally, it was built to be IFC complaint and broad enough to capture all the different business scenarios which exist in the construction domain. Several other studies in the literature have developed building-centric ontologies for enhancing interoperability, data integration, and process integration to support many business functions within the AEC domain [7].

8.2.2 Transportation Infrastructure Management

On the other hand, knowledge management practices in the transportation infrastructure domain have been slow compared to the building industry [9]. Formal representations that allow for reasoning and capture of tacit knowledge are scarce in the extant literature. One of the prominent works in formalized representation in this area involves the development of the TransXML (NCHRP Project 20-64) schema which was sponsored by the National Cooperative Highway Research Program

[12, 13]. The aim of this schema was to provide an extensive framework for the exchange of transportation-related data throughout the planning, design, construction, maintenance, and operation phases of transportation infrastructure [13]. The key business areas of this schema were roadway survey/design, transportation construction, highway bridge structures and transportation safety. It was built on key concepts from other schemas like LandXML, Geography Markup Language (GML), and other existing XML-based schema. However, one of the major limitations of this schema is that it lacks sufficient depth for pragmatic function-specific applications [13]. More importantly, like other XML-based schema developed earlier, it primarily serves as a data exchange mechanism but cannot support reasoning and knowledge extraction that can be relevant for pragmatic highway decisions to be made. In spite of this, there have also been other studies that have proposed ontologies for broad and specific applications in the infrastructure management domain. El-Diraby and Kashif [14] proposed a distributed ontology to support knowledge management during highway construction to capture the complex relationships that exist between the design and construction phases of highway projects as well as the role of relevant stakeholders in the process. Le and Jeong [12] also proposed and implemented an ontology-enabled data integration system which was used to support highway asset management. That study demonstrated how ontologies could be used for process integration and seamless information flow from infrastructure condition survey events to supporting M&R projects selection.

8.2.3 Research Gap

These studies notwithstanding, there still remains a lack of formalized knowledge representations which provide a standard format for planned highway projects information exchange and documenting spatial-temporal conflicts analysis. More specifically, there is the need for a representation that supports reasoning about cross-functional inter-project conflicts that may arise from the "silo" approach to planning in highway agencies. Previous works have focused more on design and construction of highway projects without accounting for the cross-functional nature of highway projects planning. Accordingly, the existing representations in the literature fail to acknowledge the potential spatial-temporal conflicts that may arise due to the different schedules of highway projects planned for the same network but proposed by different functional groups working in the same agency on the same network.

8.3 Research Objective and Approach

To address this gap in knowledge representation, this paper proposes an ontology to serve as a formal representation for planned highway project information and identified inter-project conflicts in highway plans. An ontology is used because it provides a unifying framework within an organization via reducing the conceptual and terminological confusion in the vocabulary used in a certain domain or application context. In the context of this problem, the use of ontologies will enable a shared understanding and communication between relevant decision-makers/functional groups with varying application needs but common information requirements concerning highway projects planning [15]. The proposed approach to ontology building is based on a hybrid systematic framework which combines the ontology building approach by Uschold and Gruninger [15] and the "methontology" approach by Fernández-López et al. [16]. The former provides a useful set of guidelines for developing the purpose, scope, and approach of the ontology to be built whereas the latter method provides a detailed approach for knowledge acquisition, conceptualization, and implementation (as shown in Fig. 8.1). Accordingly, the ontology building began by answering questions about why the ontology was being built, the target domain information to be represented, the intended users, and scenarios of use. After the ontology scope specification, the authors identified the relevant concepts and relationships for the ontology via reviewing publicly available projects information (transportation plans, online highway project portals, and project databases) from over 30 SHAs, existing XML-based schema, and prior ontologies in the literature. This was followed by ontology conceptualization and formal implementation of the ontology via the Web Ontology Language (OWL) in the Protégé 5.2.0 Ontology Editor environment. Finally, ontology verification was done via the built-in Pellet Logic Reasoner [17] in the Protégé environment whiles the competency evaluation included the use of SPARQL, a query language for Resource Description Framework (RDF) graphs, in answering select competency evaluation questions [12].

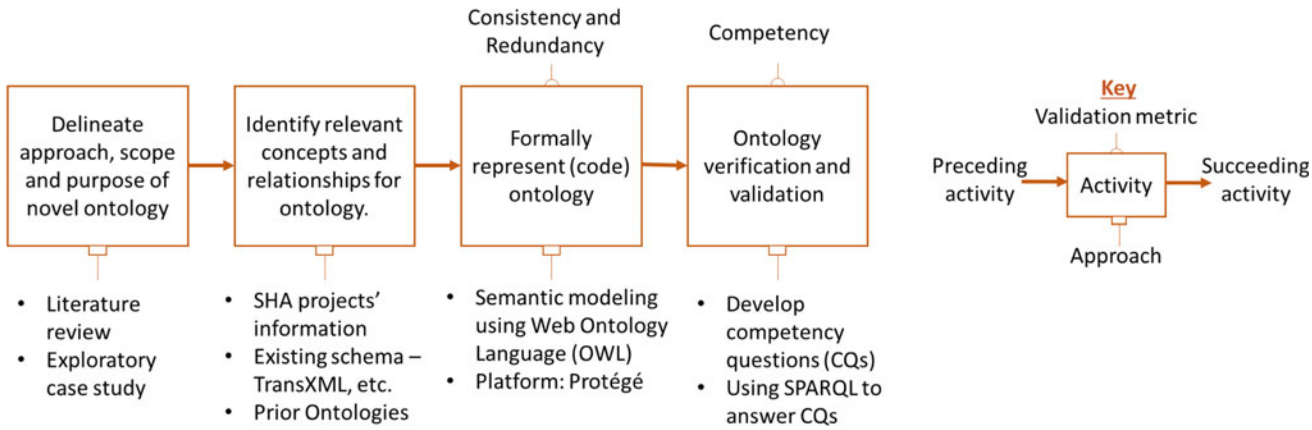

Fig. 8.1 Research methodology for proposed ontology

8.4 Proposed Ontology

The ontological model proposed for this study builds on the Actor-Process-Product-Attribute model which has been utilized in several upper-level ontologies in the transportation infrastructure delivery domain [7, 9, 11]. Hence, the model in Fig. 8.2 can be interpreted as an "actor" performs a "process" that has an output that can be a "knowledge item, decision action or physical product" that has "attributes." These concepts are supported by a "constraint" and/or "mechanism." Within this context, a highway project is represented as a decision action (product) which is as a result of a prior "planning process" (not included in this ontology). In this paper, the attributes of a planned highway project (Product | Decision Action) and an inter-project conflict (Product | Knowledge Item) are presented in detail.

8.4.1 Highway Project

The highway project component of the ontology focuses on the representation of planned highway projects and their attributes as needed in mid- to long-term transportation plans of SHAs. The major attributes presented include the project type, project location, project schedule, project cost, project status, and the overseeing project entities as shown in Fig. 8.3. The project type can have instances (individuals) based on the Federal Highway Administration's (FHWA) classification [12] or locale-specific statewide project classifications. This ontology also allows planners to connect the project type to the funding category since

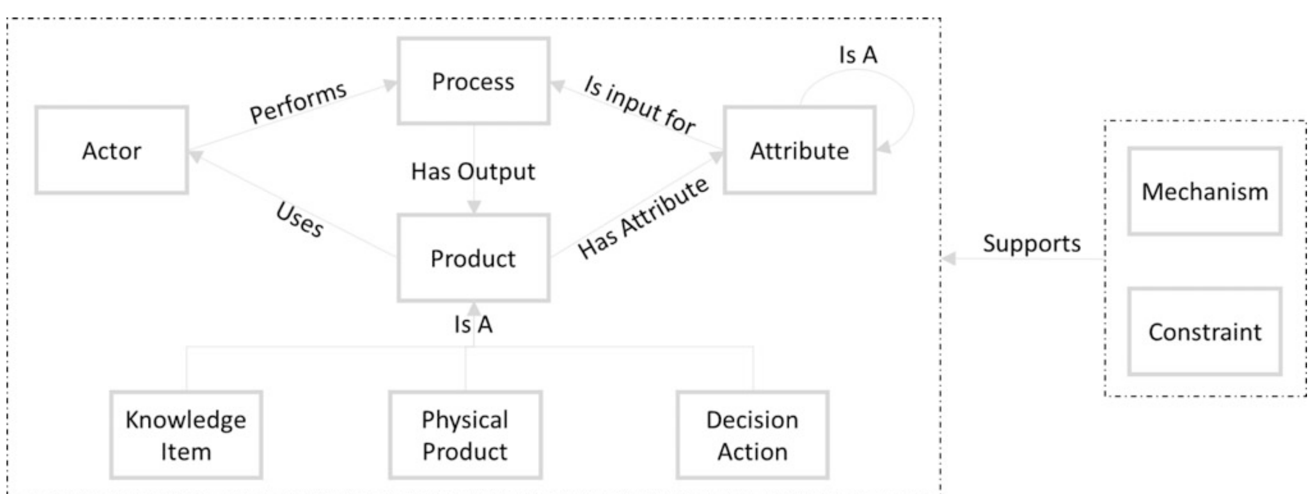

Fig. 8.2 Parent ontological model Adapted from El-Gohary and El-Diraby [7]

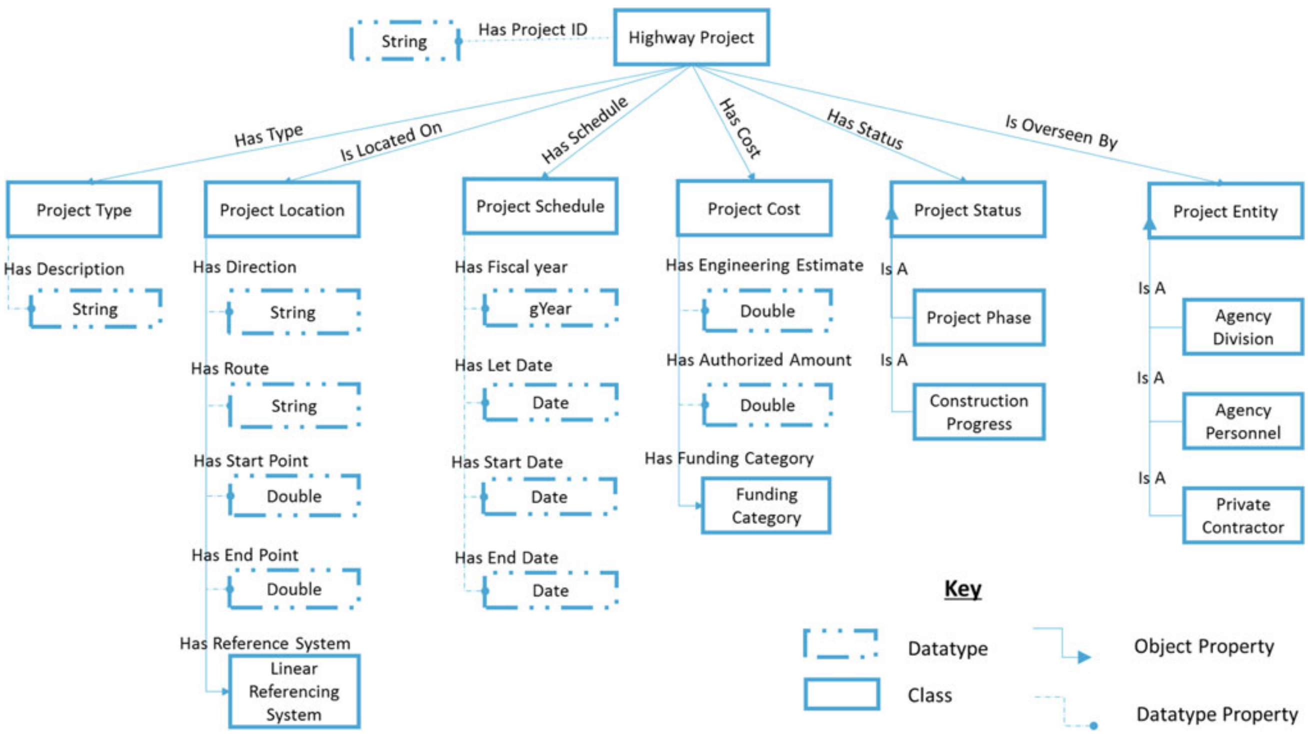

Fig. 8.3 Proposed ontology (highway project component)

some funding categories have restrictions on project type eligibility. Additionally, unlike El-Diraby and Osman [9] which represented infrastructure products spatially using the latitude/longitude coordinate system, this representation accounts for a more dominant description of highway project locations. SHAs typically use linear referencing systems (LRS) like the Milepoint, Milepost and other state-specific LRSs. The project cost also accounts for the difference in the engineering estimate of the project and the authorized amount from the agency since these figures are not always the same.

Furthermore, the "Project Status" class allows for decision-makers to track the current phase of the highway construction project. For example, the relevant phases for major capital projects (new construction as classified by FHWA), may include the preliminary engineering phase (environmental review, geotechnical studies, traffic studies, etc.), design, and construction phases. More often than not, before capital projects are added to highway projects plans, they have already undergone the initial problem screening and concept development phases. Finally, this ontology accounts for the responsible actors for highway projects including when they are outsourced (Private contractor) or when they are done using in-house forces (Agency Personnel and Division). This specification in practice is also important because it can have implications as to the eligible funding categories and reasoning after the inter-project conflict detection is conducted.

8.4.2 Conflict Detection Process

The conflict detection process can be conducted via a Geographic Information System (GIS) visualization, traditional database operations, or a hybrid of both. The inter-project conflict detection process used in this study was based on a prior study by France-Mensah et al. [4]. The study presented a GIS-based approach for the detection of conflicts in proposed highway projects by different functional groups within the same agency. The major steps included (1) Data processing which involved converting all the planned projects data to a common syntactic and semantic format; (2) Conducting spatial checks to see if any number of projects occur on the same road section via the highway name and specified project limits; (3) Checking for a close temporal sequence among projects that have spatial conflicts and (4) Checking the project types to ensure that the identified spatial-temporal conflicts are not complementary highway projects. Complementary highway projects are projects that are scheduled to be executed in the same location but in a close temporal sequence. Accordingly, if there are spatial-temporal conflicts in an integrated highway projects plan which are unintentional, these conflicts are referred to as inter-project conflicts (in this study). To enable an efficient documentation and coordination of these identified conflicts, it is important to develop a formal structure to capture key aspects about the spatial-temporal context of the conflict as well as a structured evaluation and response to resolve these errors in projects plans.

8.4.3 Inter-project Conflict

The inter-project conflict component of the ontology provides a formalized structure for representing the context and response to addressing identified conflicts in highway projects plans. It consists of classes including the conflicting project (s), conflict location, conflict period, conflict evaluation and the conflict response (Fig. 8.4). First, it is important to identify which highway projects (originally residing in disparate databases) are having spatial-temporal conflicts. The connection of these projects to the "Highway Project" class allows us to re-use all the information known about these projects during reasoning about the conflict and how to best resolve it. For example, knowing the details about the types of projects that have been identified as conflicts can inform an agency about lapses in communication between the responsible functional groups for these projects. The "Funding Category" information also allows decision-makers to ascertain extra funds that have become available for other candidate projects not considered earlier. The data from the "has Time Gap" datatype property is the time difference between the start times of a pair of conflicting projects. This information can be useful to planners in assessing the suitable conflict response options based on the time gap between the conflicting projects. Conflict evaluation also informs the responsible group about the cause and type of the conflict and consequently, how urgent a solution is needed. Lastly, the "Conflict Response" class captures information on what action has to be taken to resolve the conflict, the status of conflict response, and who has the responsibility to perform this action. This allows for accountability in conflict response and ensures that there is a formal approach to tracking all the identified inter-project conflicts in a highway projects plan.

8.5 Implementation and Validation

The validation of an ontology usually has two major parts; internal and external validation. Internal validation also referred to as ontology verification is a test on the internal consistency of the Description Logic (DL) inherent in the proposed ontology. However, this test does not check for comprehensiveness or the pragmatic usability of the ontology to support typical decision-making tasks. The use of competency questions (CQs) is therefore used to demonstrate how the ontology can be used to answer select questions which are useful for the pragmatic decision-making process that an ontology is intended to support [12, 16]. External validation often involves focus groups or one-on-one interviews with Experts to gain

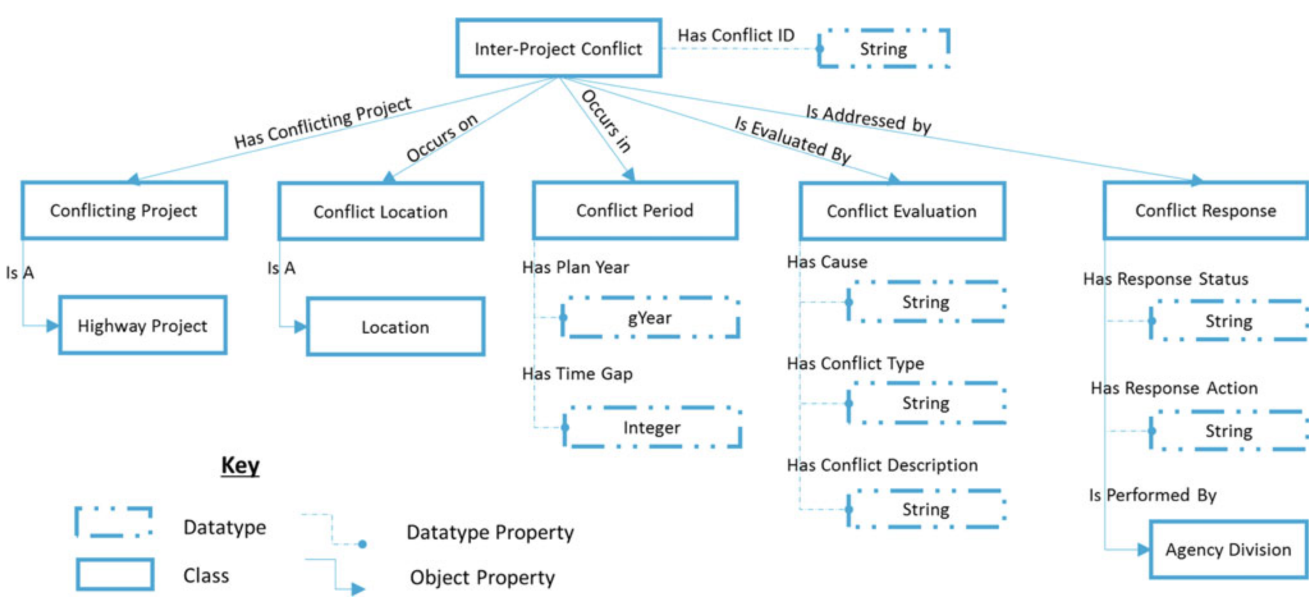

Fig. 8.4 Proposed ontology (inter-project conflict component)

their perspective on the comprehensiveness and pragmatism inherent in the proposed ontology. In this paper, the logical consistency checks and evaluation through CQs are presented.

8.5.1 Logical Consistency (Ontology Verification)

The proposed ontology was coded in the Protégé Ontology Editor Environment [17] using OWL language. The in-built Description Logic (DL) reasoner, Pellet, was used for reasoning to ensure consistency in the class hierarchy and the asserted relationships between the concepts in the proposed ontology. It also checks for implicit subclass relationships induced from the asserted class relationships within the ontology. Having satisfied the conditions for consistency by the Pellet Reasoner, the ontology was confirmed to be internally consistent.

8.5.2 Competency Evaluation

The next validation step aimed at demonstrating that the ontology can be used to answer certain competency questions in line with the intended purpose of the ontology. The CQs included, but was not limited to, queries about where an inter-project conflict was occurring? What were the conflicting projects? What was the cause of the identified conflict? What was the conflict response action? Who was responsible for taking the action to resolve the conflict? The ability for the proposed ontology to answer these questions were demonstrated via SPARQL. A set of instances (individuals) were added to the proposed classes to demonstrate how the ontology was used to extract useful information in an example conflict scenario. Hence, Fig. 8.5 shows the result of an inter-project conflict with ID: C0001 which occurs on route: IH0020 and was caused by a "project location change." The conflict was classified as a "Hard Conflict" and was resolved by the Maintenance Group of the agency by removing the conflicting resurfacing project from the projects plan. It is important to note that the instances used in this example case are not necessarily a part of the proposed ontology.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX onto: <http://www.semanticweb.org/ontologies/2018/integratedprojects#>

SELECT ?ID ?route ?cause ?type ?status ?action ?responsible_actor

        WHERE { onto:Conflict_1    onto:has_Conflict_ID       ?ID.
                onto:Conflict_1    onto:occurs_On             ?section.
                ?section           onto:has_Route             ?route.
                onto:Conflict_1    onto:is_Evaluated_By       ?evaluation.
                ?evaluation        onto:has_Cause             ?cause.
                ?evaluation        onto:has_Conflict_Type     ?type.
                onto:Conflict_1    onto:is_Addressed_By       ?response.
                ?response          onto:has_Response_Status   ?status.
                ?response          onto:has_Response_Action   ?action.
                ?response          onto:is_Performed_By       ?responsible_actor}
```

ID	route	cause	type	status	action	responsible_actor
"C0001"	"IH0020"	"Project location change"	"Hard Conflict"	"Resolved"	"Remove Resurfacing Project"	Maintenance_Group

Fig. 8.5 Results of a SPARQL query on inter-project conflict information

8.6 Conclusion

Planning for highway infrastructure involves several functional groups working in tandem with each other to propose and execute projects for optimal infrastructure delivery and asset management. Since several of these groups tend to use silo information systems for planning, the resulting projects' information between planning groups tends to suffer from semantic and syntactic heterogeneity. This paper proposes an ontology which supports formally representing and capturing information concerning planned highway projects and inter-project conflicts in highway plans.

The validation tests demonstrate that the proposed ontology is internally consistent and is also able to support the intended pragmatic objectives for the development of the ontology. While ontologies about infrastructure delivery tend to be extensive and hence, difficult to comprehensively validate, this proposed ontology focuses on a specific application which makes it more feasible to validate. Future validation will include feedback from domain experts via one-one interviews on the usefulness, coverage, and ease of implementation. Additionally, future work will include the capture of tacit knowledge on inter-project conflict planning and decision-making by highway Engineers. This will enable information reasoning with rules via the Semantic Web Rule Language (SWRL) in the proposed ontology.

References

1. Arif, F., Bayraktar, M.E., Chowdhury, A.G.: Decision support framework for infrastructure maintenance investment decision making. J. Manag. Eng. **32**, 04015030 (2015)
2. France-Mensah, J., O'Brien, W.J.: Budget Allocation models for pavement maintenance and rehabilitation: comparative case study. J. Manag. Eng. **34**, 05018002 (2018)
3. Porras-Alvarado, J.D.: A Methodological Framework for Cross-Asset Resource Allocations to Support Infrastructure Management. University of Texas at Austin (2016)
4. France-Mensah, J., O'Brien, W.J., Khwaja, N., Bussell, L.C.: GIS-based visualization of integrated highway maintenance and construction planning: a case study of Fort Worth, Texas. Vis. Eng. **5**, 7 (2017). https://doi.org/10.1186/s40327-017-0046-1
5. Chi, S., Hwang, J., Arellano, M., Zhang, Z., Murphy, M.: Development of network-level project screening methods supporting the 4-year pavement management plan in Texas. J. Manag. Eng. **29**, 482–494 (2013). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000158
6. Seedah, D.P., Sankaran, B., O'Brien, W.J.: Approach to classifying freight data elements across multiple data sources. Transp. Res. Rec. J. Transp. Res. Board 56–65 (2015)
7. El-Gohary, N.M., El-Diraby, T.E.: Domain ontology for processes in infrastructure and construction. J. Constr. Eng. Manag. **136**, 730–744 (2010)
8. Horridge, M., Knublauch, H., Rector, A., Stevens, R., Wroe, C.: A Practical Guide to Building OWL Ontologies Using the Protégé-OWL Plugin and CO-ODE Tools Edition 1.0. University of Manchester (2004)
9. El-Diraby, T.E., Osman, H.: A domain ontology for construction concepts in urban infrastructure products. Autom. Constr. **20**, 1120–1132 (2011)
10. Wang, L., Leite, F.: Formalized knowledge representation for spatial conflict coordination of mechanical, electrical and plumbing (MEP) systems in new building projects. Autom. Constr. **64**, 20–26 (2016)
11. Lima, C., Diraby, T.E., Fies, B., Zarli, A., Ferneley, E.: The e-COGNOS project: current status and future directions of an ontology-enabled IT solution infrastructure supporting knowledge management in construction. In: Construction Research Congress Wind Change Integration Innovation, pp. 1–8 (2003)
12. Le, T., Jeong, H.D.: Interlinking life-cycle data spaces to support decision making in highway asset management. Autom. Constr. **64**, 54–64 (2016)
13. Ziering, E., TransXML: XML schemas for exchange of transportation data. Transportation Research Board (2007)
14. El-Diraby, T.E., Kashif, K.F.: Distributed ontology architecture for knowledge management in highway construction. J. Constr. Eng. Manag. **131**, 591–603 (2005)
15. Uschold, M., Gruninger, M.: Ontologies: principles, methods and applications. Knowl. Eng. Rev. **11**, 93–136 (1996)
16. Fernández-López, M., Gómez-Pérez, A., Juristo, N.: Methontology: from ontological art towards ontological engineering. AAAI Symposium on Ontological Engineering, Stanford, CA (1997)
17. Sirin, E., Parsia, B., Grau, B.C., Kalyanpur, A., Katz, Y.: Pellet: a practical owl-dl reasoner. Web Semant. Sci. Serv. Agents World Wide Web **5**, 51–53 (2007)

9 An Automated Layer Classification Method for Converting CAD Drawings to 3D BIM Models

Mengtian Yin, Zihao Ye, Llewellyn Tang, and Shuhong Li

Abstract

In recent years, Building Information Modelling (BIM) has been pushing forwards the digitalization of global AEC industries continuously. Developing countries with low computerized level, such as China, still use CAD drawings as delivery in building project. It is significant to transform architecture drawings to BIM models in a cost-efficient way. Current researches on 3D reconstruction of architecture drawings are restricted by accuracy and automation level. In this paper, an automated layer classification method is proposed as pretreatment in transforming CAD to BIM models. It analyses the content in each layer of a drawing and classifies the layer into a specific category. Detailed methods to find out grid text layer, dimension layer, window and door layer and wall layer are presented in the paper. The approach is tested using 70 sample drawings. The average accuracy degree of classification is around 95%. Based on layer classification, the existed recognition algorithms could have better performance since obstructs are removed, and the detection method of section drawings can be optimized.

Keywords

Building information modelling (BIM) • Computer aided design • Geometric and parametric modelling • 3D reconstruction

9.1 Introduction

Building information modelling (BIM) can be served as one of most powerful technology in global architecture, engineering and construction (AEC) industry. BIM not only achieves technical breakthroughs in multi-dimensional visualization and real-time synchronization of building models, but also brings multi-disciplinary collaboration and integrated coordination throughout the project lifecycle, which consists of several main phases including planning, design, construction, operation and maintenance [1]. Currently, the application and development of BIM in some developed countries is mature including the UK, USA and Korea while in the developing countries, the development is weak, and application is limited. For

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example, in China, a survey by the D-CiTi Lab[1] indicated that less than 20% of 283 interviewed Chinese AEC industry employee have confidence to apply BIM in their project [2]. However, another report indicated that China is the top five fastest-growing regions for BIM implementation by contractors [3]. It means that there is a high BIM implementation demand in China. Currently, most of projects in China are using 2D CAD drawing as compulsory delivery and if they want to apply BIM in their project, they need to convert 2D drawing to BIM model manually. It wastes lots of time and labor cost.

In this paper, the research will investigate how to use layer information in CAD drawings to improve the current work on 3D reconstruction. An automatic method of layer classification in order to increase efficiency of conversion is presented based on current research.

9.2 Methodology

Based on the review of current architecture drawing standard, a statistic experiment through 80 pieces of real-life architecture drawings from various types of building sorts out the most frequent layer. Meanwhile, on top of the literature review of current study of 3D model converting, a structure of classification is described, and detailed methods for specific layers are given and tested through 70 drawings.

9.3 Literature Review

9.3.1 Architecture Drawing Standard

Currently, there are two main kinds of 2D CAD drawings that are commonly used in construction project [4]. One is used to present the design idea from the architect and the drawing only includes some basic components such as door, window and wall. Another one includes more information and is widely used in construction process, called construction structural drawing. In a construction structural drawing, different engineering data including the dimensions, construction object and annotation [5] are provided in both plan view and elevation view. As BIM model is still not taken as a compulsory delivery in some developing countries such as China, 2D CAD drawings are frequently utilized to convey design concept and construction instructions. When design party pass on their architecture drawings to construction party, these drawings are usually construction structural drawings, which contains rich information for engineers to understand designer's idea. One of important information in construction structure drawings is layer property, which has been neglected by the previous researches on 3D reconstruction of architecture drawings. Layer is a basic function supported in vector-based CAD system that enables to organize design information in a methodical way [4]. This function involves allocating graphical elements with identical type to the same layer, which can be switched on or off to meet the visibility and plotting requirement [5]. Compared with assigning wealthy building information on BIM family, description of each layer in architecture drawings provides fundamental information to building elements [6], such as designators, element group and status of work. Therefore, it is significant to apply layer information on the process of transforming CAD drawings to BIM model. Namely, if the family type of every geometry elements in architecture drawings can be interpreted via layer information in advance, the accuracy of recognition of architecture drawing is expected to be improved.

9.3.2 Current Work on 3D Model Converting

In the past, many construction drawings were still done on paper. Before 3D converting, these drawings need to be converted into CAD document by pattern recognition techniques [6]. With the development of CAD, most of the construction projects use digital CAD drawings to convey design information. Therefore, currently study on the 3D modelling converting are normally based on this kind of CAD drawing.

Rick Lewis and Carlo Séquin from the University of California, Berkeley [7] develop a system that can create detailed 3D polygonal building models based on AutoCAD floor plan. This system divided each kind of architectural symbols into

[1]D-CiTi Lab: Digital City Infrastructure and Technology Innovation Laboratory, a multi-million-pound living lab that integrates research and innovation on BIM and Smart City development located in the University of Nottingham Ningbo China.

dedicated layers and avoid the errors and ambiguities by correcting disjoint and overlapping edges [7]. In another research, Clifford from Hong Kong University of Science and Technology (HKUST) [8] develop an approach on the automatic wall extrusion, object mapping, and ceiling and floor reconstruction. However, above approaches still rely on manual adjustment.

Tong Lu from the Nanjing University have done many works with his team on the automatic 3D model converting based on the 2D drawing. They came up with an INDAI (Normalization of Dispersive Architectural Information) method [9] to collate the dispersed and diversified information for 3D modelling. They have also done some great arithmetic on the recognition of structural objects and recognition of architectural symbols for the 3D modelling [10]. However, the accuracy is not too high and due to the complexity of the arithmetic, and it costs some time to do the calculation. Dominguez, Garcia and Feito presented a method to extract topological information from 2D drawing [7] and use this information to reconstruct 3D model. This method depends on the detection of walls and joint point amid walls and openings, and the search of intersection point amid walls. The accuracy of this method is high. But in terms of the 3D reconstruction, it can only build the wall and floor and demands picking up corresponding layers by hand. Thus, it is a semiautomatic method. In all, Lu and Dominguez's works are state-of-art techniques. But their methods have restrictions on either accuracy or automation level.

In the current market, there are a few software companies involving in the development of 3D model converting products. For example, the Ganlanshan fast modelling software from the Glssoft, which is a Chinese software company, can covert 2D drawings semi-automatically. Users should select axis net, axis text and construction element on their own. Another Chinese company PMSbim provides a software that has similar function. Meanwhile, Handaz, a company from Egypt provides a software that can convert 2D CAD into 3D BIM automatically, but the layer and block still need to be selected manually. These commercial software also have a common drawback. They don't recognize the section view. As a result, some positions of the elements such as window, door and stairs can be misplaced and need to be corrected by hand.

From the above review, the automaticity, accuracy and the simplicity of the current studies and products need to be improved. In this paper a layer classification method for 3D model converting is presented to solve the limitation of current work on 3D model converting.

9.4 Automatic Layer Classification Method

9.4.1 Layer Property in Construction Structural Drawings

To systematically analyze the principal of relating layer property to architecture drawing recognition, the standard of layer naming format and content is to be determined first. There are already numbers of international and national CAD standards which make specifications or guidelines for layers [4, 6]. However, after viewing 80 pieces of real-life CAD drawings, it is found that most of construction structural drawings didn't follow the rules of national or international CAD standards. For example, the layer containing wall elements is predefined to be named "A-WALL-FULL-TEXT" in AIA CAD Layer Guidelines [4], which indicates "Architectural, Wall, Full-height, Text" [4]. In real-life drawings, this layer is usually simply named "WALL" or "A-WALL". This phenomenon results from the following reasons. (1) The national CAD standard for construction industry in China is not complete, and government has not requested design institutes to follow any international standards. (2) More CAD standards are at enterprise level. Namely, the specification of layer varies among different design companies. Hence, it is not reliable to determine the content of an architecture drawing layer according to international or national standards. This paper uses statistics method to induce the common characteristics of layer in real-life

Table 9.1 Frequently occurred layers in sample 2D CAD drawings

Layer name	Occurrence rate (%)	Content
AXIS_TEXT	100	Consist of texts, representing reference of grid lines
BK-LINE, DOTE	100	Consist of lines, representing grid lines
Wall, A-WALL	100	Consist of lines, representing walls
WINDOW	100	Consist of arcs and lines, representing windows and doors
PUB_DIM	100	Consist of texts and lines, representing dimension notations
WINDOW_TEXT	100	Consist of texts, representing type specification of nearby doors and windows
STAIR	93.75	Consist of lines, representing stairs and elevators

CAD drawings. In detail, 80 pieces of CAD drawings from 10 design companies are studied, and the most frequently occurred layers and corresponding content can be shown in Table 9.1.

From Table 9.1, it can be seen that each fundamental component in a building design, such as wall, door and window, always reside on a particular layer excluding other components. The name format is not unified but the content of layer is conserved. Consequently, it is not creditable to identify what component is placed on a layer by the name of layer. Instead, the feasible solution is analyzing the geometric and semantic content in a layer to realize what this layer describes. An automated layer classification method is thus proposed to classify the property of layer in 2D drawings.

9.4.2 Overview of Automated Layer Classification Method

Previous recognition systems focuses on detecting architecture elements based on their geometric constrain [7–9], topology characteristics [10, 11] and semantic relationship [12–14]. Whereas, these information can also be adopted to identify layer property in architecture drawings.

The classification starts from searching feature elements (FE) in each layer. Feature element is the most distinguishable and representative element with regards to a structural object or annotation. From Table 9.1, it can be found that FE of wall is line, while FE of door and grid text are arc and text separately. Next, the attribute of FE should be checked whether it satisfies some conditions. A FE will have larger possibility to match a targeted category if the attribute of FE accords with characteristics of that object. Apart from self-attribute of FE, the surrounding environment of FE is another essential factor to determine the match degree to an object. The nearby elements that have relational constrains to feature elements are named "related element" (RE). Same as FE, the attribute of RE is also required checking. Moreover, the relationship between FE and RE should meet kinds of criteria. Considering the complexity of shape and topology of some members in architecture drawings, a FE might have multiple related elements, and a RE can also possess related elements if topology of RE should be explored.

Due to the otherness of drawing conventions [7] and variety of design, some conditions used to judge attribute and topology relationship of FE and RE are strict, while other conditions are weaker with less influence on the result. For example, an exterior wall is always drawn as two parallel lines, and thickness of a wall often lies between 100 and 300 mm. Hence, the parallel relationship between FE and RE is a strict condition to identify whether FE is part of wall lines, but the distance between FE and RE is not rigidly limited within [100, 300] because there exist walls exceeding this range. Therefore, the condition can be divided into two types: necessary condition (NC) and sufficient condition (SC). Necessary condition suggests that only the condition is satisfied can the FE stands for targeted structural object or annotations. On the other hand, sufficient condition is not a necessity to determine whether a FE is describing the targeted object, but the likelihood is increased if such condition is met.

Figure 9.1 presents a basic structure of automatic classification method, where Attr denotes attribute and Rel denotes topology relationship between element and its preceding element. When distinguishing whether a tested layer belongs to a targeted category, every FE and it's corresponding RE should be evaluated in the tested layer. All the necessary conditions in each group of <FE, RE1, RE2…Ren> should be checked prior to sufficient conditions. Provided that all NC are passed,

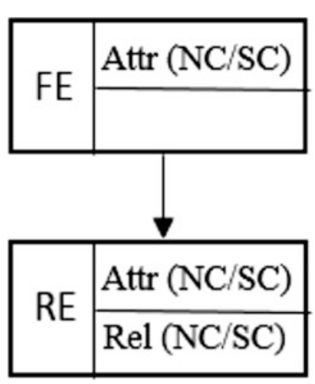

Fig. 9.1 Basic structure of automatic layer classification method

sufficient conditions are subsequently verified. The result is reflected by a score, which implies the probability that the testing FE is describing the objective category.

$$Score = \begin{cases} 0 & (\exists NC == False) \\ \frac{N(SC==True)+1}{N(SC)+1} & (\nexists NC == False) \end{cases} \quad (1)$$

The formula of calculating score of a FE is shown above, "N(SC == True)" indicates the number of satisfied sufficient conditions. Both numerator and denominator are added 1 in case that the number of sufficient conditions in some special categories is zero. Once the score of every FE in a layer is computed, the total score to assess the probability for a layer to match targeted category can be derived:

$$Total\,score = \sum_{N(FE)}^{i=1} Score(i) \quad (2)$$

At the end, the layer with the largest total score with regards to one category is selected, which is recognized that this layer is most likely to contain demanding structural objects or annotations. The entire procedure of layer classification method can be formalized in algorithms shown below.

Algorithm1 **ALCM:** Automated layer classification method	Comment
Input:	
adwg	//The test architecture CAD drawing
tglayers	//The target layers for classification
Output:	
rlayers	//The result of classification result consisting of part of layers in adwg that is recognized as target layers.
procedure ALCM(Adwg, tglayers)	
alayers ⟵ getLayer(adwg) ;	// get a list of layers of input drawing
foreach tglayer **in** tglayers **do**	// loop every target layer in tgLayers
tgFE ⟵ getFeatureelement(tglayer) ;	// get feature element of target layer
tgRE ⟵ getRelatedelement(tglayer) ;	// get related element of target layer
foreach Alayer **in** Alayers **do**	// loop every test layer in alayers
foreach tgFE **in** Alayer **do**	// loop every FE in test layer
if checkNC(tgFE) = true **then**	// check if all necessary conditions of FE are met
foreach tgRE in Alayer **do**	
if isConnect(tgFE, tgRE) = true **then**	// check if tgRE is related to tgFE
if checkNC(tgRE) = true **then**	
TSC ⟵ checkSC(tgFE,tgRE) ;	// check all the sufficient conditons of FE and RE, and count numbers
else continue;	
else continue;	
score ⟵ calculateScore(TSC) ;	// calculate score
totalscore += score ;	// add score to total score of alayer
else continue;	
if totalscore > maxscore **then**	// check if the total score of current test layer is the largest score; if so, the target layer match current layer
rlayer ⟵ alayer ;	
rlayers +=rlayer ;	// append classified layer to output result
return rlayers;	

The above Pseudocode provides a general description of how automatic layer classification works. The output is a list of layers in CAD drawings that correspond to target layers. The functions checkSC and checkNC vary in structure and procedure depending on particular target layer. Therefore, NC, SC of each layer requires verified.

9.4.3 Detailed Method to Classify Typical Layers

In the previous section, the basic framework of classification method is introduced. Based on this framework, detailed method to classify demanding layers is presented, and the content of FE, RE, NC and SC specific to each category is discussed. In this paper, the proposed automated layer classification method will discern 4 of the most frequent layers from

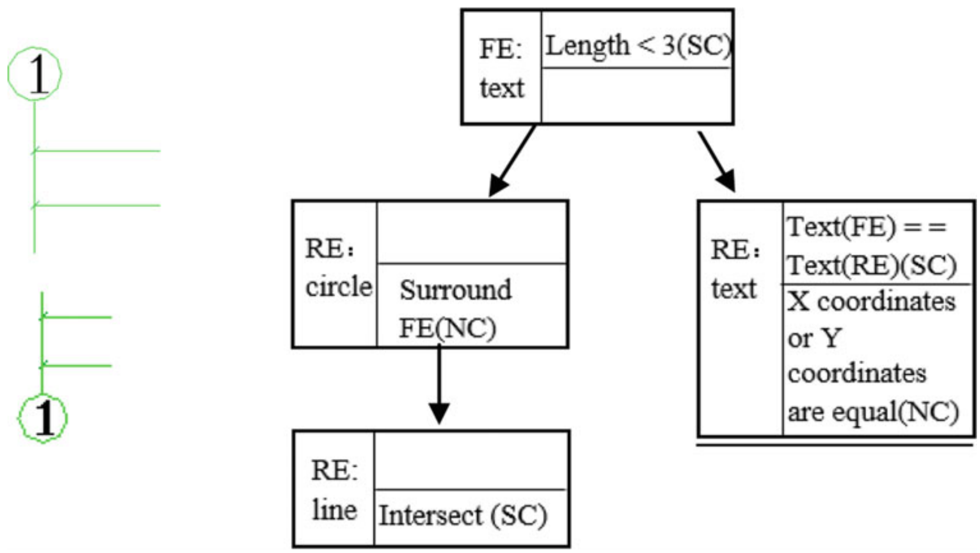

Fig. 9.2 Example of axis text and its layer classification method

statistics result, which are axis text, dimensions, walls and doors layers, and assumption is made that there is only one layer existed for every targeted category in a piece of 2D drawings.

9.4.3.1 Axis Text Layer

Axis text is a group of strings consisting of pairs of number or letter in 2D drawings, which express the label of grid lines. Filtering out the layer of axis text is meaningful to reconstruct grid nets. Apparently, FE of axis text is text, of which the attribute should take string length into account. Usually axis text is made up of short words like "1", "A" or "1-1". Therefore, a sufficient condition can be set that the string length is less than 3 characters. The related element of FE is circle. It is a fixed drawing convention that a grid text should be placed into a circle [15]. This rule forms a necessary condition in terms of topology relationship of RE. Furthermore, there is usually a line connected with this circle, which can be taken as SC. Another RE is text because there are always same axis texts at both ends of a grid line, and these two texts always rely on a horizontal line or vertical line. However, it is observed that not all grid lines have two corresponding axis texts. So whether there is an identical text in the layer becomes a sufficient condition (Fig. 9.2).

9.4.3.2 Dimension Layer

Dimension in CAD drawings shows the size of structural members or grid nets. As Jensen explained [16], a dimension is mainly composed of dimension lines, extension lines and text. In CAD drawings, there are additional two oblique short lines at both ends of dimension lines to illustrate the scope of a dimension. The key problem in recognizing dimensions is figuring

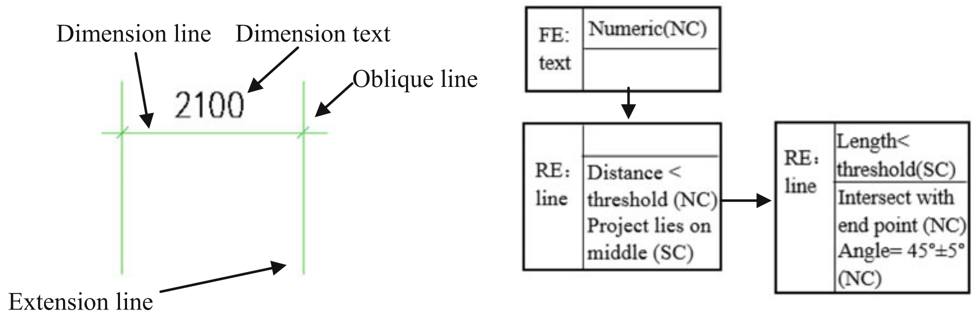

Fig. 9.3 Example of dimension and its layer classification method

out the correct dimension text for a dimension line [14]. Dimension text is not permanently written at the center of dimension line. Moreover, the distance between dimension text and its related dimension line might not be the least distance compared with other texts. Therefore, with the influence of existence of other numbers such as elevation in 2D drawings, mistakes would occur in matching dimension text and line. FE is chosen to be text implying dimension text rather than dimension line for the sake of less computation cost. It is necessary for FE that the text should be a numeric number because it represents size of an object. Next, RE is line implying dimension line. The distance between FE and RE should be less than a threshold. A sufficient condition is that the projection of FE on RE is at middle part of line since dimension text usually stays at center of a dimension. The related element of dimension line is oblique line. It must intersect with end of dimension line and angle between them should be around 45°. The length of this RE should be smaller than a threshold for the oblique line is always short (Fig. 9.3).

9.4.3.3 Window and Door Layer

In 2D drawings, window members and door members are plotted in the same layer. Hence, decision should be made that the feature element is picked up from window symbol or door symbol. Yin et al. [17] pointed out that designers are not used to obey a particular standard in terms of shapes of window and door. In fact, the drawing style of these symbols comes from architecture's artistic motivation, which makes the extraction of FE difficult. In order to study the common characteristics of these shapes, 80 pieces of 2D drawings are reviewed. As presented in Figs. 9.4, 9.5 and 9.6, it can be concluded that variance of window symbol is larger than that of door symbol. Moreover, in some 2D drawings, window is simply delineated as a rectangle, which is easily misunderstood as a wall. In contrast, door symbol has more static geometry constrain and representative elements. Consequently, FE of window and door layer is chosen to be arc from door symbol. Some sufficient conditions are applied on the attribute of FE. The angle of arc needs to be approximately 90° while the radius should range from 0.6 to 1 m, which is common value of width for single-flush door. The related element is line with similar length with FE's radius. For the sake of imitating the basic fashion of a door, the topology relationship of RE with regard to

Fig. 9.4 Different shapes of window in real-life 2D drawings

Fig. 9.5 Different shapes of door in real-life 2D drawings

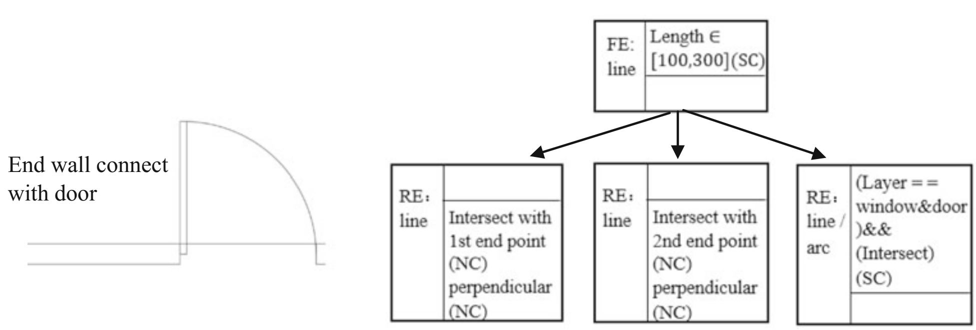

Fig. 9.6 Example of wall and its layer classification method

FE can be summarized as two conditions. A necessary condition is that RE must connect with either end of arc. Another condition is a sufficient condition demanding the distance of center of arc to RE should be smaller than a given threshold.

9.4.3.4 Wall Layer

Automatic detection of wall segments is one of core problems in 3D reconstruction of architecture drawings. The most popular solution is looking for line pairs that are parallel and overlapped with each other [7, 15, 18]. However, there are amounts of obstacles in 2D CAD drawings that can interfere the extraction of wall lines. The first group of obstacles attributes to structural objects that are also formed of parallel lines, such as stair, window and column. The second group of obstacles is matching a wrong parallel line from other types of lines. When a wall line is looking for its parallel line, it might match a nearby grid line which is also parallel. Hence, the wall layer classification method focuses on end of wall rather than middle part. FE is line with length greater than 100 mm and smaller than 300 mm. As discussed before, the wall width limitation is a sufficient condition. Two relative elements are two lines that intersect with two ends of FE. Also, these two RE should be perpendicular to FE. Third RE stems from the dependence relation between other structural members and wall. It is common sense that door and window are built relying on walls. Since the door and window layer classification method has been proposed in previous section, the RE is line or arc from this layer. In other words, FE would be more possibly to be a wall end line if it associates with graphical elements of door or window. Consequently, the intersection between FE and the third RE turns into a sufficient condition.

9.5 Performance Evaluation

70 2D CAD drawings are used as testing data to evaluate the accuracy of classification. On each drawing, the most possible grid text layer, dimension layer, window and door layer and wall layer are picked off using above methods. Correctness of result is verified by analyzing the practical property of sorted layer artificially. Dividing total score by number of FE in a layer, average score of FE is generated in order to reflect the similarity between FE and targeted object. And average total score shows the ordinary maximum total score of a layer in the test, and its value is closely related to quantity of FE and score that every FE obtains with regard to a category.

As shown in Table 9.2, the average scores of grid text layer and dimension layer are relatively higher than that of window and door layer and wall layer, which are above 0.5. It suggests that when recognizing FE of these two layers, the system has more confidence that FE is part of grid text or dimension symbol. As a result, the higher average score brings about higher accuracy of classification. In 70 drawings, the classification system successfully sorted out the two layers without mistakes. In comparison, the accuracy of selecting the rest two layers are about 95 and 85% respectively. In terms of window and door layer, the error results from a drawing putting door symbols on two layers. This drawing has been modified twice in the design stage, and the added elements including new doors in the second turn of modification were placed on a particular layer. The degree of correction on wall layer recognition is the lowest among testing layers. It attributes to the system misdeems column layer for wall layer. In 2D drawings, the contour of column is similar with wall, but it is more frequently located around grid points [14]. Therefore, it is significant to identify column layer before wall layer so that accuracy can be improved.

In general, the overall performance of the layer classification method is optimistic except for wall layer recognition. The average correction rate is around 95% and average time for running algorithms takes up 0.5–2 min depending on scale of drawing. The results suggest that the method could be efficient when input 2D CAD drawings is well-organized. Further adjustment would address on the optimization of NC/SC design and order of recognition such as column and wall.

Table 9.2 Testing result of layer classification

Layer category	Avg. score	Avg. total score	Accuracy (%)
Grid text	0.694	44.220	100
Dimension	0.666	50.1354	100
Window and door	0.567	45.243	97.96
Wall	0.298	68.286	85.7

9.6 Value of Automated Layer Classification

Substantially, automated layer classification is a pretreatment of 3D reconstruction of 2D drawings. It sorted out valid layers with clear property. Based on automated layer classification, each structural object and annotation can be detected and modeled within its resident layer. Therefore, the accuracy of existed recognition algorithms can be effectively improved as disturbance is removed. In addition, some completed modelling algorithms are written in a complicated structure. As a result, the computation cost is high, and it's difficult to meet the configuration requirement of computers in many design institutes and construction companies. Automated layer classification can relieve pressure on computation to some extent. Even though it wastes time to operate automated layer classification codes at the beginning, the entire time spent on transforming 2D drawings to BIM models is reduced because less data is inputted into latter complex algorithms.

One issue addressed on the current commercial products of transforming CAD drawings to BIM model is that they can only process floor plan views but ignore section views which contains important information relevant to height. The hardship on recognition of section drawing results from complexity of geometry. In contrast to plan view, section view is drawn closer to the realistic appearance of building rather than presenting structural objects by conventional symbols. However, it is feasible to detect structural member by layer information rather than shape parameters. A prerequisite is constructing a global coordinate system to integrate different views of building. Lu et al. [14] published SINIHIR model that merges dimension and grid line to form several local coordination systems, and then selects one benchmark to transform all local coordination systems into a unified global system. Based on his model, the exact coordination of every detected elements in floor plan can be obtained. After that the same position is located in section view. Instead of conducting geometry and semantic analysis, intended object is distinguished by searching graphical elements with identical layer of the structural element. As a result, height information is acquired from section view. The detailed method of recognition of section drawings can be further explored.

The main contribution of this method addresses on improving automation level of current conversion algorithms. A state-of-art transform method proposed by Dominguez and his colleagues [7] requires selecting layer manually. Using automated layer classification, their method can switch from semi-automation to full-automation. The secondary contribution of this method is improving accuracy as well as reducing computation cost for some comprehensive algorithms. The SINEHIR method proposed by Lu et al. [14] can be used to recognize dimensions, coordinate system and structural components at the same time but the accuracy is not high. Automated layer classification can decrease SINEHIR method's recognition computation cost and subsequently improve correction rate. The third contribution is that the method provides a potential of multi-view recognition. Current commercial product can only process plan view. The adoption of automated layer classification make section view identification become possible.

9.7 Conclusion

In this paper, the status of BIM development in China is stated and one key issue is addressed, which is a waste of time and money on transforming CAD to BIM models manually. Then construction structure drawing and previous 3D reconstruction of architecture floor plans are studied. To make up for shortcomings, an automated layer classification method is proposed as a pretreatment in the process of 3D reconstruction.

Layer property in construction structure drawings is firstly investigated by reviewing standards and real-life CAD drawings. It is found that naming format of layer in real-life drawings does not strictly follow international standards but accords to enterprise-level specifications. However, all 2D drawings put one category of objects in one layer, so the contents remain constant. Hence, the layer classification method uses geometry and topology content in each layer to identify its property. The classification checks attributes of feature element specific to a category, and subsequently checks its related elements. The conditions on FE and RE are grouped into necessary conditions and sufficient conditions. This division method results from some drawing conventions are rigid while others are loose. Finally, the layer with maximum total score is recognized as the targeted layer. Based on this structure, detailed method of classifying grid text layer, dimension layer, window and door layer and wall layer are discussed. The testing result shows high recognition rate in the first three categories. But the accuracy of classifying wall layer is only 85% due to the interference of column layer. Further adjustment should focus on the order of classification and setting more reasonable conditions.

Assisted by layer classification, the accuracy and automation degree of existed recognition and modelling algorithms can be improved because disturbance from irrelevant layers is eliminated. In addition, layer classification system is expected to expert effects on section view recognition combined with global axis coordinate system.

References

1. Eastman, C.M., et al.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Wiley (2011)
2. Ye, Z., et al.: The potential cooperation and communication between China and UK base on the application of BIM in Chinese Market. In: 33rd ARCOM Annual Conference. Cambridge, UK (2017)
3. Bernstein, H.M.: The Business Value of BIM in China. Dodge Data and Analytics, Bedford, MA (2015)
4. Schley, M. et al.: AIA CAD layer guidelines. http://papers.cumincad.org/cgi-bin/works/_id=ecaade2013/Show?7b96 (1997)
5. Howard, R., Björk, B.-C.: Use of standards for CAD layers in building. Autom. Constr. **16**(3), 290–297 (2007)
6. Björk, B.-C., Laakso, M.: CAD standardisation in the construction industry—a process view. Autom. Constr. **19**(4), 398–406 (2010)
7. Domínguez, B., García, Á.L., Feito, F.R.: Semiautomatic detection of floor topology from CAD architectural drawings. Comput. Aided Des. **44**(5), 367–378 (2012)
8. Or, S.-H., et al.: Highly automatic approach to architectural floorplan image understanding & model generation. Pattern Recognit. 25–32 (2005)
9. Dosch, P., et al.: A complete system for the analysis of architectural drawings. Int. J. Doc. Anal. Recogn. **3**(2), 102–116 (2000)
10. Gimenez, L., et al.: Automatic reconstruction of 3D building models from scanned 2D floor plans. Autom. Constr. **63**, 48–56 (2016)
11. Ahmed, S., et al.: Automatic room detection and room labeling from architectural floor plans. In: 10th IAPR International Workshop on Document Analysis Systems (DAS), 2012. IEEE (2012)
12. Lu, T., et al.: Understanding of complex engineering tables for automatic 3D modeling. In: International Workshop on Graphics Recognition (GREC'07) (2007)
13. Lu, T., et al.: 3D reconstruction of detailed buildings from architectural drawings. Comput. Aided Des. Appl. **2**(1–4), 527–536 (2005)
14. Lu, T., et al.: A new recognition model for electronic architectural drawings. Comput. Aided Des. **37**(10), 1053–1069 (2005)
15. Lu, T., et al.: Automatic analysis and integration of architectural drawings. IJDAR **9**(1), 31–47 (2007)
16. Jensen, C.H., Helsel, J.D., Espin, E.: Interpreting Engineering Drawings. Cengage Learning (2011)
17. Yin, X., Wonka, P., Razdan, A.: Generating 3D building models from architectural drawings: a survey. IEEE Comput. Graph. Appl. **29**(1), 20–30 (2009)
18. de las Heras, L.-P., et al.: Statistical segmentation and structural recognition for floor plan interpretation. Int. J. Doc. Anal. Recogn. (IJDAR) **17**(3), 221–237 (2014)

10 Defining Levels of Development for 4D Simulation of Major Capital Construction Projects

Michel Guevremont and Amin Hammad

Abstract

Each construction project goes through the cycle of different phases such as feasibility studies, engineering design, bid, construction, commissioning, and operations and maintenance. Within these phases, the 3D models and the project schedules have different levels of development (LODs) ranging from summarized to detailed operational information. These LODs affect the development of 4D simulation and result in ill-defined LOD of the 4D models. For example, applying 4D simulation in rehabilitation projects requires special attention to the operational constraints imposed by the need for the continuity of service of the facility. For this purpose, the 4D simulation should be applied at several LODs in order to capture the potential issues in the rehabilitation plan. The objective of this paper is to provide a guideline for defining 4D-LODs for the simulation of major capital construction projects based on the needs and available information. This guideline can provide a handy reference for the project personnel and help reducing the project cost.

Keywords

4D-LOD • 4D simulation • Construction

10.1 Introduction

Recently, 4D simulation is applied in most major capital construction projects (over 50M$) and some smaller but complex projects. This simulation is beneficial in the execution of design-bid-build contracts to both the project owner and the contractors. 4D simulation is not required with contracts that have self-explanatory scope or obvious milestones and timing and sequencing. 4D simulation can be performed with a multitude of intents, such as optimizing processes and resources, adapting best practices in health and safety, or enabling collaboration at the site. BIM Forum [1] proposed a nomenclature for 3D objects LOD from LOD100 to LOD400 as follows: 100 for symbolic, 200 for approximate, 300 for specific, 350 for detailed coordination models, and 400 for fabrication. Tolmer et al. [2] explained the definition of the LOD of the 3D model, and distinguished it from the Levels of model Information (LOI), which describe non-graphical data. The combination of LOD and LOI consists the Levels of Development (LODt) as defined by the BIMForum [1]. The 3D-LOD includes numerical and textual information associated with both geometrical and non-geometrical data (e.g., quantity takeoff and costs). For simplicity, the Levels of Development are referred to as LOD in this paper. Stephenson [3] defined five LODs for the scheduling of construction projects: Level 1 for the summary schedule, Level 2 for the project master schedule, Level 3 for the project control schedule with deliverables, Level 4 for the contractor's execution plan (production schedule) and Level 5 for the weekly look-ahead operational schedule with resources for each task. In general, the LOD of the 3D model

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increases with more design and construction information becoming available throughout the project lifecycle [4]. However, the iterative design process can generate negative evolution of LOD or generate continuous evolving LOD in progress transitions of projects [5]. The iterative design can be associated with project phasing as can be experienced in rehabilitation projects. The integration of the 3D models and the project schedules provides a 4D simulation model that has a certain LOD (4D-LOD). The 4D-LOD can be different at each phase because of the available information and the specific purpose of the simulation. The evolution of the best information available for these 4D-LODs is part of a normal process described with the rolling wave concept in planning. However, 4D-LOD is not well defined in the literature. The objective of this paper is to provide a guideline for defining 4D-LODs for the simulation of major capital construction projects based on the needs and available information. This research benefits from the previous 4D simulation work of the authors [6–9].

10.2 Related Work

4D-LOD. The following review is non-exhaustive but lists significant contributions on 4D-LOD. Gigante-Barrera et al. [10] reviewed the 3D-LOD specifications developed for the UK government with different end-uses such as 4D simulation. They mentioned that the UK PAS 1192:2 document is stage-dependent and includes 3D-LOD granularity definitions. Kumar and Cheng [11] mentioned that the effort spent by layout planners in performing unnecessary calculations would be significantly reduced by using 4D simulation, allowing them to focus on decision making. Synchro [12] suggested four 4D-LODs. They described low, medium, medium/high and high 4D-LODs, respectively for planning the master plan, scheduling the master plan, look-ahead planning, and project controls and operation analysis. Lui and Li [13] mentioned that 4D-LOD is as detailed as the minimum detail of the 3D model or schedules. It should be mentioned that there is a difference between the needs of modelling and the needs of realistic visualization, and that the early phase of planning does not require high 4D-LOD as there is much uncertainty at this phase. Boton et al. [14] discussed the LOD from spatial and temporal points of view. At the 4D-LOD that includes equipment movements, basic animation components are described by type (place, translate, rotate, appear and disappear) and arguments (position, translation vector, rotation axes and angles). Wang et al. [15] considered schedules up to the minute and identified that future work in this area with respect to automatic animations and multi-LOD support of schedule. Su and Cai [16] proposed workspace generation from generic representations such as buffer, attach and rotate.

10.3 Methodology

This article identifies and describes five 4D-LODs for major capital construction projects as shown in Table 10.1. These LODs are based on established 3D-LODs and schedule LODs, and apply for numerous needs, such as safety, construction of new facilities, rehabilitation projects, claims management and claims avoidance. This analysis provides a classification of 4D-LODs for enhanced quality of 4D simulation (e.g. considering safety workspaces at the operational LOD) and consideration of multiple 4D-LODs in the same simulation (e.g. in the case of rehabilitation projects). The 4D-LOD provides an understanding of some limitations associated with the analysis of workspaces, visualization, constructability, clash detection and automation in 4D simulation. From the temporal standpoint, the schedule can use different units of time such as months, weeks, days, hours and minutes. The 4D-LOD typically gets more detailed over the course of the lifecycle of a project. An advanced project typically requires general operational gains tagged to a constructible scenario. In some cases, it could be useful to provide multiple feasible scenarios for the same project. The 4D-LOD has to be considered in relation to the project risks, concerns, available schedule and 3D mock-up information. From both the spatial and temporal considerations, a high 4D-LOD implies very detailed information and a low 4D-LOD equates to poor information details.

4D-LOD A (Demonstrative/Summary): At the early stage of a project, there is a lack of relevant existing data about the project. The 4D-LOD can be achieved with partial design information, and revisited with a completed design. As additional project information becomes available, the 4D-LOD will increase.

4D-LOD B (Major work coordination and feasibility): This LOD should consider the density of components and the economic value of resources (equipment, materials, labor) at the specific location of interest. The time step (e.g. a week or a day) for the simulation is selected based on the schedule LOD. It can also be different for different contracts in the same project. The master schedule can be used as the basis of this 4D-LOD. This schedule is available all along the project lifecycle, but is typically most useful at the phase of feasibility analysis or early in the detailed design phase. As both the 3D mock-up and the schedule are less detailed in these phases, the relationship match between the mock-up components and

Table 10.1 Comparison of different 4D-LODs with related units of time, needs and justifications

4D-LOD label	4D-LOD description	Units of time/schedule LOD	Need/application	Justification of need
A	Demonstrative/summary	Month to week/Sch. LOD 1–2	Scenario selection	Strategic: illustration and communication of a summary plan
B	Major work coordination and feasibility analysis	Week to day/Sch. LOD 1–3	Scenario selection, constructability	Strategic/tactical: choosing the best scenario option for the project
C	Contractual baseline at the time of bid	Day to hour/Sch. LOD 2–3	Scenario selection, constructability, workspaces, claims	Tactical: confirmation of the feasibility of a selected scenario
D	Operational field work	Hour to minute/Sch. LOD 4–5	Safety, operations, workspaces, equipment, claims	Operational: progress and control measurement. This 4D-LOD can be used to show how the facility manager performs his operations
E	Detailed equipment movements (e.g. rotations and translations) and workspaces	Hour to minute/Sch. LOD 4–5+	Safety, operations, workspaces, equipment, claims	Operational: avoidance of spatio-temporal conflicts and enabling logistics planning

schedule activities can be close to 1:1. Hence, 4D-LOD B is minimalist, but is still appreciated in a complex project. This LOD is used mainly by the middle and upper management for strategic decisions on contract milestones of the owner's master schedule.

4D-LOD C (Contractual baseline at the time of bid): At the time of bidding, just before the construction phase, more detailed 3D mock-up and schedules are available and the 4D-LOD has to be adjusted accordingly. For the planning and estimating groups and the project team, a 4D-LOD C is a minimum to allow visualization of a feasible project schedule and comprehensive cost. In the construction phase, detailed schedules are generated for each contract and typically depict a 4D-LOD C. These schedules can either be the owner's bid schedules or the contractors' detailed schedules. However, from the perspective of the owner, too many details are not required for strategic decisions even at this phase. Therefore, some components may be grouped together to reduce the 4D-LOD. It should be noted that this grouping should be done based on the type of components, and may greatly vary from one contract to another. It is still a challenge to define 4D-LOD in a systematic way for major capital projects, where there are thousands of components and activities to be considered.

4D-LOD D (Operational field work): This operational LOD is adequately detailed for the field personnel at the site and includes contractor's full detailed execution plan. In this LOD, the schedule must include activities for material and equipment movements (displacement and rotations). This LOD contains generic movements of equipment and perhaps general workspaces such as prisms. The equipment displacements require additional lines in the schedule. The useful unit of time for these activities is to consider the hours of the day for all moves. Another recommendation at this 4D-LOD is to make sure the schedule meets the main contract requirements ahead of performing the 4D simulation. For example, if a project execution is expected in a strict ten weeks window, then this requirement must be addressed prior to the development of the 4D simulation. For this LOD, a Level 4 schedule [3] is required. The need is similar for the construction method specialists for ensuring that the equipment use and strategy intent fits with the 3D environment. This implies all specific equipment movements and deliveries of the project must fit in potentially heavily congested areas in a new or an existing facility.

4D-LOD E (Detailed equipment movements and workspaces): At this 4D-LOD, detailed workspaces for crews and equipment are added to better consider the spatio-temporal criticality aspects of the project. Workspaces are detailed and adjusted specifically to follow equipment and resource movements. This enables detecting and resolving 4D clashes and revising the mock-up and/or the schedule accordingly until the simulation scenario is corresponding to the project needs. Several rounds of coordination are required in this step to get a clash-free model including safety considerations.

In order to provide enough details for claims avoidance, it is recommended to use the highest possible LOD for both the schedule and the mock-up. The 4D-LOD accepted by courts should relate to a Level 4 schedule as minimal LOD if operational constraints are required.

Table 10.1 provides five different 4D-LODs. However, it is not easy to quantify the added value of more detailed 4D simulation. Practice has shown that a higher LOD is useful where there is a higher density of materials and activities, and/or a great economic value for the project. For example, a 3D-LOD of 300 matched with a Level 1 schedule could perhaps only enable scenario selection. The same concept applies for a 3D-LOD 100 and a Level 3 schedule: it could only enable scenario selection. Therefore, it could be beneficial to apply a filter in the BIM software to automatically adjust the LOD from more detailed (i.e. LOD 400) to a summarized LOD (i.e. LOD 200). This could be done with parent components and schedule activities. The decision about the proper 4D-LOD defines the level of sophistication of representing equipment workspaces. The 4D-LOD D represents these workspaces as simple prisms, which lack accuracy, versus 4D-LOD E, which animates the virtual equipment and their workspaces. Selecting the proper 4D-LOD will provide a reliable visualization of the critical path and delay events. This selection requires using the best available information for the as-planned and as-built schedules, and geometry data for developing the 3D mock-ups.

Based on the above discussion, Fig. 10.1 shows how to adjust the 4D-LOD with several iterations to select the suitable LOD of the schedule, 3D mock-up and 4D simulation. The 4D-LOD has to be adjusted based on the interest of the stakeholder and the phase of the project. This depends on: (1) the contract requirements, (2) the available time for the development, (3) the contractor's experience with the type of work, and (4) the experience of the personnel developing the schedules and the mock-ups. The relationships between the mock-up components and schedule activities can be *1:1, 1:n, m:1 or m:n*. The number of components (n) of the mock-up is typically larger than the number of activities (m) of the schedule. In general, m components and/or n activities should be grouped together or split into smaller components or activities to come to a compromise that allows matching components and activities in a way that satisfies the requirements of the 4D-LOD.

If the schedule LOD is used as a reference, the adjustments are performed by splitting or grouping the components in relation to the schedule activities. This process is based on experience and cannot be done by automatic reasoning at the time being. In rehabilitation projects, new 3D components can replace old 3D components and the new components can occupy new locations (e.g. an upgrade of a pump changing its size and new building code regulating location considerations). Further, changes in the construction methods can require new elements to be considered (e.g. representation of 3D objects such as construction equipment or temporary works) with the corresponding changes to the schedule.

10.4 Case Studies

This section shows four case studies to explain the 4D-LOD proposed in Table 10.1. At this time, for all the case studies, the information is not contractually binding and requires quality analysis checks. It could be in the interest of the stakeholders (e.g. the contractors) to visualize the 4D simulation of their projects. From the duration point of view, the case studies in Table 10.1 with schedule LOD's ranging within Levels 1–3 span in years.

4D-LOD B: This case study is for the rehabilitation of a powerhouse that generates about 2000 MW from 36 TGUs. The powerhouse has three old overhead cranes that will be disassembled and decommissioned, and three new ones that will replace

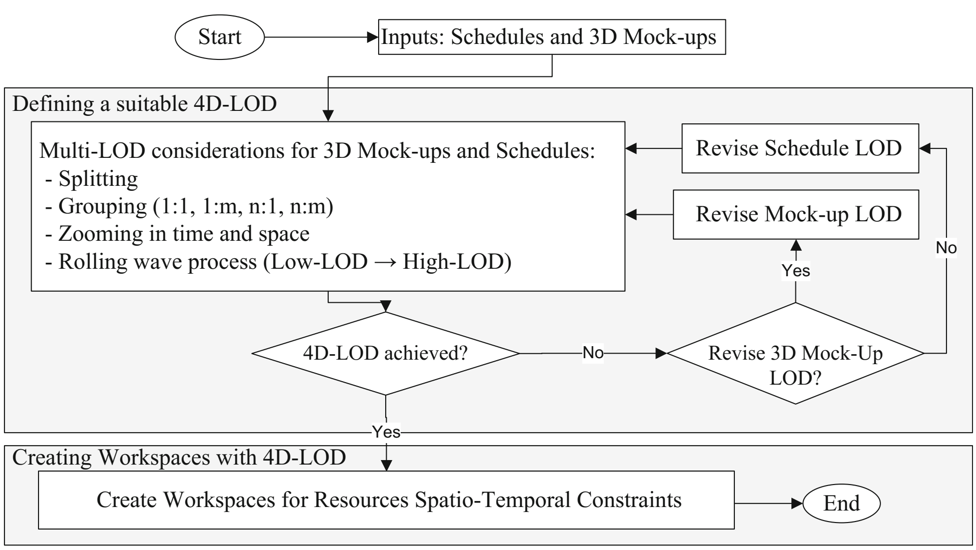

Fig. 10.1 Process of 4D-LOD adjustment

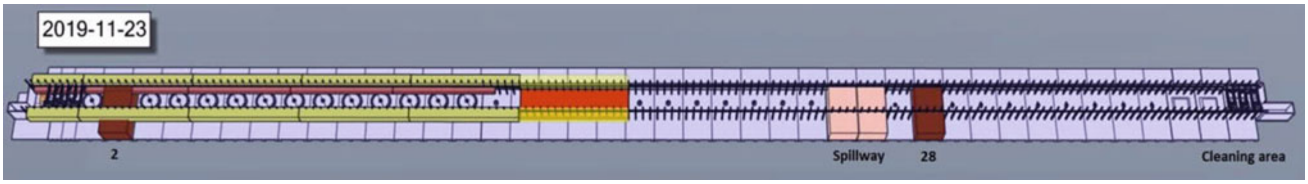

Fig. 10.2 Example of 4D-LOD B [8]

the old ones. The project includes: (1) adding three new overhead cranes for the facility management to execute the normal operations of preventive and reactive maintenance, (2) dismantling the three existing overhead cranes, (3) realigning the powerhouse structural steel columns, (4) changing the electrical systems, and (5) changing the overhead crane tracks. One important part of the 4D simulation is the TGU. A very detailed 3D model of TGU is obtained from the supplier including all design components (about 50,000 components) and manufacturing details. The TGU model is simplified to a single prism, which is sufficient for the initial scenario selection of the construction method and for validating the feasibility of the whole project. For data capturing of the initial 3D mock-up, a scan of the facility was done. Additional project parts were modeled and added to the converted scan, such as tracks, overhead cranes, gantry crane, TGUs and space reservations. For this simplified 4D Simulation for the feasibility study, a simplified 3D model of the whole facility is created. This model has about 100 components including the prism models of the 36 TGUs. The 4D model is created by linking the 3D model (LOD 100) with the activities of both the master schedule (Level 2) and the turbine-generating units (TGUs) maintenance activities for the project period. Figure 10.2 shows the 4D model of the scenario with a progress view of the 4D simulation.

4D-LOD C: This case study is about a hydroelectric powerhouse project that involved over 25,000 m^3 of concrete and 1450 tons of structural steel. The project baseline schedule considered 24 months for construction. In the case study, 286 associations were considered from two main contracts for the concrete and steel components of the powerhouse. The progress of the project showed an average of 18 activities per month with the average duration of an activity just over five days. This case study has a 3D-LOD of 350 and a Level 3 schedule. Only about 90 and 30% were kept of the original components of the mock-up for the concrete and the steel superstructure components, respectively. This was done for the clarity of the simulation and to satisfy the required 4D-LOD for decision-making related to contract strategy. For the same reason, in typical mechanical-electrical and TGUs contracts, grouping components can result in ratios of 20–30% and less than 1%, respectively. Sectors of the mock-up can be compared based on their criticality from the scheduling point of view, as well as from the level of spatial concentration of activities in these sectors. This enhanced visualization (Fig. 10.3a) is useful for decision-making and filtering based on the criticality of activities. It helps to generate ideas about the contract strategy and optimization.

4D-LOD D: 4D simulation was recently deployed a major construction projects with TGU. As shown on Fig. 10.3b, the main components considered of each TGU are: rotor, stator, Francis wheel, turbine shaft, upper bracket, lower bracket, buttress bearing, distributor and bottom ring. The displacement of TGU parts is sequenced with the availability of the overhead crane and performed from the service area, where it is pre-assembled before installation, to the group pits. The simulation was performed to include major contracts: powerhouse concrete, powerhouse superstructure, mechanical and electrical, overhead crane and TGU. The simulation was required since it is the first time that the owner company built a TGU in twelve months (a first worldwide) from access to first commissioning and including pre-assembly on the service area of the powerhouse. To answer both strategic and operational needs, the baseline of the four contracts included over 4000 activities and ultimately allowed 983 links in the 4D simulation. The links breakdown was as following: 747 for electrical and mechanical, 80 for the TGU, 115 for the concrete and 41 for the structural steel. For the geometry of the parts in the mock-up, if lack of detailed information was encountered, then a color code was put in place for space reservations. The 3D-LOD starting point was with near 50,000 parts from multiple mock-ups: one from the supplier of the TGU and one from the owner with concrete, superstructure, overhead crane and mechanical-electrical. The 4D simulation was performed from detailed contractor's schedules as baseline and enhanced with multiple questions and comment period with the owner's field personnel. The equipment displacements were estimated and integrated with the schedule but with a different timescale and involving crossing points from the mock-up or the spreadsheet software. The added value for the construction team was a high 4D-LOD tagged with short time horizons. The validation of the 4D simulation confirmed savings associated with earlier commissioning of the TGU and, accordingly, saving on indirect costs at the site associated with these earlier commissioning. Before this project, the typical installation duration of these units was 16 months. Figure 10.3b shows pre-assembly of a TGU in the service area. Project stakeholders can verify if parts have enough space for proper installation. Figure 10.3c

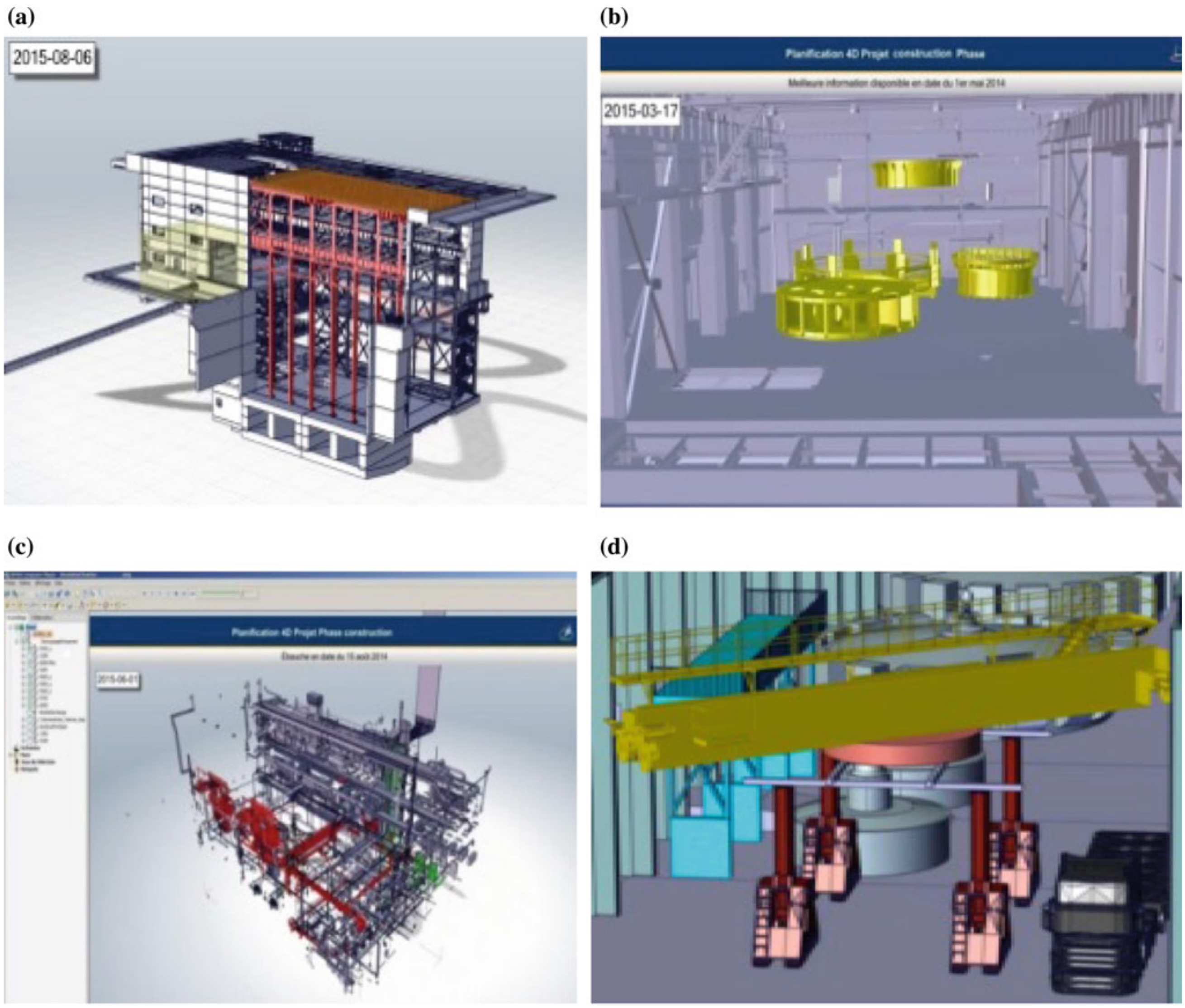

Fig. 10.3 **a** 4D-LOD C [7], **b** 4D-LOD D: parts displacements [6], **c** 4D-LOD D: mechanical and electrical systems [6], **d** 4D-LOD E: construction method including displacements [8]

shows the possibility to help engineering disciplines to view their specific systems individually or with other systems for conflict management. In this example, the electrical parts are shown in red and some mechanical work is shown in green. This 4D-LOD has been helpful for conflict detection. That can be validated for interference or viewed cut plans by room or by floor. Requests for information could be minimized through early use of 4D simulation.

4D-LOD E: Related to the same rehabilitation case study explained above [8], a detailed 4D simulation is developed for specific activities that are more critical and require detailed spatiotemporal analysis, such as the installation of the overhead cranes. The assembly of a new overhead crane requires a hydraulic gantry crane to lift the parts of the overhead crane over the existing tracks of the powerhouse. The summary LOD schedule for the main construction activities shows the beams of the overhead cranes. The initial setup is done by the existing overhead cranes. The gantry crane is a fixed assembly but can lift pieces from a truck height up to the existing tracks height. A fork lift is used to move small parts from the trailer truck to the gantry crane. The operating overhead crane can perform multiple operations when displacing and assembling equipment such as: locating the crane at the right place, lowering hook, lifting the material, raising the hook, moving the main beam of the crane, lowering the hook with the material and unhooking the material on the ground at the new location. These movements of overhead cranes must be accurate and require proper overhead design and assembly. In order to optimize these movements, the movement ranges and constraints (e.g. rules, sequences and dependencies) are required. The detailed

4D model (4D-LOD E) links the highest LOD-3D model (LOD 400), including the construction equipment, and the highest LOD schedule of the detailed execution of the work (Level 5). The resulting 4D simulation captures the movement of the truck and gantry crane used in the delivery and lifting of the overhead crane beam. Figure 10.3d shows a snapshot of the detailed 4D simulation. Workers workspaces were considered in the detailed model for the continuity of operations in the rest of the powerhouse using safety corridors for access. At this highly detailed LOD, it was observed that the key drivers for implementing this LOD are, in order: (1) the construction method, (2) it is adjusted and challenged with technical experts in classical engineering disciplines (civil, mechanical, and electrical), (3) it has to fit into the prescribed project schedule, for schedule driven projects. This hydroelectrical rehabilitation project has a cost that is relatively small, but the impact cost resulting with the risk of not completing the project on time and losing revenues from missing power generation can be up to ten times the cost of the project itself.

10.5 Summary and Conclusions

The suitable 4D-LOD is the one that allows for reliable decisions and depends on the required intent of the simulation. A high 4D-LOD tends to provide operational gains, whereas fewer details suggest strategic owner benefits. This paper provided a guideline for defining 4D-LODs for the simulation of major capital construction projects. The method explains each 4D-LOD along with various 4D simulation case studies of hydroelectric powerhouses. The 4D simulation case studies integrate several models executed under multiple contracts and are used to visualize and analyze the critical paths of the projects.

References

1. BIM Forum 2017. LOD Specification. http://bimforum.org/lod/. Last accessed 2018/04/09
2. Tolmer, C.E., Castaing, C., Diab, Y., Morand, D.: Adapting LOD definition to meet BIM uses requirements and data modeling for linear infrastructures projects: using system and requirement engineering. Vis. Eng. **5**(21), 18 (2017)
3. Stephenson, L.: Scheduling management: classifications vs levels. In: 51st Annual Meeting of the Association for the Advancement of Cost Engineering, pp. 1–10, USA (2007)
4. GSA: Building Information Modeling Guide 04-4D Phasing 39 pages United States General Services Administration, USA (2009)
5. Bolpagni, M., Ciribini, A.L.C.: The information modeling and the progression of data-driven projects. In: Dimyadi, J., Solihin, W (eds) Proceedings of the 33rd International Conference on CIB W78, pp. 293–307, Finland (2016)
6. Guevremont, M.: Virtual construction management. In: Proceedings of the 61st Annual Meeting of the Association for the Advancement of Cost Engineering, pp. 1–20, USA (2017)
7. Guevremont, M., Hammad, A.: Criticality visualization using 4D simulation for major capital projects. In: Chan, W.K.V., D' Ambrogio, A., Zacharewicz, G., Mustafee, N., Wainer, G., Page, E. (eds.) Proceedings of the 50th WSC, pp. 2360–2371, IEEE, USA (2017)
8. Guevremont, M., Hammad, A.: Multi-LOD 4D simulation in phased rehabilitation projects. In: Proceedings of the 17th International Conference on Computing in Civil and Building Engineering, Finland, pp. 724–731. (2018)
9. Guevremont, M., Hammad, A.: Visualization of delay claim analysis using 4D simulation. ASCE J. Legal Aff. Dispute Resolutions **10**(3), 05018002 (2018)
10. Gigante-Barrera, A., Darshan, R., Crunden, M., Ruikar, K.: LOD object content specification for manufacturers within the UK using the IDM standard. J. ITCon. **22**, 80–103 (2017)
11. Kumar, S.K., Chang, J.C.P.: A BIM-based automated site layout planning framework for congested construction sites. Autom. Constr. **59**, 24–37 (2015)
12. Synchro. LOD for 4D project management. http://blog.synchroltd.com/level-of-development-for-4d-project-management. Last accessed 2018/04/09
13. Lui, Y., Li, S.: Research on virtual construction phase and its 4D LOD analysis. In: Wang, Y., Lennert, K., Shen, G.Q.P., Bai, Y., Xue, X., Sun C., Gao, Z., Wu, Y., Xue, W. (eds.) Proceedings of the International Conference on Construction and Real Estate Management, Germany (2013)
14. Boton, C., Kubicki, S., Halin, G.: The challenge of level of development in 4D/BIM simulation across AEC project lifecycle. A case study. Procedia Eng. **123**, 59–67 (2015)
15. Wang, H., Lin, J., Zhang, J.: Operational-level 4D modeling and visualization for modular building based on standard activity library. In: Bosche, F., Brilakis, I., Sacks, R. (eds.) Proceedings of the Joint Conference on computing in construction (JC3), pp. 841–848, Greece (2017)
16. Su, X., Cai, H.: A 4D-CPM based graphical scheduling system. In: ASCE Computing in Civil Engineering, pp. 786–793 (2013)

Check for updates

11 Modularized BIM Data Validation Framework Integrating Visual Programming Language with LegalRuleML

Pedram Ghannad, Yong-Cheol Lee, Johannes Dimyadi, and Wawan Solihin

Abstract

A building design must satisfy diverse requirements including building codes, owner's specifications, design guidelines, and project requirements. In addition, there is a growing need for an automated design evaluation process involving intelligent checking and reporting capabilities that addresses the inefficiency and error-prone nature of the current manual checking practice. To leverage the automated rule checking procedure, we need to overcome two existing key challenges, which are the inherent complexity of rules and the impracticability of checking methods. To address these challenges, this research proposes a node-based visual language approach integrated with the emerging open standard LegalRuleML, which allows the flexibility in defining and executing design rules in a machine-readable and implementable format. The approach effectively facilitates the entire rule-checking process including the rule interpretation from natural language-based requirements to machine-readable forms, rule categorization, rule parameterization, and checking execution with a BIM model. The LegalRuleML-based visual programming language approach for rule checking will help automatically and iteratively evaluate the quality and defects of information conveyed in a given building model interactively as an essential part of design process.

Keywords

Building information modeling • BIM data checking • Visual Programming language • LegalRuleML

11.1 Introduction

A building design must fulfill a myriad of requirements including building codes, normative standards, owner's specifications, design guidelines, and project requirements. These requirements consist of various types of rules and execution plans. Rule-checking is an integral part of the design process to evaluate and maintain all the requirements iteratively throughout the entire project. However, the conventional compliance checking practice is laborious, time-consuming, and error-prone. Since rule-checking is frequently a costly bottleneck of the project delivery process, its automation can be a method to save a significant amount of time and cost for the project [5]. The role of automated rule checking has been critically recognized prior to the advent of BIM and it has been investigated as early as the 1960s [4]. In recent decades, the advancement of the BIM technology has offered the opportunities for establishing automated rule-checking systems and their interactive implementation interconnected with a BIM authoring tool.

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LegalRuleML [12] is derived from RuleML [2] with extended features which aim to specifically represent legal documents in a formalized format. This open standard XML has been developed to formalize logical content of norms, guidelines, and codes being used in diverse domains such as Engineering, Commerce, Law, etc.

Rules can be stated in natural language, in some formal notation, or in a combination of both. Currently, encoding codes from natural language to formal rules is a manual process. However, development of LegalRuleML in conjunction with natural language processing (NLP) and other artificial intelligence (AI) methods may be able to make most of the encoding process fully automated.

Using the open standard LegalRuleML for the rule-checking process generally helps convert natural language-based codes and rules into machine-computable forms that can be automatically analyzed and implemented in appropriate software. Since it has been successfully adopted in various domains, the AEC industry also needs to get an attention on its application to address the complex requirements and heterogeneous structure of a building project.

A visual language can be described as a "formal language with a graphical notation", which employs a modular system of signs and rules with visual elements instead of textual ones on the semantic and syntactic level [14]. Visual Programming Languages (VPL), which utilize visual elements can be interpreted much faster and easier by humans. In recent years, VPL has been established particularly in the field of a building design. Known software products in the domain of a building design are the Grasshopper for Rhinoceros3D, Dynamo for Autodesk Revit, and Marionette for Vectorworks. Although these applications primarily focused on expediting the 3D parametric modeling, their features have been significantly extended by further functionalities [13].

To explore the potentials of formal representation of design rules for VPL-based rule checking, this study involves the investigation of the LegalRuleML format and its execution on VPL. Because of the flexibility and usability, the node-based programming approach for automated rule checking will help users properly coordinate necessary features and readily execute a large number of rules with modularized rule sets iteratively for validating a BIM model.

To achieve this goal, this research includes the study of a formal procedure of rule translation from compliant design requirements to LegalRuleML and its possible execution plan using the graphical scripting language. This study adopted Marionette, which supports a graphical programming language embedded in Vectorworks, one of popular BIM authoring tools. To build the rule translation and implementation frame-works using LegalRuleML and visual programming, this study focuses on the simple and fundamental design requirements needed during the early design phase. The case studies and implementation details using the early design's requirements are described in the section of R304 (Minimum room areas) of the International Residential Code (IRC) published by International Code Council (ICC) [8] showed the flexibility of automated rule checking using LegalRuleML-based modularized rule parameters.

Using Marionette with Vectorworks in conjunction with LegalRuleML, the pro-posed approach elevates automated rule-checking capabilities for iteratively evaluating a BIM model regarding conformance with a set of predefined rules as well as consistently maintaining the initial conditions and quality of a BIM model and its data. The checking libraries developed on Marionette give a clear indication of the potentials of a flexible and extensible rule checking method that can handle multiple parameters and rulesets. In other words, this approach executes diverse checking features with a limited amount of checking nodes. The use of a node-based rule definition and analysis approach also improves the transparency of the encoded rule system, which is completely readable and understandable for end users. This notable feature of node-based rule checking provides users with intuitive rule coordination opportunities that have not been available in previous rule checking approaches such as Solibri Model Checker (SMC), which is one of the most popular rule-checking commercial software. Although it has several practical limitations, SMC allows the user to understand and inspect every single processing step and adjust the checking procedures accordingly.

11.2 Literature Review

Building design is subject to various compliance checking in order to meet various types of requirements. This process should be executed for every aspect of the building design to ensure owners, designers, and end users that the product of that design fulfills their requirements and regulatory codes. This process is not only limited to the design phase and assessment of the building compliance must be carried out during other phases of its life cycle. In recent years, there has been an extensive number of researches conducted in the field of automated rule-checking for AEC industry. The traditional methods of rule-checking in AEC industry use a manual process which is significantly error-prone and inefficient. In addition, the increasing complexity of a building design makes the manual practice more time consuming and costly. Over the last three decades, numerous studies and attempts have aimed to improve and automate the process [4], but several reasons have caused the progress to be very slow, such as the inherent complex nature of the industry, fragmentation, various stockholders, lack of motivation towards the use of new technologies [6, 7].

The most common approach for automating the compliance checking process is the rule-based system. In this approach, the natural language normative texts are manually encoded into computer-readable rules. The building model is then checked against these codified rules. Eastman et al. [5] surveyed different types of rule-based compliance checking systems, such as DesignCheck, SMARTCodes, ePlanCheck, Solibri Model Checker. Lee et al. also reviewed several rule-based platforms and applications such as dRofus, Solibri Model Checker. Revit reviewer add-on, and Invicara [9]. One of the shortcomings of these systems is their inflexibility. They prevent users from defining and executing their own rules or modify the pre-defined rulesets [10]. Another challenge with hard-coded rulesets is the inflexibility to changes and updates in response to changes in the normative requirements. This would require a system developer to maintain the codes for every minor rule update [12]. The lack of transparency is also another limitation of hard-coded systems resulting in domain experts not being able to verify or validate the checking process easily.

11.2.1 Formal Representation and Semantic Interoperability Using RuleML and LegalRuleML

Legal texts (e.g. legislation, regulations, contracts, and case law) are the source of norms, guidelines, and rules. For the domain of a building design, rules and regulations exist in different forms. International, national, local, and even project-specific rules may need to be complied with before, during and after a building is built. Today, rules are typically written in natural languages that require significant domain knowledge to "interpret" before they can be processed by machines. There are several challenges associated with nature of textual content such as exchanging specific data between parties, searching for and extracting structured information within the text, and automatically doing further process. Although patterns exist in many rule structures and clauses, they entail detailed variations that make it hard to capture all required information. The extraction of such patterns, hidden assumptions, and dependencies with other rules are challenging because they require experience with different rule applications and inductive reasoning [15]. The primary challenge for exchanging legal data is the heterogeneous terminology or jargons and its representation structure. In addition, since legal statements of each domain encompass various intents, interests, and targeted realms, their definitions, and representations are frequently abstract and unclear, leaving open-ended interpretations flexibly applicable in relevant cases and situations. Thus, legislators, legal practitioners, business managers have been impeded from comparing, contrasting, integrating, and reusing the contents of the texts, since any such activities are manual. In the current web-enabled context, where innovative eGovernment and eCommerce applications are increasingly deployed, it becomes essential to provide machine-readable forms (generally in XML) of the contents of the text.

The formalization of the appropriate and expressive conceptual, machine-readable format of the multifaceted aspects of norms, guidelines, and general legal knowledge is a fundamental factor for the successful development of rule-Checking processes. To ameliorate this issue, one study has adopted the LegalRuleML to produce a rule inter-change language for the legal domain [1]. Using the representation tools, implementers can structure the contents of the legal texts in a machine-readable format, which then feeds further processes of interchange, comparison, evaluation, and reasoning.

LegalRuleML is built on top of RuleML to facilitate modeling various classes of rules and adding the deontic logic (e.g., obligation, prohibitions, permissions), priorities and the relationships between them. Metadata of rules and normative elements can also be captured by LegalRuleML. In addition, it supports the legal isomorphism principle to maintain the connection between legal source provisions represented by its complementary standard, LegalDocML, and their formal representations or rules [3].

LegalRuleML offers facilities to model different types of norms, deontic effects (e.g., obligations, prohibitions, permissions), and supports defeasibility to resolve contradictions. In addition, it has features to capture the metadata of norms and other normative elements (such as jurisdiction, authorities, validity times, etc.) [1].

11.2.2 Graphical Scripting or Visual Programming Language in Rule Checking

Due to the low-level computation and programming in current design checking implementation, the conventional checking practice is laborious, time-consuming, and error-prone. Even though there are numerous approaches for automated code compliance checking, there are still inadequacies in flexibility, extensibility, and practicability of rule definition and execution. VPL is flow-based and composed by a set of nodes. Each node generally represents a piece of a modularized code as

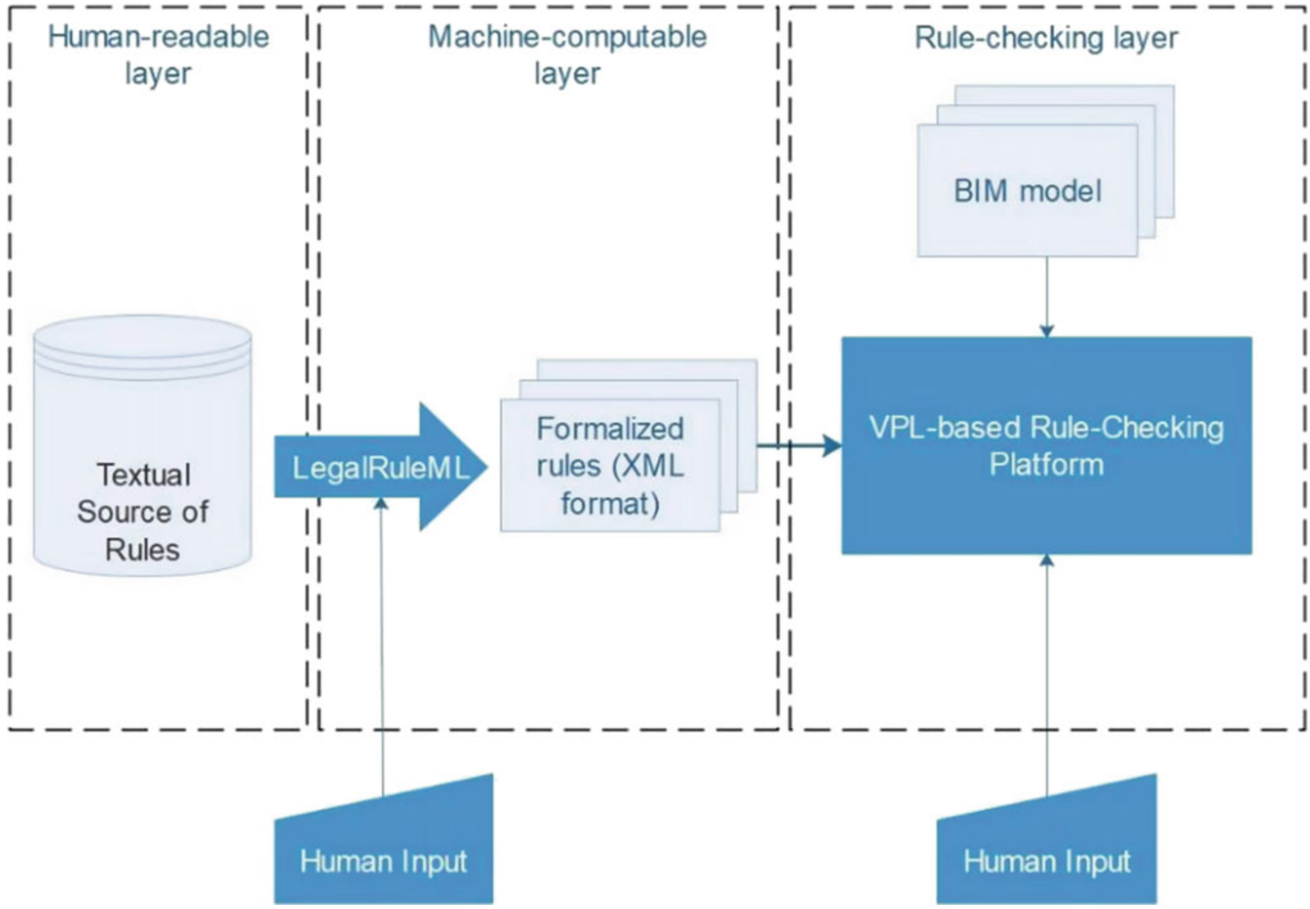

Fig. 11.1 Diagram for the proposed approach of LegalRuleML and visual programming-based rule-checking system

well as the basic unit of programming. This graphical notation also can be used to represent design rules in a machine- and human-readable language. The collection of nodes is similar to a network flowchart that provides the readability and the flexibility so that users can implement compliance checking [13].

11.3 Methodology

This study utilizes open standard LegalRuleML and node-based scripting to develop an integrated framework of a flexible rule-checking approach for the early design phase. This research study employed VPL on the BIM authoring platform, which allows users to intuitively generate and manipulate BIM objects in order to expose and use embedded building information. For a case study, the authors used Marionette which is the VPL feature of Vectorworks. The scope of rule checking includes the rule sets required for the early design phase. In order to develop a robust framework, the first step was the collection and the identification of the early design requirements and rules. The investigation of the requirements for the early design phase allows this research team to confirm that rules are mostly about the spatial and geometric controls and the relationship between different building objects. Examples of these types of rules are as follows: circulation, room size, space sorting, space ratio, geometric property, and object existence.

These rules are formally presented by the XML schema based on LegalRuleML principles. LegalRuleML is integrated with visual programming platform to categorize the rules and implement the module-based rule-checking process. The integrated frame-work addresses mapping of rule types, parameters, and reporting methods into each code and the execution of semi-automated rule-checking.

According to the objectives of this research, we develop a process diagram of the proposed approach (Fig. 11.1). The process has three layers of the human-readable layer, machine-computable layer, and rule-checking layer. The first two layers will connect to each other by utilizing features of LegalRuleML. Then Marionette as visual programming platform will integrate these two layers into the rule-checking process.

11.4 LegalRuleML and Visual Programming-Based Rule-Checking System

11.4.1 The Human-Readable Layer and Machine-Computable Layer

The first major part of rule checking is the rule definitions. Rules are typically written in natural languages that require significant domain knowledge in order to interpret them into a machine computable form. There are many ways to approach the interpretation, as mentioned earlier, but most rule checking studies focus merely on the language representation of syntax and grammar of the rules. In practice, expert knowledge is often required to interpret the meaning or semantics of the rules: the intent, base, and hidden assumptions, assumed a general knowledge of the subjects, and dependencies with other rules.

11.4.2 The Rule-Checking Layer

Based on the functionalities of rule checking, in this research study, the authors identified four steps of rule definition and implementation process: (1) object selection, (2) rule definition, (3) rule implementation, and (4) validation report. These steps are implemented in VPL (marionette in our study) because of two main reasons. Firstly, VPL does not need extensive programming knowledge. Consequently, compliance checking process can be easily designed and modified by domain experts. In addition, marionette is a VPL embedded in Vectorworks, which is a BIM authoring tool, and this can significantly facilitate retrieving and query of building model data required for compliance checking.

The nodes utilized in the development of rule checking network can be categorized according to the aforementioned four steps. To avoid complex and ambiguous networks, each step of the rule checking process can utilize predefined nested nodes as modules which propose the required and identified parameters of the rules. These modules can be used iteratively in various steps and whenever they are needed. Predefined modules are logical nodes, mathematical nodes, geometric nodes, and building model related nodes. By this method, a rule checking process will improve from three aspects: readability, flexibility, and extensibility.

11.5 Rule Classification and Parametrization

11.5.1 Rules and LegalRuleML

One of the major problems in automated rule-checking is addressing how domain expertise is utilized in the interpretation of rules which is currently carried out manually. Rule interpretation is a significant step in the process of rule checking. To address this issue, Solihin and Eastman [15] find it useful to classify rules in four general classes: class (1) that require a small number of explicit data, class (2) that require simple derived attribute, class (3) that require extended data structure, and class (4) that require "proof of solution".

Based on LegalRuleML principles rules are classified mostly into two major categories: constitutive rules and prescriptive rules. The function of constitutive rules is to define and create the so-called institutional facts [1]. Where an institutional fact is how a particular concept is understood in a specific institution. Thus, constitutive rules provide definitions of the terms and concept used in a jurisdiction. On the other hand, the scope of prescriptive rules is to dictate what are the obligations, prohibitions, permissions, etc. in a legal system, and the conditions under which we have them. Legal-RuleML has various other capabilities that can model normative documents with their distinct characteristics, such as defeasibility, superiority, suborder, penalty, etc.

A rule set consist of relevant criteria (data model) and required an operation that must be used to assess different aspects of that data model. In order to organize and execute diverse rule sets more efficiently, with a minimum number of nodes, rule parameters can be classified based on their characteristics and attributes. In order to organize the nodes for rule checking, avoiding complex and ambiguous networks, and integration of the approach a rule mapping process is needed to recognize relevant parameters in formalized rule and VPL. Then each step of the rule checking process can be implemented by using predefined nested nodes as modules which address the required and identified parameters of the rules.

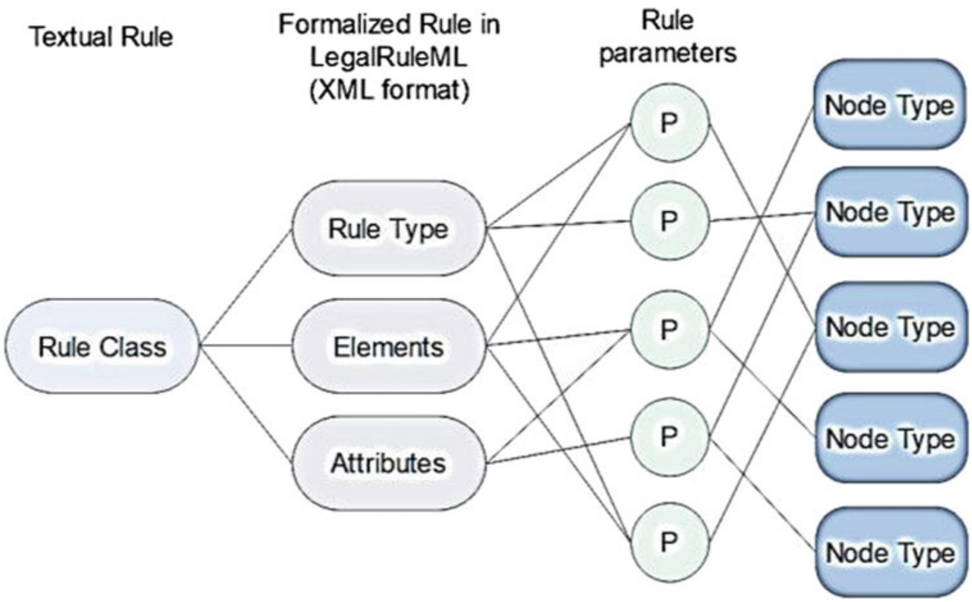

Fig. 11.2 Schematic rule mapping process

11.5.2 Rule Mapping in LegalRuleML

In order to integrate LegalRuleML with the BIM-based rule-checking process, the authors mapped compliant design rules required for the early design phase into rule classes in LegalRuleML. Rule mapping offers a robust framework for the user to design the most effective rule-checking network in VPL. In a proposed approach, it is the user's role to decide how to organize the VPL network for rule-checking implementation. This rule mapping offers a better understanding of the compliance checking process. Furthermore, this step is promising step to move toward automation of the rule-checking process. Figure 11.2 illustrates a schematic process of rule mapping.

11.6 Example Case Study

The proposed automated rule-checking approach is capable of executing the entire rule-checking process. To investigate the applicability of the approach and to accomplish the objective, a case study has been conducted using an early design requirement as described in section R304.1 (Minimum room areas) of the International Residential code [8], which stipulates:

> Habitable rooms shall have a floor area of not less than 70 square feet (6.5 m^2). Exception: Kitchens.

A single-story building model with multiple-rooms was used as a test model for this case study. The above normative textual provision is translated into XML format based on LegalRuleML principles by using the XML schema published by OASIS [11]. The logical content of above provision can be formalized into two rules, "*IRCsecR304.1Statements*" and "*IRCsecR304.1MinimumAreaException*" as follows:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<lrml:Statements key="IRCsecR304.1Statements">
    <lrml:PrescriptiveStatement key="IRCsecR304.1MinimumArea">
      <ruleml:Rule>
        <lrml:hasStrength>
          <lrml:DefeasibleStrength iri="http://spin.nicta.com.au/spindle/ruleStrength#defeasible"/>
        </lrml:hasStrength>
        <ruleml:if>
          <ruleml:Atom>
            <ruleml:equal>
            <ruleml:Expr>
              <ruleml:Fun iri="buvo:Function"/>
              <ruleml:Var>BuildingSpaceFunction</ruleml:Var>
            </ruleml:Expr>
            <ruleml:Ind>Habitable</ruleml:Ind>
            </ruleml:equal>
          </ruleml:Atom>
        </ruleml:if>
        <ruleml:then>
         <lrml:Obligation>
            <ruleml:atom>
              <ruleml:Rel>Greater than</ruleml:Rel>
              <ruleml:Var>BuildingSpaceArea</ruleml:Var>
              <ruleml:Data>6.5 square meters</ruleml:Data>
            </ruleml:atom>
          </lrml:Obligation>
        </ruleml:then>
      </ruleml:Rule>
    </lrml:PrescriptiveStatement>

    <lrml:PrescriptiveStatement key="IRCsecR304.1MinimumAreaException">
      <ruleml:Rule>
        <ruleml:if>
          <ruleml:Atom>
            <ruleml:equal>
            <ruleml:Expr>
              <ruleml:Fun iri="buvo:Function"/>
              <ruleml:Var>BuildingSpaceName</ruleml:Var>
            </ruleml:Expr>
            <ruleml:Ind>Kitchen</ruleml:Ind>
            </ruleml:equal>
          </ruleml:Atom>
        </ruleml:if>
        <ruleml:then>
         <lrml:permission>
            <ruleml:atom>
              <ruleml:Rel>Less than</ruleml:Rel>
              <ruleml:Var>BuildingSpaceArea</ruleml:Var>
              <ruleml:Data>6.5 square meters</ruleml:Data>
            </ruleml:atom>
         </lrml:permission>
        </ruleml:then>
      </ruleml:Rule>

    </lrml:PrescriptiveStatement>
```

The above representation has one obligatory condition and one permission condition, i.e. if the function of a space is habitable the area must be greater than 6.5 ft^2. This rule can be defeated if the function of the habitable area is "kitchen". Table 11.1 indicates the rule mapping for this rule which contains rule classification and parametrization discussed before.

Table 11.1 Rule parametrization

Textual format		LegalRuleML format	Rule parameters		Node types	
Class 2	Elements	<ruleml:if>, <ruleml:then>, <lrml:Obligation>, <lrml:permission>, etc.	Relationship	Greater than	Logical nodes	Greater than
	Attributes	Var: BuildingSpaceFunction	Target building object	Space	Building model related nodes	Selection
			Name or function of a building object	Habitable	Building model related nodes	Filter
		Var:BuildingSpaceName	Target building object	Space	Building model related nodes	Selection
			Name or function of a building object	Kitchen	Building model related nodes	Filter
		Var:BuildingSpaceArea	Geometric property of a building element	Area		Get area
		Data: 6.5 m^2	Value	6.5 m^2		

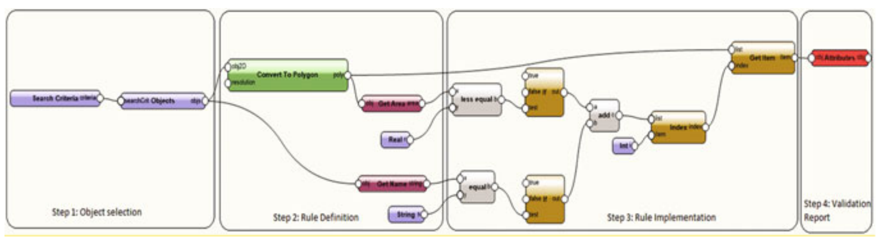

Fig. 11.3 Node network for checking minimum area rule

The output of this step is identifying required nodes for retrieving essential information from the data model to implement the effective rule-checking process.

Figure 11.3 shows the node network for executing this rule. The network carries out this geometric property checking process in four mentioned steps: object selection, rule definition, rule implementation, and validation reporting. The output of this network is a visual report that highlights the spaces which do not fulfill the requirement (Fig. 11.4).

11.7 Discussion and Conclusion

This paper proposes a new rule checking approach that integrates formal procedure of rule translation from compliant design requirements to LegalRuleML and its execution plan using the graphical scripting language. A simple example of early design phase requirements is used to demonstrate how the proposed approach carries out rule checking process from textual normative documents to final validation report of BIM model checking. The current practice of rule-checking in the AEC industry is conducted manually and is a time-consuming, error-prone, and costly process because of the extensive amount of normative requirements and the highly complex building design models. The rule-checking process consists of repetitive tasks that can be performed much more efficiently and effectively by machines. However, most of the previous attempts to automate the process have the inclination to hard-code rules into the checking system. These approaches also have shortcomings such as the lack of transparency, the need for extensive knowledge of programming, and inflexibility. This research team believes that using the open standard LegalRuleML in conjunction with VPL can address listed shortcomings and has the potential to provide unique contributions to defining and organizing rules consistently and implementing them interactively with BIM models.

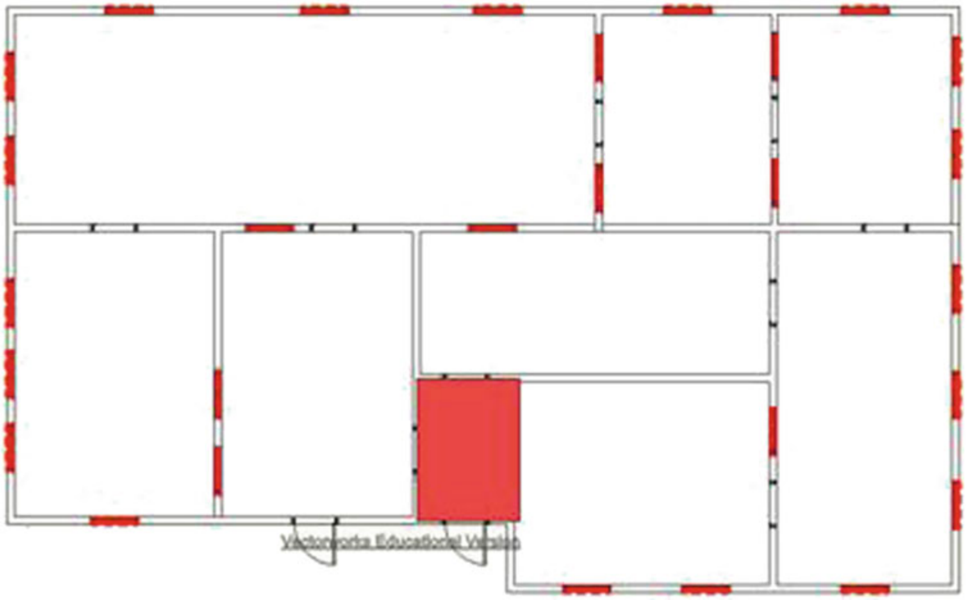

Fig. 11.4 The highlighted room violates the minimum area rule

References

1. Athan, T., Boley, H., Governatori, G., Palmirani, M., Paschke, A., Wyner, A.: Oasis legalruleml. In: Proceedings of the Fourteenth International Conference on Artificial Intelligence and Law, pp. 3–12. ACM (2013)
2. Boley, H., Paschke, A., Shafiq, O.: RuleML 1.0: the overarching specification of web rules. In: International Workshop on Rules and Rule Markup Languages for the Semantic Web, pp. 162–178. Springer, Berlin, Heidelberg (2010)
3. Dimyadi, J., Governatori, G., Amor, R.: Evaluating legaldocml and legalruleml as a standard for sharing normative information in the AEC/FM domain. In: Proceedings of the Lean and Computing in Construction Congress (2017)
4. Dimyadi, J., Amor, R.: Automated building code compliance checking–where is it at. In: Proceedings of CIB WBC, pp. 172–185 (2013)
5. Eastman, C., Lee, J.M., Jeong, Y.S., Lee, J.K.: Automatic rule-based checking of building designs. Autom. Constr. **18**(8), 1011–1033 (2009)
6. El-Diraby, T.E., Kinawy, S.: Effective semantic web-based solutions for civil engineering. In: Proceedings of CIB W78 Conference, pp. 1–6 (2008)
7. Froese, T., Han, Z., Alldritt, M.: Study of information technology development for the Canadian construction industry. Can. J. Civ. Eng. **34** (7), 817–829 (2007)
8. IRC Web page: https://codes.iccsafe.org/public/document/toc/553/
9. Lee, Y.-C., Eastman, C.M., Lee, J.-K.: Validations for ensuring the interoperability of data exchange of a building information model. Autom. Constr. **58**, 176–195 (2015)
10. Lee, Y.C., Ghannad, P., Shang, N., Eastman, C., Barrett, S.: Graphical scripting approach integrated with speech recognition for BIM-based rule checking. In: Construction Research Congress, pp. 262–272 (2018)
11. OASIS Homepage: https://www.oasis-open.org/
12. Palmirani, M., Governatori, G., Rotolo, A., Tabet, S., Boley, H., Paschke, A.: Legal RuleML: XML-based rules and norms. In: Rule-Based Modeling and Computing on the Semantic Web, pp. 298–312. Springer, Berlin, Heidelberg (2011)
13. Preidel, C., Borrmann, A.: Towards code compliance checking on the basis of a visual programming language. J. Inf. Technol. Constr. (ITcon) **21**(25), 402–421 (2016)
14. Schiffer, S.: Visuelle Programmierung: Grundlagen und Einsatzmöglichkeiten, vol. 245. Addison-Wesley, München (1998)
15. Solihin, W., Eastman, C.: Classification of rules for automated BIM rule checking development. Autom. Constr. **53**, 69–82 (2015)

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12 Coupling Between a Building Spatial Design Optimisation Toolbox and BouwConnect BIM

Sjonnie Boonstra, Koen van der Blom, Hèrm Hofmeyer, Joost van den Buijs, and Michael T. M. Emmerich

Abstract

This paper presents a framework in which a building spatial design optimisation toolbox and a building information modelling environment are coupled. The coupling is used in a case study to investigate the possible challenges that hamper the interaction between a designer and an optimisation method within a BIM environment. The following challenges are identified: Accessibility of optimisation methods; Discrepancies in design representations; And, data transfer between BIM models. Moreover, the study provides insights for the application of optimisation in BIM.

Keywords

Optimisation • Building information modelling • Building spatial design • Structural design • Building physics

12.1 Introduction

Optimisation of building designs has gained significant focus in recent years. One of the reasons is that design objectives have become more demanding and higher in number, making it more difficult for human engineers to manage and oversee a building design process. To make matters worse, the built environment is seeing an increase in disciplines that each have their own effect on the design objectives.

Building Information Modelling (BIM) aims at structuring data, such that the different disciplines involved in Architecture, Engineering, and Construction (AEC) projects can work together efficiently. However, this data structure is complex, which makes it difficult to apply optimisation techniques on BIM models. For example, the number of design variables may change when modifications are made to a BIM model. As a consequence, it is hard to define frameworks for optimisation algorithms in a BIM context.

This paper explores an integration of optimisation techniques into design processes that use a BIM environment. A framework that couples a building spatial design optimisation toolbox [5] to a BIM environment is proposed in Sect. 12.2

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Accordingly, a case study to investigate the interaction between a designer and an optimisation method is presented in Sect. 12.3. Finally the conclusions and an outlook are given in Sect. 12.4

The following topics are discussed in the remainder of this section: building design optimisation in Sect. 12.1.1; optimisation and BIM in Sect. 12.1.2; and finally a motivation for the presented work in Sect. 12.1.3.

12.1.1 Building Design Optimisation

Building design optimisation research is a well defined field with different approaches, a thoughtful overview of the field is found in [10]. In this field, researchers try to hand support tools to designers, e.g. for feedback on design decisions in early stage design [12]. Others focus more on the application of state-of-the-art algorithms, as is carried out in [7]. Also parametrisation of designs and the impact of parameters [9] are well treated topics in the field. However, application of optimisation techniques in the built environment is not common. Therefore, the authors of [11] investigate how to make current optimisation and design techniques available to designers and policy makers. But, for industry, application of such techniques may not be straightforward. Usually, research on building design optimisation is presented with (sometimes academic) examples, but it is rarely studied how the methods are applicable to- or experienced by industry.

12.1.2 Optimisation and BIM

BIM is accepted more and more as a standard in the AEC industry [1]. For the application of building design optimisation it is thus important that it is well fitted within a BIM context. Examples of optimisation in BIM environments can be found, usually BIM models are parametrised, e.g. [2]. A parametrised BIM model can however be unsuitable for optimisation, e.g. because parameters appear or disappear after the model is modified. Such behaviour can be dealt with by defining meta parameters, which describe the value of the dynamic parameters in the problem. This is for example carried out in [6], in which a structural design is created for a BIM based building spatial design by using different functions as a meta parameter to generate structural parts in the BIM model. Optimisation tasks that are carried out within a BIM environment are, however, almost always limited by the BIM data structure. As a consequence, also the design search space will be limited when a BIM environment is used.

12.1.3 Motivation

Building design optimisation is a well developed field of research, however it is not widely used in industry. BIM is the de facto standard for building design modelling, but its complex data structures make it hard to apply optimisation methods. It is desirable that optimisation methods become more accessible, preferably for modern standards like BIM.

The work in this paper is part of a wider research scope, in which the multi disciplinary optimisation of building spatial designs is researched. The research that has been carried out so far within the latter scope is academic, and thus somewhat removed from the building design practice. In this paper, the aim is to identify the barriers that keep designers from using optimisation methods in a BIM context. To that purpose, here a study is conducted on an interaction between a designer and an optimisation method that has been developed in the wider research scope.

12.2 Framework

First, an optimisation toolbox for building spatial design, structural design, and building physics design is introduced in Sect. 12.2.1. Second, a commercial BIM environment that is used in the Dutch built environment is introduced in Sect. 12.2.2. Finally, a coupling between the toolbox and the BIM environment is presented in Sect. 12.2.3.

12.2.1 Optimisation Toolbox

A detailed description of the building spatial design optimisation toolbox is given in [5]. Here, a short outline of the relevant parts of the toolbox is given.

Building Spatial Design Representation The representation of a design determines the parameters that can change the design. Therefore, it also affects the type of optimisation methodology that can be applied. In the toolbox, a building spatial design is defined as a collection of spaces. Two representations have been implemented in the toolbox, both of which are limited to represent only cuboidal spaces in an orthogonal grid. One representation uses the so-called *supercube* (SC), in which cells are defined by a 3D orthogonal grid and each cell can be controlled individually to be active or inactive for a space in the building spatial design, see Fig. 12.1a. The SC representation can be expressed in mathematical terms, and is therefore suitable for evolutionary algorithms (EAs). The other representation uses two sets of three parameters per space, i.e. the location (x, y, and z) and the dimensions (w, d, and h). Spaces can be moved and dimensioned freely, the representation is—in the context of the toolbox—therefore termed the *movable and sizeable* (MS) representation, see Fig. 12.1b. This representation is relatively easy to interpret for humans, which makes it suitable for heuristic design rules that are defined by designers and engineers.

Design Grammars In order to obtain discipline specific performances from a building spatial design it is necessary to evaluate a model for that discipline. Such a model can be derived from a building spatial design using a design grammar, i.e. a set of design rules. These design rules use spatial and geometric relations within the spatial design, e.g. internal or external walls, to decide what is modelled at different locations in the discipline specific model. The toolbox is equipped with a design grammar that can generate a building structural model. This can be used to evaluate displacements, reaction forces, stresses, and strains. Moreover, a design grammar for a building thermal model is implemented in the toolbox. This can be used to evaluate the heating and cooling energy for a space that is required to keep the temperature within a predefined (comfortable) range.

Optimisation Methods In previous work, two different optimisation approaches have been developed within the context of the toolbox. First, an approach that uses a simulation of co-evolutionary design processes, which is presented in [8]. Second, an approach that uses an EA, which is introduced in [3] and which is further developed to what is presented in [4]. The first approach uses the MS, and the second uses the SC-representation to describe a solution.

12.2.2 The BouwConnect BIM Environment

BouwConnect is a Dutch commercial BIM environment (www.bouwconnect.nl). It consists of a product library and a building model environment. The product library contains information about nearly all building products that are available on the Dutch market. It is structured such that products are composed of data objects that describe part(s) of a product, e.g. material, shape, and function. A product in the library contains 2D- and 3D-CAD models and also information on costs,

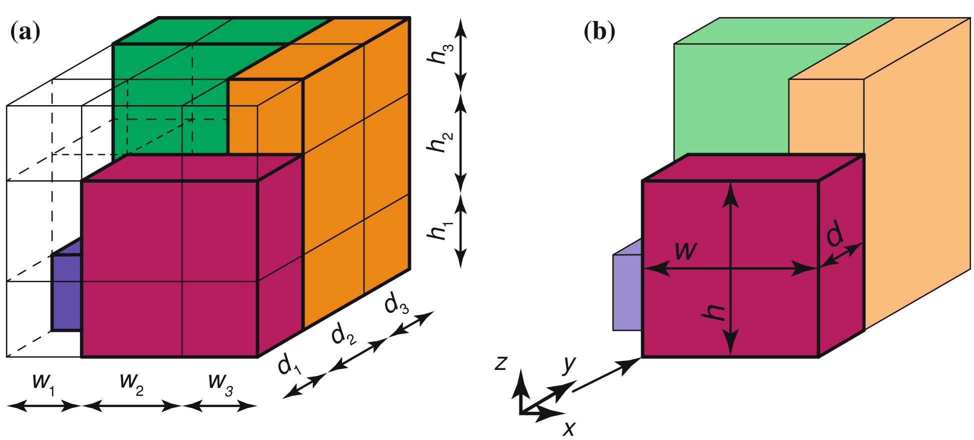

Fig. 12.1 The two building spatial design representations in the toolbox, different spaces are each indicated with a color. **a** Depicts the *supercube* representation with active (filled) and inactive (empty) cells in a 3D orthogonal grid. **b** Depicts the *movable and sizeable* representation, in which individual spaces can be moved freely

pictures, descriptions, and suppliers. Products can be placed/linked in a building spatial model via the building model environment. Using this environment, calculations and checks regarding energy, daylight, ventilation, fire security, and so on can be carried out. Both the product library and the building model environment can be linked (two-way) with other software (e.g. Revit and AutoCad), Industry Foundation Classes (IFC), and local Dutch software.

12.2.3 Coupling

The coupling between the toolbox and the BIM environment is realised by means of the Extensible Mark-up Language (XML). An XML file holding data on a building spatial design model can be parsed by both software environments. Parsing the file with the toolbox results in a model in the MS representation. If the file is parsed in the BIM environment it results in a collection of building elements that have been assigned to spaces. Each building element owns a geometry, which is an ordered list of 3D vertices ($x_1, y_1, z_1, x_2, y_2, z_2, x_n, y_n, z_n$). As such, a space's geometry is defined by that of its building elements and not by one of its own. The XML data structure, which is similar to the data structure of the BIM environment, is illustrated in Fig. 12.2. The presented data structure is implemented such that it can be extended, e.g. with the data that is generated by the design grammars. It should be noted that in Bouwconnect and the XML file, in contrast to the toolbox, a space is not a direct representation of geometry.

12.3 Case Study

This section presents a case study in which an optimisation result is used to modify a building design. The case study is followed by a discussion.

12.3.1 Design Process

Incorporating optimisation into a BIM based design process is here proposed as follows. First, a design that has already been developed in the BIM environment is selected. Accordingly, the design is exported to and optimised in the toolbox.

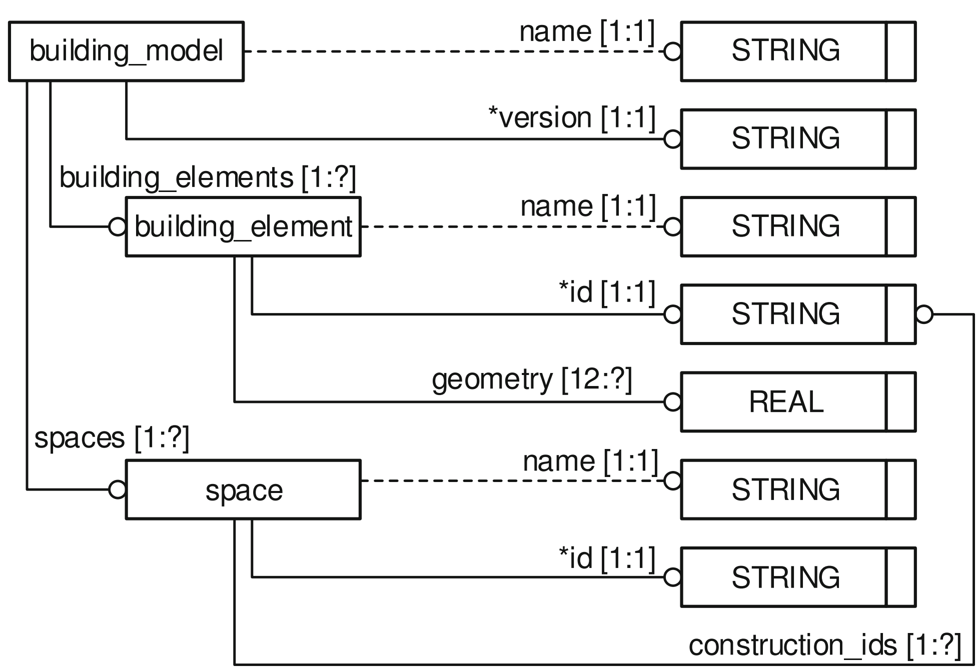

Fig. 12.2 Data structure of the XML file, visualised in EXPRESS-G

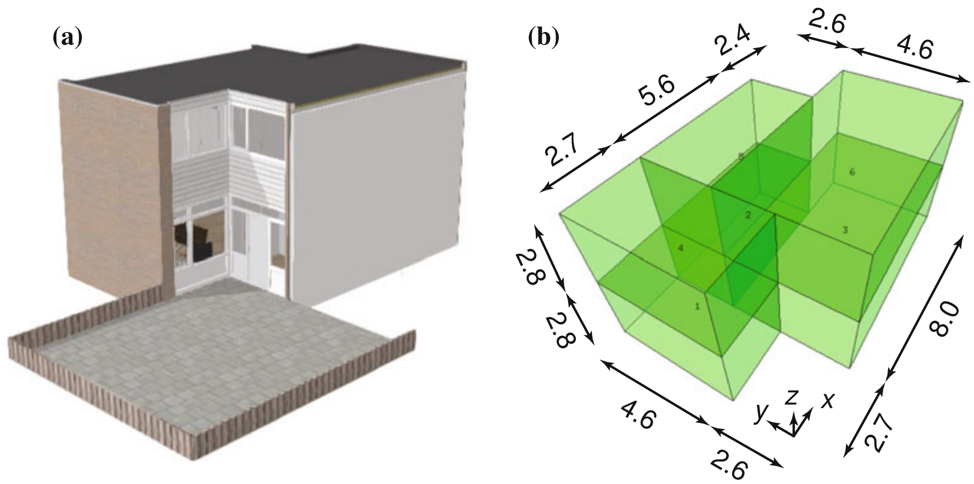

Fig. 12.3 The selected design. **a** Shows the visualisation in BouwConnect. **b** Shows the visualisation in the toolbox together with the dimensions (in [m])

Thereafter, the selected design is modified based on the optimisation results. The new design is then compared with the original.

Selected Design Fig. 12.3 presents the design that has been selected for the study. It has been selected for its rectangular properties, because the toolbox can only represent designs with cuboid spaces. It should be noted that the design is a terraced house, the light grey wall in Fig. 12.3a and the wall adjacent to it are shared with similar terraced houses.

Conversion Although automated, the conversion from BouwConnect to the toolbox is limited. This limitation results from the fact that geometries of building elements in BouwConnect extend beyond rectangular geometries, however the toolbox does not. Therefore, for this study the vertices of all geometries in the XML file are listed together. Accordingly, by mapping that list, the corner points of spaces are selected visually. Spaces are then manually defined in a representation that is readable for the toolbox, resulting in the design of Fig. 12.3b.

Optimisation For optimisation, the EA in the toolbox is used and the settings for the design grammars and the algorithm are borrowed from [4]. From that study, the SMS-EMOA-SC algorithm is selected because in the study it performed best.

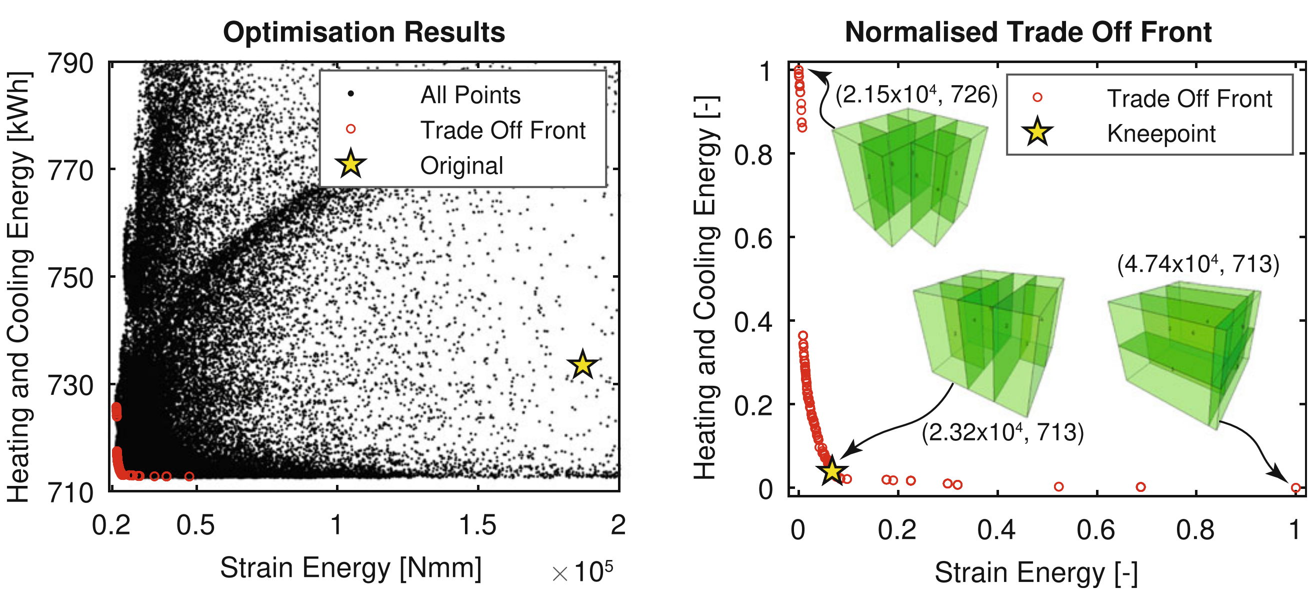

Fig. 12.4 The left graph shows all evaluated results and the trade off front (over all 10 runs), note that outliers are not shown (<5% of all solutions). The right graph shows the normalised trade off front and some designs and their performances: The best structural- (0, 1); The best thermal- (1, 0); And, the kneepoint performance

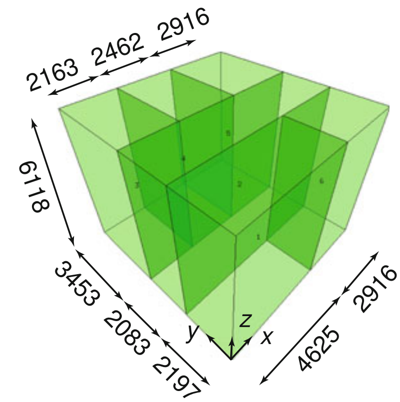

Fig. 12.5 The design with the kneepoint performance, visualised in the toolbox and an indication of the dimensions (in [mm])

Table 12.1 Comparison of characteristics between the original and the optimised design

Source[a]	Characteristic	Unit	Original design	Optimised design
TB	Volume	[m^3]	357	357
BC	Floor area	[m^2]	118	59
TB	Strain energy	[N mm]	1.871e5	0.2322e5
TB	Heating and cooling energy	[kWh]	733.5	713.3
BC	Total annual energy use[b]	[MWh]	32.82	25.45
BC	Energy index[b]	[−]	1.85	2.03

[a]TB for toolbox and BC for BouwConnect; [b]According Dutch regulation NEN-7120

Two objectives are set, i.e. minimisation of strain energy and minimisation of the heating and cooling energy. Equality constraints have been defined to enforce a constant volume, cuboid spaces, and no vertical gaps between spaces. Also, inequality constraints have been defined to bound space dimensions. The algorithm is given an evaluation budget of 10,000 and it is run ten times to decrease dependencies of the result that may be caused by stochastic processes such as initialisation and mutation. Problem specific optimisation settings are derived from the selected design (Fig. 12.3b): 6 spaces; volume of 357 m^3; and a supercube of 3 × 3 × 2 (w, d, h) is used. The optimisation results are given in Fig. 12.4, where the kneepoint is determined as follows. All values of the trade off front—over all runs—are normalised to a [0, 1] interval between the minimum and maximum found values in each objective. Accordingly the kneepoint is defined as the normalised point with the smallest (Euclidean) distance to the origin [(0, 0) for the 2-dimensional case].

Design Modification In this step, in BouwConnect, the original design (Fig. 12.3) will be modified using the optimal design, i.e. the design that corresponds with the kneepoint performance, see Fig. 12.5. The following procedure is followed, first, the kneepoint solution is imported from the toolbox into the BIM environment. Accordingly—using the imported design data—some data of the original design is modified such that an energy performance calculation within BouwConnect can be performed. Although possible, the procedure does not entail a full modification of the original design, due to time restrictions and—for the study at hand—it would only add a visualisation. During the modification procedure, the designer had to make design decisions, some of which are: The walls parallel to the y-direction, are in the optimised design assumed to be fully shared with other buildings; As a consequence, also the orientation of some windows had to change; Functions of spaces were redistributed.

Comparison Both the original and the optimised design are compared by using characteristics that were generated by both the toolbox and BouwConnect, see Table 12.1. First to notice is a 50% reduction of floor area in the optimised design, but the volume is unchanged due to the optimisation constraints. Moreover, the two objectives in the toolbox (minimal strain energy, and heating and cooling energy) have successfully been improved. This improvement also leads to a smaller total annual energy use according to the calculations by BouwConnect. However, the energy index, which is used to asses a building's energy efficiency, becomes higher (higher being worse) for the optimised design. This is caused by the reduction of floor area in the building, because—regarding efficiency—the energy use per useful floor area has increased (32.82/118 = 0.28 MW h m^{-2} has become 25.45/59 = 0.43 MW h m^{-2}). Note that in Table 12.1, the heating and cooling energy from the toolbox results from a simulation of three hot and three cold days. Whereas, the total annual energy use from BouwConnect is an estimate for a full year but it also includes energy use by ventilation, hot water, and lighting.

12.3.2 Discussion

Use of optimisation methods by industry is desirable, and—considering modern standards—such methods should be well incorporated in a BIM environment. A case study has therefore been conducted in order to identify the challenges and barriers while attempting to integrate an optimisation method for building spatial designs into a BIM based design process.

Looking at the results in Table 12.1, a critical remark may be that the optimised design is not practical. Although less energy is needed for exploitation of the building, there is a significant reduction in useful floor area. A building's floor area is an important measure for practical uses of a building like fitting furniture, selling price, and comfort. Optimality can, in this case, thus be questioned. It should, however, also be noted that a lesson can be learned, albeit obvious. Namely, in order to reduce energy use, one may have to consider to reduce the floor area of a design. Nonetheless, it would be desirable to introduce an inequality constraint in the EA to ensure a minimal floor area. Which in this case is a non trivial task for a designer, because the used optimisation method is highly tailored to the problem. Implementation of such a constraint requires knowledge of the algorithms that are used in the method.

Connecting the toolbox and BouwConnect via the proposed coupling did not lead to a seamless conversion between the two environments. This is mostly caused by the differences in the geometric representation of a design. BouwConnect is based on geometries of building elements, as such, a space's geometry is defined by that of building elements and not by its own. An approach that is not uncommon in BIM data structures. The toolbox uses 3D geometries to define spaces, and if applicable, defines building elements by using (parts of) their surfaces. This discrepancy requires a solution in either the BIM environment or the optimisation method, in order to allow for a seamless conversion.

Data transfer between models is another issue that must be addressed. In the case study, the optimised design could not inherit some of the features in the original design. Transferring data between the optimised and the original design thus requires design decisions, a process that is currently labour intensive. A method that can automatically inherit data from another BIM model based on similarities could be useful here. Such a method could also be extended, in order to present a designer with design decisions when certain features are not present in the new model. Not only would this method be useful for optimisation, it could also be used to initialise a new model for buildings that show strong similarities with buildings that have already been modelled.

Finally, it should be noted that the case study was limited to importing an optimised design and assigning its properties to another design. Findings may, therefore, not be generally applicable to optimisation in BIM environments. However, they can serve as starting points for optimisation of BIM models.

12.4 Conclusion and Outlook

In this paper, a coupling between an optimisation research toolbox and a commercial BIM environment has been presented. Using the coupling, a case study has been performed in which an optimisation result has been used in a BIM design process. The study showed that optimisation techniques should be—to some extent—adjustable by the designer. Moreover, it was concluded that discrepancies in problem representations require a thoughtful conversion between the two. Also, an automated transfer of data between BIM models based on similarities between the models would be beneficial. The findings from this study may be used to extend the optimisation research toolbox or the commercial BIM environment to further investigate the integration of optimisation methods into BIM environments. The study can also provide starting points for other optimisation approaches of BIM models.

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References

1. Abdirad, H., Dossick, C.S.: BIM curriculum design in architecture, engineering, and construction education: a systematic review. J. Inf. Technol. Constr. (ITcon) **21**(17), 250–271 (2016)
2. Asl, M.R., Zarrinmehr, S., Bergin, M., Yan, W.: BPopt: a framework for BIM based performance optimization. Energy Build. **108**, 401–412 (2015), https://doi.org/10.1016/j.enbuild.2015.09.011
3. van der Blom, K., Boonstra, S., Hofmeyer, H., Emmerich, M.T.M.: Multicriteria building spatial design with mixed integer evolutionary algorithms. In: Parallel Problem Solving from Nature—PPSN XIV, pp. 453–462. Springer (2016). https://doi.org/10.1007/978-3-319-45823-6_42
4. van der Blom, K., Boonstra, S., Wang, H., Hofmeyer, H., Emmerich, M.T.M.: Evaluating memetic building spatial design optimisation using hypervolume indicator gradient ascent. In: Numerical and Evolution Optimization-NEO 2017, pp. 62–86, Springer (2019). https://doi.org/10.1007/978-3-319-96104-0_3
5. Boonstra, S., van der Blom, K., Hofmeyer, H., Emmerich, M.T.M., van Schijndel, J., de Wilde, P.: Toolbox for super-structured and super-structure free multidisciplinary building spatial design optimisation. Adv. Eng. Inform. **36**, 86–100 (2018). https://doi.org/10.1016/j.aei.2018.01.003
6. Geyer, P.: Component oriented decomposition for multidisciplinary design optimization in building design. Adv. Eng. Inform. **23**(1), 12–31 (2009). https://doi.org/10.1016/j.aei.2008.06.008
7. Hamdy, M., Nguyen, A.T., Hensen, J.L.: A performance comparison of multiobjective optimization algorithms for solving nearly-zero-energy-building design problems. Energy Build. **121**, 57–71 (2016). https://doi.org/10.1016/j.enbuild.2016.03.035
8. Hofmeyer, H.D., Delgado, J.M.: Coevolutionary and genetic algorithm based building spatial and structural design. AI EDAM. **29**(4), 351–370 (2015). https://doi.org/10.1017/S0890060415000384
9. Hopfe, C.J., Emmerich, M.T.M., Marijt, R., Hensen, J.: Robust multicriteria design optimisation in building design. In: Proceedings of Building Simulation and Optimization, pp. 118–125, Loughborough, UK (2012)
10. Machairas, V., Tsangrassoulis, A., Axarli, K.: Algorithms for optimization of building design: a review. Renew. Sustain. Energy Rev. **31**, 101–112 (2014). https://doi.org/10.1016/j.rser.2013.11.036
11. Oh, J., Hong, T., Kim, H., An, J., Jeong, K., Koo, C.: Advanced strategies for net zero energy building: focused on the early phase and usage phase of a buildings life cycle. Sustainability **9**(12), 2272 (2017). https://doi.org/10.3390/su9122272
12. Ritter, F., Geyer, P., Borrmann, A.: Simulation-based decision-making in early design stages. In: 32nd CIB W78 Conference, pp. 1–10, Eindhoven, The Netherlands (2015)

Reusability and Its Limitations of the Modules of Existing BIM Data Exchange Requirements for New MVDs

13

Yong-Cheol Lee, Pedram Ghannad, and Jin-Kook Lee

Abstract

Model View Definition (MVD) is developed as a subset of the IFC schema to define BIM data exchange requirements of the architecture, engineering, construction, and facility management industries. Several domains such as the Precast/Pre-stressed Concrete Industry, the American Concrete Industry (ACI), the American Industry of Steel Construction (AISC), and the U.S. Federal Highway Administration (Brim MVD) have defined or are currently defining model views for formally representing their BIM data exchange requirements and assisting their exchange processes using the neutral data format, IFC. However, even though several domain industries involve the same or similar sets of data exchange requirements for their MVDs, a lack of a proper approach for reusing existing MVDs results in that a data exchange process of new MVD including the same entities, attributes, and relationships of other MVDs contains inconsistent and heterogeneous sets of data exchange requirements. For accelerating the consistent MVD development reusing previous efforts and the interoperable BIM data exchange environment, this paper involves the investigation of existing MVDs and their module-based definition processes to identify the current problems in MVD development regarding reusability and contains the discussion of the promising method for utilizing predefined MVDs for new MVD development.

Keywords

Model view definition (MVD) • IFC schema • BIM data exchange • Interoperability

13.1 Introduction

Building information modeling (BIM) is not only an approach for digital representation of characteristics of a facility, but also a process of creating and managing such information as a tool for decision making throughout the lifecycle of the facility [1]. The key factor for success of BIM in industry is an efficient and flawless interoperability solution for its information flow between different disciplines [2].

Interoperability is imperative for sharing data between BIM software supporting different phases of building. There are various domains of AEC-FM industry that have already defined and been developing their exchange requirements of BIM data. The BIM data exchange should include a geometry of the model and an appropriate level of detail regarding building components [3].

Industry Foundation Classes (IFC) has been developed as a standard to support a full range of BIM data exchanges among different disciplines and heterogeneous BIM applications. Each domain adopts the part of the IFC schema to represent a BIM model with the pertinent domain knowledge. The subpart of the IFC schema is Model View Definitions

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(MVD) [5]. In addition, Information Delivery Manual (IDM) is developed for identifying exchange requirements (ER) of BIM data [4]. Since several BIM data exchanges of project phases consists of duplicated information, a concept that specifies information of an entity, an attribute, a relationship, or a property set, is repetitively utilized to avoid a redundant definition of BIM data exchange. Developing a well-defined MVD plays a pivotal role for successful building information exchange throughout a building project.

One primary idea in MVD development and data mapping processes is modularization. Modularization organizes a block of code with reference names and bindings so that it can be re-used. Modularization is an important means to classify and re-use information in most areas of software design and production. However, because of a lack of a feasible method or a robust standard for retrieving and utilizing the existing data exchange requirements and MVDs, the academia and the industries have been struggling to reuse predefined IDM and MVD for developing their MVD by reusing the definitions of the same requirements. As a result, several MVDs entail heterogeneous requirements and semantic compositions for the same BIM data exchange process with exiting MVDs. For the interoperable BIM data exchange environment in the AEC industries, this paper involves the investigation of existing MVDs and their development processes to identify the current status of industries' MVD development and develop an innovative framework for semantically and syntactically integrating BIM data exchange requirements of existing MVDs. In addition, this paper presents current development and potential uses of modularization to respond to the redundancies in the MVD development process and their benefits in making model views easier to define and implement.

13.2 Background

The development of MVDs mainly has four phases: (1) IDM development, (2) MVD concepts and mapping, (3) application implementation and certification, (4) BIM validation [6]. IDM is defined by industry professionals to create human-readable references for ER of specific exchange scenarios in use-cases [4]. ER is specified as Exchange Requirement Models (ERMs) and Functional Parts (FPs) mapped to a data model schema (IFC) to define model views. This step principally involves MVD developers and software vendors to carry out the specification process for the relevant use cases.

Then, these MVDs can be implemented in applications to develop translators in BIM authoring tools in order to execute IFC import and export routines for target exchange scenarios [7]. In the validation phase, an IFC instance model exchanged between different applications is examined to ensure that the model satisfies ER. Currently, according to this process, various groups have developed IDMs and MVDs for their target domain model exchanges. Developed MVDs and on-going projects are listed on the webpages of buildingSMART-tech.org [6].

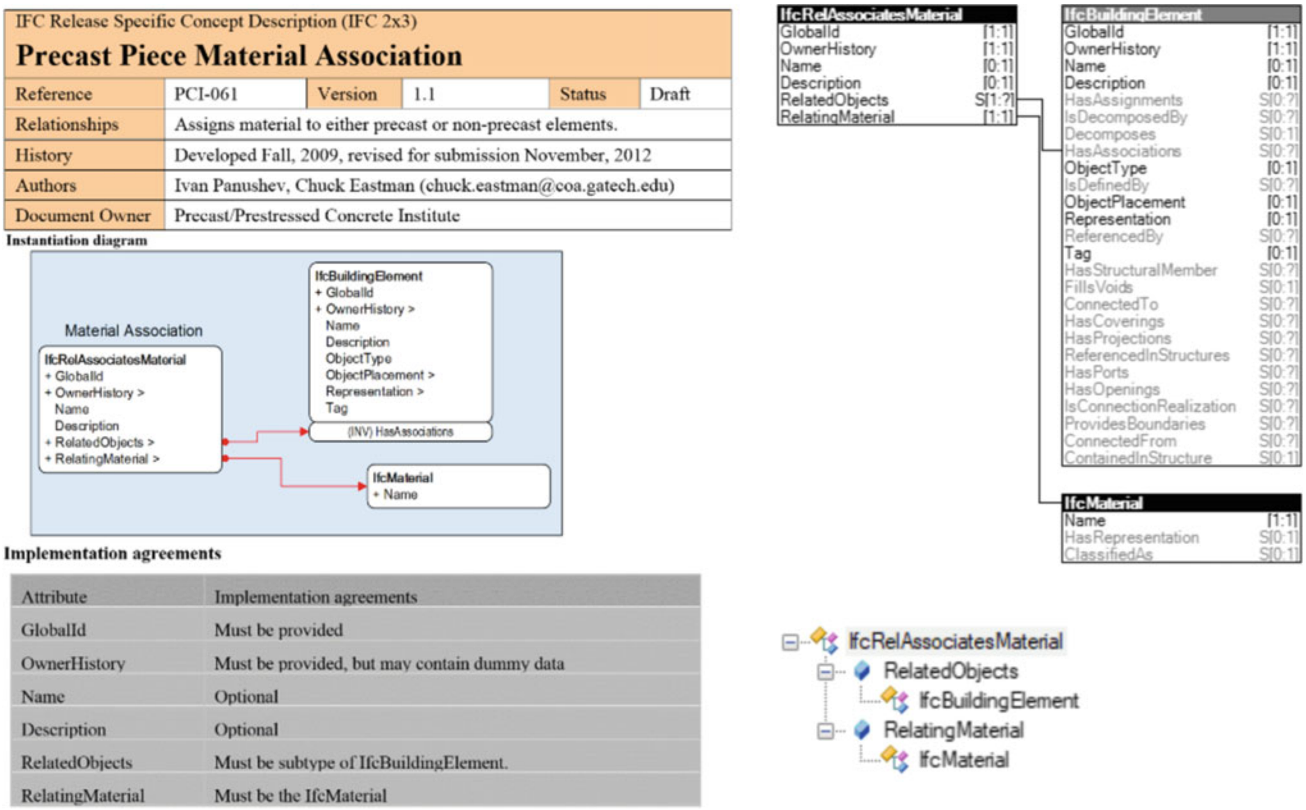
For the sake of the MVD development, domain industries identify exchange models from the outset that illustrate who exchanges what BIM models and their information in what phase of the project. With the purpose of obtaining practical information of industries and professionals, the previous MVD development projects investigated the information from diverse user communities and software vendors.

13.3 Methodology

While most of developed MVDs focused on a particular domain, a large-scale project such as civil infrastructure construction generally involves diverse domains and requires iterative BIM data exchange processes among heterogeneous project participants. For providing a knowledge base and a development framework for defining an MVD standard, this study explores the in-depth analysis of existing MVDs in diverse industry domains and has a discussion of a promising approach for efficiently reusing BIM data exchanges and their requirements. To identify the heterogeneous sets of existing MVDs, the authors investigated the following MVDs: The Precast/Pre-stressed Concrete Industry (PCI), the American Concrete Institute (ACI), and American Industry of Steel Construction (AISC).

13.3.1 A Modularized Concept

Previous project of IDM and MVD development focusing on a general domain has shown that the concepts are highly redundant. Many repetitions exist of entity structures, features, relations and properties within different types of building elements. Redundancies may not be recognized without addressing multiple exchanges within a domain rather than


IFC Release Specific Concept Description (IFC 2x3)

Precast Piece Material Association

Reference	PCI-061	Version	1.1	Status	Draft
Relationships	Assigns material to either precast or non-precast elements.				
History	Developed Fall, 2009, revised for submission November, 2012				
Authors	Ivan Panushev, Chuck Eastman (chuck.eastman@coa.gatech.edu)				
Document Owner	Precast/Prestressed Concrete Institute				

Instantiation diagram

Implementation agreements

Attribute	Implementation agreements
GlobalId	Must be provided
OwnerHistory	Must be provided, but may contain dummy data
Name	Optional
Description	Optional
RelatedObjects	Must be subtype of IfcBuildingElement.
RelatingMaterial	Must be the IfcMaterial

Fig. 13.1 A Blis concept defined for the precast piece material binding association and developed in the IfcDoc tool

singularly at the EM level. Software engineers extending their different BIM applications recognize redundancies when they write them and develop their own libraries of these data models, re-using them instead of coding them anew so as to reduce software maintenance efforts. Modules in IFC, were presented by Hietanen and See [5]. They adopted the word "Concept" as a way to organize code structure units and to name and access them. Concepts could include entity types, defined types, rules, functions and property sets and other IFC constructs. We refer to their definition as the Blis Concept definition. In practice Blis concepts were used as units of documentation, defined with a documentation template. Figure 13.1 shows a Blis Concept defined for the precast piece material binding association. The structure is diagrammed and its attribute rules are specified. IfcBuildingElement may be any sub-types of IfcBuilingElement.

13.3.2 A Concept in the IfcDoc Application

To efficiently assist MVD documentation and leverage definition reusability, IfcDoc has been developed by Constructivity, LLC and approved as a standard tool by buildingSMART international [8]. This application, which has been used for developing IFC 2 × 3 and IFC 2 × 4, facilitates the documentation of an MVD and to automatically graph the syntax specified. Parsing any MVD, say for diagramming it, requires that the MVD is syntactically correct. Thus, IfcDoc must parse the MVD against a standard version of IFC, which is usually taken until recently as the Coordination View (CV). IfcDoc has been made available as open source software, available in source and executable formats, with some documentation [9]. It adopted the way using a concept template so that the broad definition and requirements are used in several objects. Concept root was defined as a method to determine at what level in the Concept structure a particular concept should specialize. The concept template is a reusable definition skeleton that consists of the most frequently used entities, relationships, and attributes. Figure 13.2 shows a Blis Concept template of the precast piece material binding association developed in the IfcDoc tool. Concepts are focusing on specific objects, but some address a broad area, missing specific target object. This vague scope can make errors when a large sample having diverse types of entities is validated.

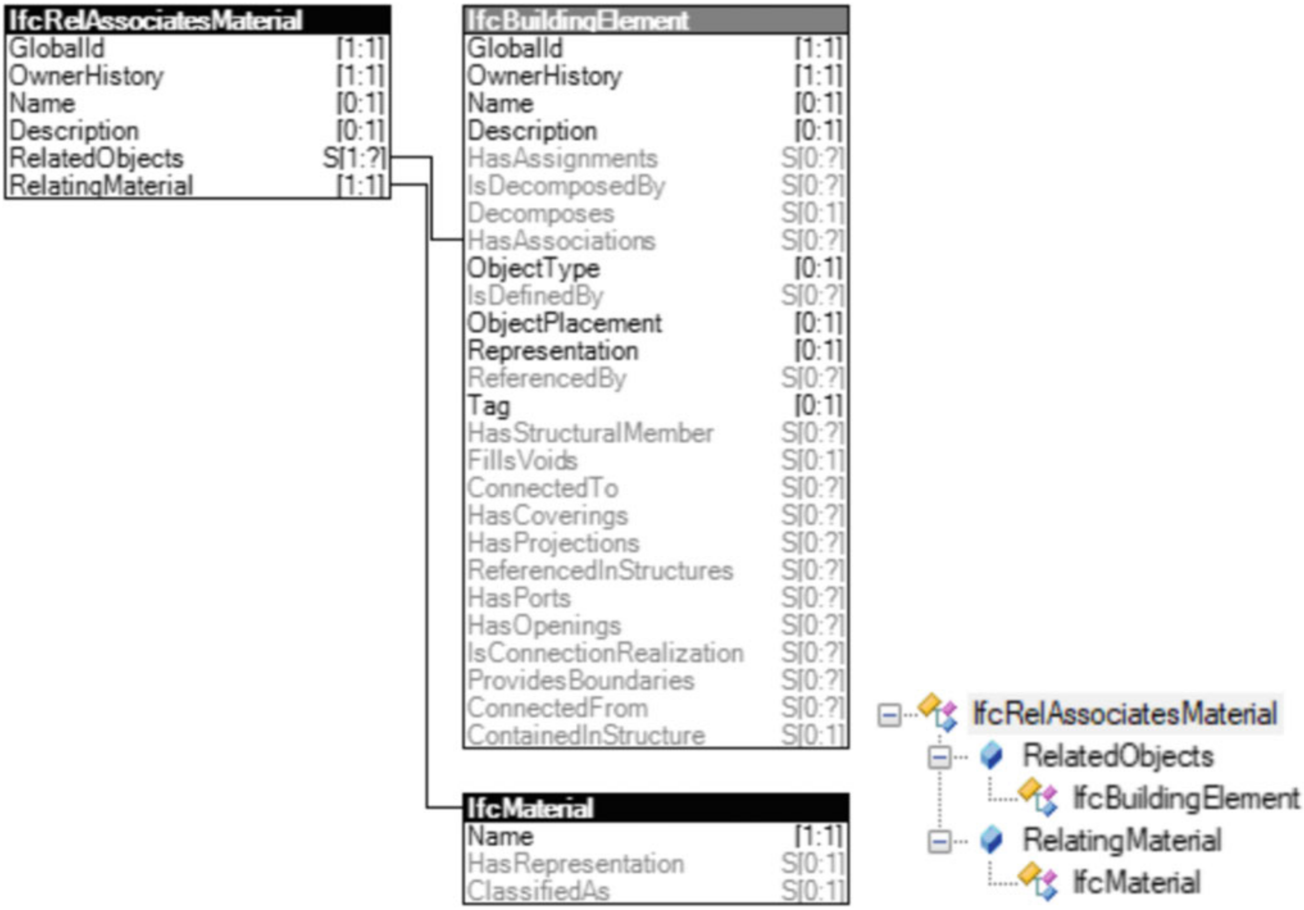


Fig. 13.2 A concept template of the precast piece material binding association developed in the IfcDoc tool

Based on this concept template, users can define concept blocks by adding more entities, relations, attributes, and properties in order to represent required exchange models. Thus, the concept templates are typically reused several times to define diverse exchange requirements that are developed as concept blocks. The composition of mandatory concept blocks is one EM. In addition, the collection of required EMs is one MVD. Figure 13.3 shows the concept block assigning the concept of the precast piece material binding association (PCI-061). The concept template can be reused by several entities, attributes, relationships, and property sets for efficiently representing BIM data exchange requirements with a limited set of definitions.

IfcDoc incorporates procedures to read and arrange IFC documentation in XML called mvdXML. It also has a checking capability to evaluate IFC instance files according to an imported EM in relation to the rules the MVD is part of. It automatically checks the MVD specification if the IFC structures make a well-defined IFC MVD sub-structure. The beginning MVD structure may be a full IFC schema, such as Release 4 or a restricted EM subschema, such as EM2 from the precast schemas. We use the schema checking capability of IfcDoc to check if a concept structure is well-defined in relation to its reference IFC schema or subschema. This paper examines the use of modularity in model view testing.

Because the modules that were identified each had their own unique scope and were independent from one another, they could also be written and debugged in different orders. In addition, some modules were quite specialized, thus they only were executed in one or a few EMs of an MVD, while other concepts were used widely, executed in most of the EMs. It is clear that the elimination of repetitious modules leads to much faster development. The implications are that modules speed up translator debugging and reduce code to translation.

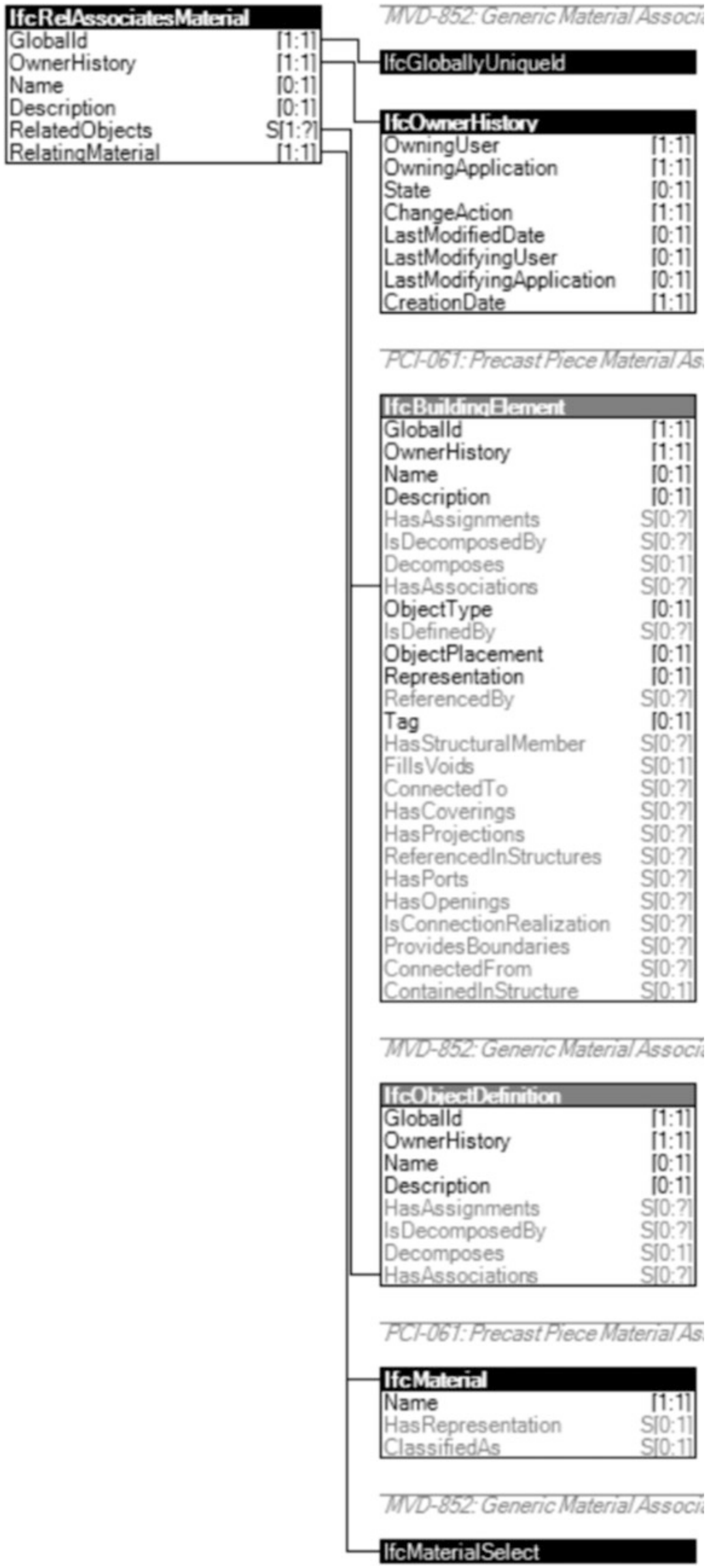


Fig. 13.3 A concept of the precast piece material binding association developed in the IfcDoc tool

13.3.3 Problems in Reusability of Concepts and MVDs for New MVD

The authors were involved in developing EMs in a variety of ways. This experience has allowed us to examine and test the benefits of modularity. However, there are the following several problems in fully reusing the concepts predefined in the previous MVD development projects:

- Heterogeneous definition processes and structure: Since each concept defines a specific entity, an attribute, a relationship, or a property set, a structure of the concept organization of new MVD should follow the one of previous one in order to use existing concepts. In other words, the structure and organization of concept templates in an existing MVD should be reused for the development of a new MVD. However, each MVD developer may have heterogeneous process of MVD development, thus, it would be challenging to utilize the same concept template again for a new MVD.
- Generalization of BIM exchange requirements: It is quite challenging to generalize and formalize a work flow and a data exchange process of a particular domain because they are subject to be varied according to diverse conditions such as a contract type, a project type, a team organization, or others.
- Reliability and representativeness of involved communities: Each MVD development project collects industry professionals and software vendors who can speak for the rest of an associated industry pertaining to BIM data exchange requirements. However, user-based requirement collection can result in varied workflow and its information according to knowledge and experience of attendees. Because of this problem, the collected EM can be inconsistent with regard to requirement definitions for the same EM of different MVDs.
- Project period and workforce: It is not only time-consuming, but also costly to organize a large number of meetings and put their opinions together for establishing EM and their requirements.

The following Figures represent different concept templates of existing MVDs: ACI, AISC, and Brim MVD. Figure 13.2 shows the concept template of the material binding association of the PCI MVD, Fig. 13.4 shows one of the ACI MVD, Fig. 13.5 shows one of the AISC MVD, and Fig. 13.6 shows one of the Brim MVD. Even though they all specifies the material binding association representing IfcObjectDefinition and IfcMaterials, they have their heterogeneous structures. The PCI MVD used IfcRelAssociatesMaterial, the ACI and AISC MVDs used IfcObjectDefinition, and the Brim MVD used IfcObject as a root entity that will be employed for being assigned by a concept template. In other words, in case of that a root entity is different, its concept block will be formed with a different organization. Even though the MVD development

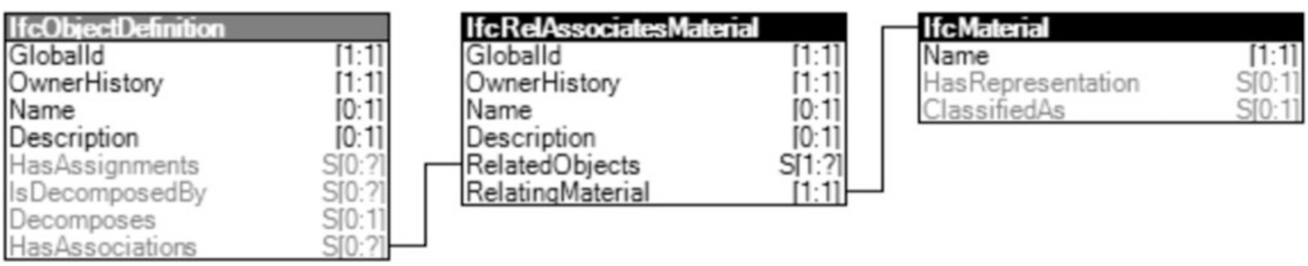


Fig. 13.4 A concept template of the material binding association (ACI)

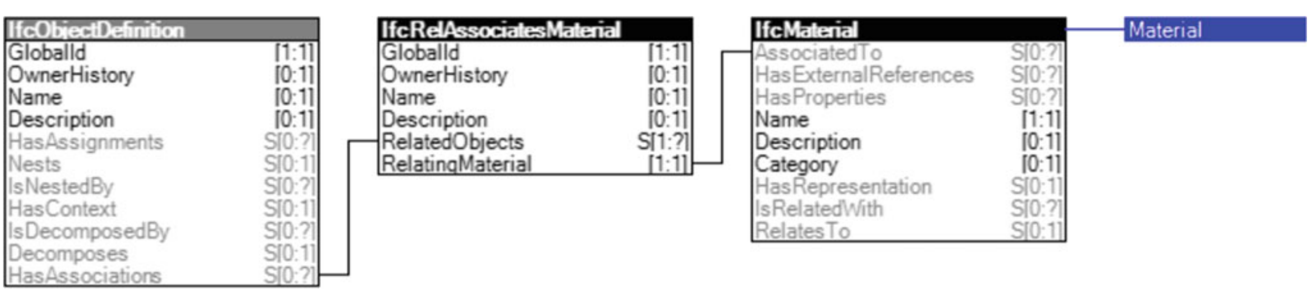


Fig. 13.5 A concept template of the material binding association (AISC)

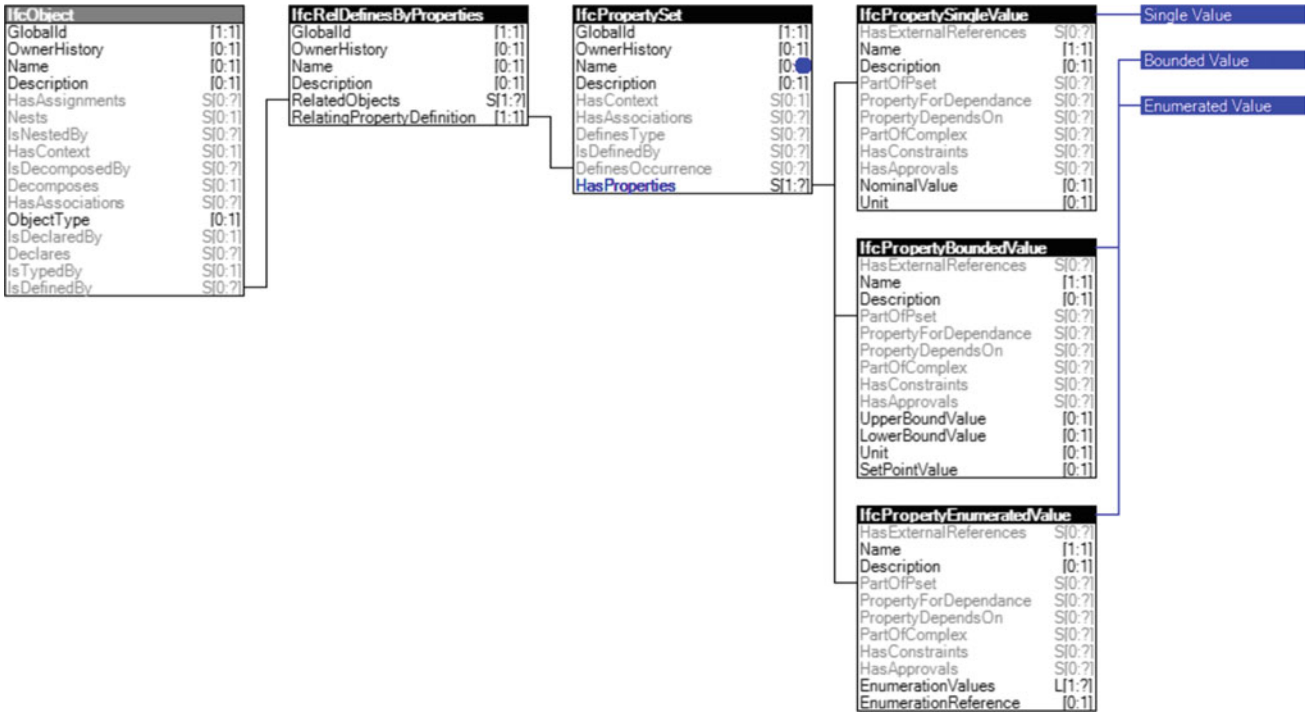


Fig. 13.6 A concept template of the material binding association (Brim MVD)

process is heterogeneous, the final contents of MVD will be the same. However, the imperative point is the reusability of concepts for expediating MVD development processes.

The structure of concept templates and blocks can also be one of obstacles for preventing modules of MVD. For the reusability of concept definitions, concept templates are provided in a IFC schema baseline in the IfcDoc format, but it might not be fit to new MVD development. Since domain knowledge entail diverse specifications, they may not need the existing concepts, but develop new concepts for their MVDs. As a result, the purpose of a concept, which is a modularized unit of knowledge for facilitating MVD development, might be useless. Thus, we recommend further investigation of concept organization and composition that provides a consistent MVD development.

13.4 Conclusion

Underneath the IFC schema, a standard for BIM data exchanges among different domains, applications, and phases, have been developed. However, MVD for developing the processes and interfaces of BIM data exchange has been overlooked, leaving academia and industry professionals to define it with their own methods. We need to deal with this increasing issue to retain our interoperability environment and facilitate BIM technology for the AEC industries. Thus, the results of this study are expected to explicitly represent the semantical and syntactical discrepancy of existing MVD sets and shows the current problems in reusing modularized concepts. MVD and its documentation tool, IfcDoc, are expected to allow all domain experts to consistently reuse pre-defined definitions and automatically developing MVD documentation. However, inconsistent structure of concept templates and block mapping have caused heterogeneous parts of MVDs that specifies even the same knowledge. Imperfection and inconsistency of concept and MVD development processes is one of critical limitations for establishing a standardized method for MVD development. Thus, formalization and generalization of concepts and their mapping processes should be discussed and investigated with diverse professionals for leveraging consistent MVD development processes and ultimately improving BIM interoperability.

References

1. NBIMS, National Building Information Modeling Standard, Version 1.0 Part 1 Overview Principles, and Methodologies, Technical Report, National Institute of Building Sciences (NIBS). http://www.buildingsmartalliance.org/ (2007)
2. Venugopal, M., Eastman, C.M., Sacks, R., Teizer, J.: Semantics of model views for information exchanges using the industry foundation class schema. Adv. Eng. Inform. **26**(2), 411–428 (2012)
3. Jeong, Y.S., Eastman, C.M., Sacks, R., Kaner, I.: Benchmark tests for BIM data exchanges of precast concrete. Autom. constr. **18**(4), 469–484 (2009)
4. Wix, J., Karlshoej, J.: Information delivery manual: guide to components and development methods. BuildingSMART Int. **5**(12), 10 (2010)
5. Hietanen, J., Final, S.: IFC model view definition format. Int. Alliance Interoperability 1–29 (2006)
6. IUG, International User Group of buildingSMART International Ltd.: An integrated process for delivering IFC based data exchange (2012). http://iug.buildingsmart.org/idms/methods-and-guides/Integrated_IDM-MVD_ProcessFormats_14.pdf/view. Accessed December 2012
7. Zhang, C., Beetz, J., de Vries, B.: Towards model view definition on semantic level: a state of the art review. In: Proceedings of the 20th International Workshop: Intelligent Computing in Engineering (2013)
8. Lee, Y.C., Eastman, C.M., Solihin, W.: Logic for ensuring the data exchange integrity of building information models. Autom. Constr. **85**, 249–262 (2018)
9. Lee, Y.C., Eastman, C.M., Lee, J.K.: Validations for ensuring the interoperability of data exchange of a building information model. Autom. Constr. **58**, 176–195 (2015)

14 Employment of Semantic Web Technologies for Capturing Comprehensive Parametric Building Models

Farhad Sadeghineko, Bimal Kumar, and Warren Chan

Abstract

Building Information Modelling is a well-known acronym in the construction industry. BIM process is more than modelling buildings, and it provides the opportunity to drive efficiency and effectiveness to the information management of build projects. Accordingly, Building Information Models (BIMs), typically known as semantic three-dimensional parametric models, are fast becoming the comprehensive information source in Architecture, Engineering and Construction (AEC), and Facility Management (FM). The use of BIM in existing buildings has been hampered by the challenges and limitations surrounding the available technologies. The most popular and commonly used approach for generating models is to manually generate 3D artefacts utilizing point measurements extracted from range-based technologies (typically 3D laser scanning). In the recent past, several studies have been carried out to make the retro t BIM development process as effective and efficient as possible by developing different methods for mapping 3D models using Point Cloud Data (PCD) as the main source of information. However, an appropriate fully generated parametric model is still some way away. In this paper, we review the-state-of-the-art to address the research gap and challenges involved in generating parametric models before outlining the proposal of our approach. In this research, we employ Semantic Web technologies to capture parametric models. Elements are first recognized in PCD, and corresponding geometric information extracted from PCD are then tagged with Universally Unique Identifiers (UUIDs). Tags are then linked with the generated Resource Description Framework (RDF) data for each element. The core and challenging part of this research is the standardization process where RDF as a serialization is translated to Industry Foundation Classes (IFC) as a data model. The generated IFC format is then utilized to capture corresponding models. The primary results are very promising and should be of interest to the modelling of all kinds of building components, particularly historical building information modelling (HBIM).

Keywords

Building information modelling • Semantic web technologies • Resource description framework

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14.1 Introduction

Building Information Models, typically known as semantic three-dimensional parametric models, are fast becoming the comprehensive information source in Architecture, Engineering and Construction (AEC), Facility Management (FM), and other associated domains [1]. The use of BIM process in build projects improves different aspects of an asset during its life-cycle, such as the decision-making process and the precision of the design during the planning process, data management, productivity, energy efficiency, sustainability, and health and safety of construction [1–4]. A semantic-rich parametric model contains two types of information, including the geometric representation of an object (geometric data) and the non-geometric information that needs to be added to the object for further use during the building's life-cycle. The use of semantic-rich parametric models has lately gained a lot of momentum in new build project for exchanging the information throughout a buildings life-cycle from the inception onwards [1, 5]. However, its use in existing assets, particularly in Historical Environments, has been hampered by the challenges and limitations surrounding the available technologies for developing retro t models. Practically, after the termination of new build projects, models captured from the initial design of a building do not necessarily coordinate with the as—built dimensions due to varying updates introduced to the asset during the construction period [6]. In a different manner, in unique conditions, such as existing assets and historic buildings, the facility may not have a proper 3D model, and the only accessible data are 2D drawings and corresponding documents. Accordingly, in the past years or so, several studies have been carried out proposing automated or semi-automated approaches for projecting BIMs utilizing 3D point measurements, typically known as Point Cloud Data (PCD). The workflow of generating BIMs using PCD can be categorized into two general processes consisting of Scan-and-BIMs and Scan-to-BIMs. The Scan-and-BIMs process involves approaches in which the as—designed 3D model is available and discrepancies, which occur between initial designs and as—is conditions, are identified by matching the datasets [7]. On the other hand, Scan-to-BIMs process is applied where the existing asset does not have a 3D model and PCD is therefore used as the main source of information for capturing BIMs [5, 8].

Historic Building Information Modelling (HBIM) has lately gained significant interest in heritage domain concerning the development of a suitable BIM frame-work for modelling historical monuments [26, 32, 33]. The suitability of HBIM framework relies on the model representation quality [27], reliability of generated geometries [9], and more importantly, required asset information embedded in models. A detailed and semantic representation of HBIM can be useful for addressing an appropriate Level of Detail (LoD) in advancing the HBIM framework. In order to collect the data from an existing asset, varying technologies are available for gathering required data in the form of images or point measurements, typically known as image-based or range-based methods [10]. Photogrammetry and Videogrammetry are considered as the commonly used data collection techniques in the image-based domain [1, 11, 12]. On the other hand, 3D Laser Scanning, as a range-based technique, is an accurate, popular, and most commonly adopted technology for extracting data from an existing building in the form of PCD [1, 6, 11, 13]. One of the challenges involved in generating reliable models from point measurements extracted from laser scanner is to record and analyze the information embedded in PCDs. The process is currently carried out manually which is a time-consuming, tedious, and error-prone owing to the human intervention [2, 14]. Although some progress has been recently made in generating parametric models from PCDs, a proper full-blown parametric model is still some way away.

In this paper, challenges and limitations involved in generating parametric models from PCD are addressed by reviewing state-of-the-art before presenting our approach. We use Semantic Web technologies, such as Resource Description Framework (RDF) in our approach to capture BIMs and manipulate the meta-data within the models. Figure 14.1 illustrates the workflow of proposed approach classified in four general steps consisting of (1) Data aggregation, (2) Data processing, (3) Data standardization, and (4) BIM capture. The first step involves extracting the information from an existing asset in the form of PCD and using corresponding 2D drawings and documents to append required information to the final result. In the data processing step, building components are recognized in the PCD, and the extracted geometric information for each element is tagged with a UUID (Universally Unique Identifier) or GUID (Global Unique Identifier). The unique Identifiers are used later to link the RDF data generated for each element to the corresponding data extracted from PCD in order to create linked data. In the third step, the SPARQL (SPARQL Protocol And RDF Query Language) is then used to extract the information required for the RDF-to-IFC translation process. The translated IFC is then used in the final step to generate the corresponding model by importing IFC into any BIM software that supports IFC format. The results of the proposed approach in this ongoing research are promising and should be of interest to the modelling of all kinds of assets, in particular, Historical Building Information Modelling (HBIM).

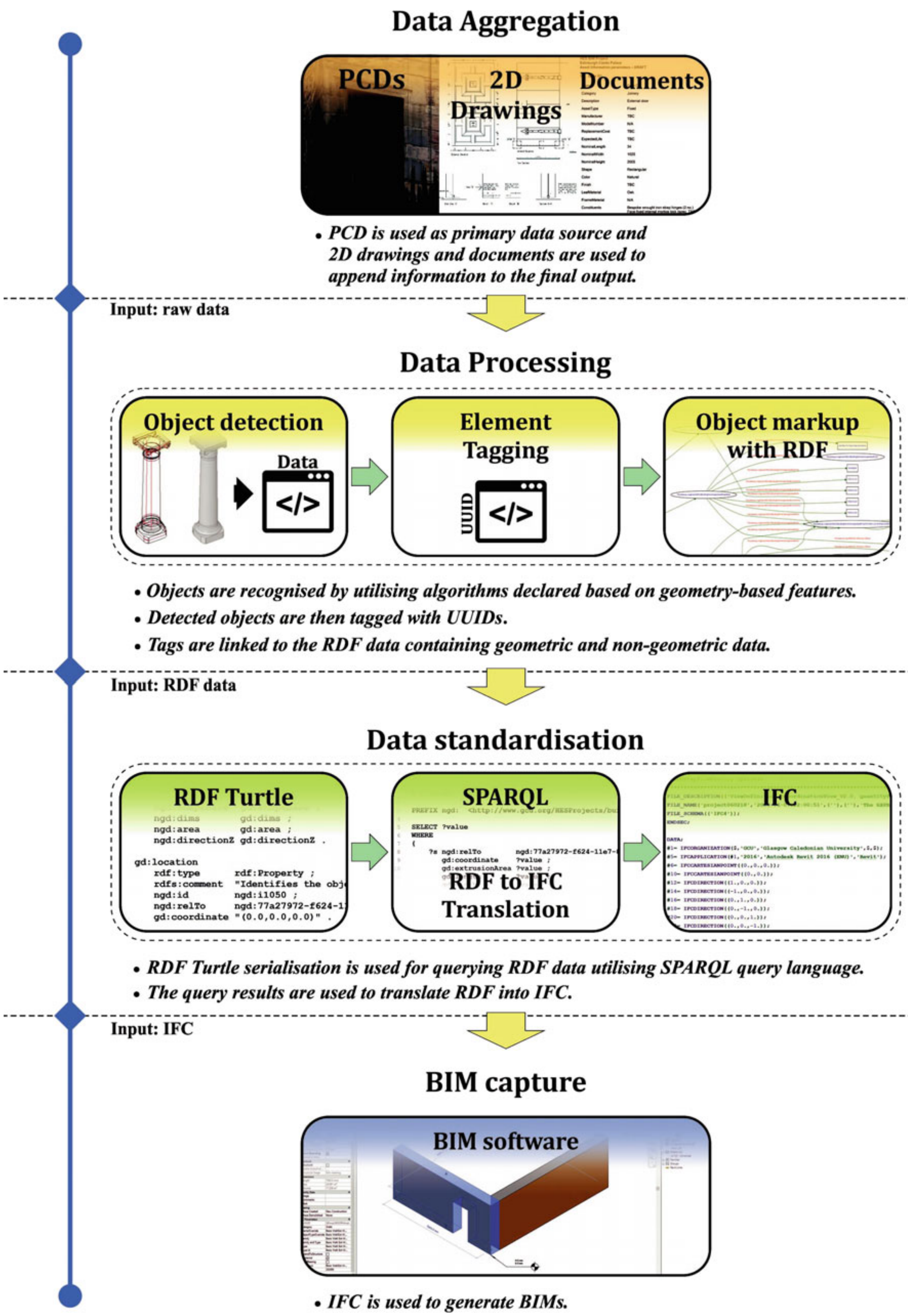

Fig. 14.1 The workflow classification of proposed approach [30]

14.2 Related Work

In the past years, several studies have been conducted to declare automated and semi-automated approaches for generating parametric models by using PCD as the main source of information. Proposed approaches are classified into two directions, including Scan-and-BIMs and Scan-to-BIMs. In the case of the availability of the CAD model (3D model), which represents the as—design condition of an asset, the process of generating BIMs is implemented through Scan-and-BIMs process where datasets are matched and compared together for the discrepancies identification and the BIM capture process. The approach proposed in Gao et al. [3] represents different algorithms for generating BIMs based on the Scan-and-BIMs process. In contrast, an existing building may not have a 3D model, and 2D drawings and documents are the only available information. In this case, the process of generating BIMs is performed through Scan-to-BIMs approach using PCD as the primary data source [8]. In this case, geometric features embedded in PCD, such as lines, boundaries, geometric primitives, and so forth are used to generate building components. The work proposed in Zhang et al. [8] is based on Scan-to-BIMs process and focuses on detecting planar patches (surfaces) of building elements using PCD as the main data source. The relationship between points and lines (shape boundaries) as geometric features are employed for the identification of object surfaces. Similar approaches—e.g. the work presented in Xiong et al. [15], and Adan and Huber [16]—have been proposed to recognize interior and exterior building elements like walls, floors, ceilings, and openings using different types of geometric spatial characteristics, such as connectivity, relative distance, and contextual relationship between points and corresponding elements.

According to the heritage environments, an accurate representation of 3D parametric models affects the performance of restoration, conservation, retrofitting, building analyses, and facility management processes [5, 17, 18]. Historical buildings in contrast to the new build projects contain complex building components, and commercial BIM software does not support such geometric complexity as they are designed to model new build projects, and are limited to irregular shapes occurring in HBIM [5]. The approach proposed in Barazzetti et al. [17] focuses on the reconstruction of an existing building in a historical environment using NURBS (Non-Uniform Rational Base-Spline) characteristics to identify discontinuity lines and corresponding surfaces for reconstructing building elements accordingly. In contrary, other methods are also proposed that concentrate on using predefined libraries of building elements in order to capture parametric models [19]. A semi-automated approach is proposed in Dore and Murphy [5] to capture building components using rule-based algorithms. More information regarding approaches developed based on libraries, and architectural ontologies can be found in Quattrini et al. [9], and Murphy et al. [19].

14.3 Parametric Modelling Using Semantic Web Technologies

14.3.1 Challenges and Limitations

In the past years or so, several studies have been carried out to make the process of generating BIMs (typically known as parametric models) as efficient and effective as possible. However, a single approach may not be applicable for different objects and environments. The level of required information embedded in generated models, which is an important part of BIM process, is one of the challenges involved in capturing BIMs. Information related to a semantic-rich model can be categorized into two general classifications, including geometric data and non-geometric data [6, 20]. Geometric data can be extracted and calculated using PCD, such as Cartesian Points, dimensions, and locations. However, non-geometric data like material, color, finishing specification, security rating, and load-bearing capacity—which cannot be extracted from PCD—needs to be appended to the final model separately to generate a full-blown parametric model. Another challenge that can be addressed is the management and manipulation of large-scale information that is needed to be included in final results. Moreover, building components generated for separate projects may share similar information, particularly in historic environments. In current practice, the information is appended to elements individually due to the lack of information interoperability among detected elements. In addition to that, required asset information is currently stored in different types of databases, such as 3D model and paper-based documents, which makes the data accessibility and management laborious. Edinburgh Castle BIM project illustrated in Fig. 14.2 carried out by Historic Environment Scotland (HES) as a case study in this research could be a good example for mapping BIMs from PCD, and for adding required asset information to the final model manually. One of the challenges involved in HES BIM projects is the management of large-scale information that needs to be added to the model. Currently, the information is stored in varying data formats (e.g. 2D Drawings, 3D CAD

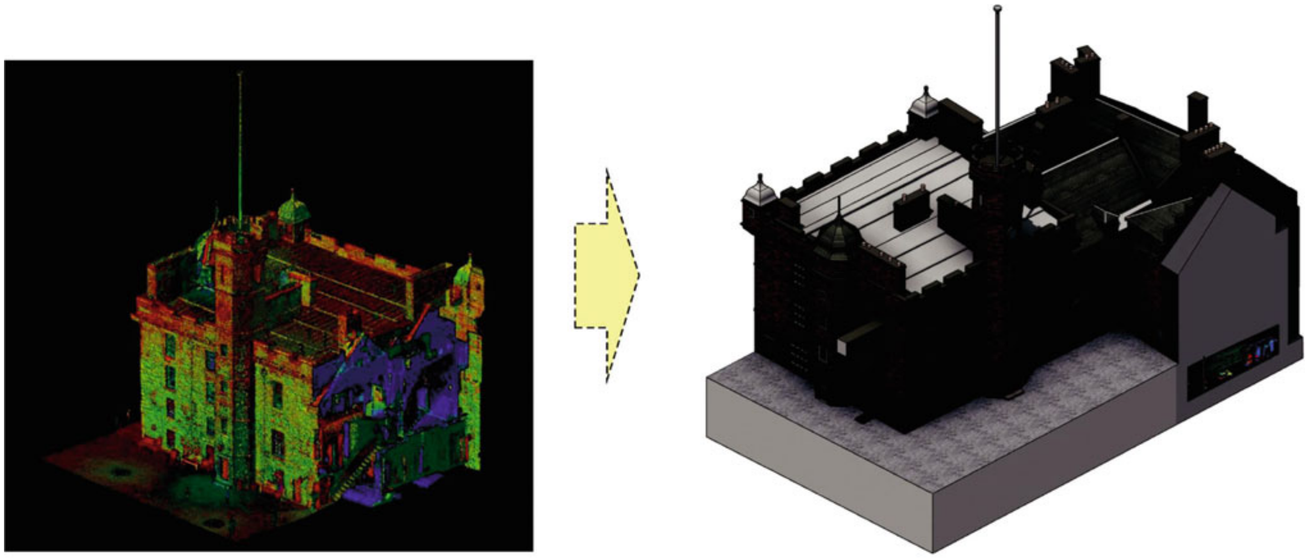

Fig. 14.2 Edinburgh Castle parametric model generated from PCDs [30]

Model, Documents, PDF, Excel etc.) which makes it difficult to access and manipulate the data associated with corresponding building components in the model.

14.3.2 RDF as a Semantic Web Standard and Technology

The use of Semantic Web technologies has lately gained interest and popularity in different domains, including the AEC. In McGibbney and Kumar [21] Semantic Web technologies are used to create a model for the legislation in AEC domain. The project carried out by Quattrini et al. [22] uses Semantic Web technologies for storing and representing information on the web. In this paper, we take advantage of Semantic Web standards and technologies—which provide a suitable framework for storing, sharing, and reusing the information on the web [23]—to attain a proper solution to the challenges and limitations in generating parametric models, particularly handling the large-scale data. RDF, as the most popular and commonly used Semantic Web technology on the web for the description and interchange of the large-scale information [24], is used in this project to append required asset information to the generated parametric models. RDF data in contrast to other databases (DBs) like Hierarchical DBs (e.g. IFC data model) does not have a concept of root or hierarchy. This feature enables RDF to connect resources without hierarchical relationships between them [25]. RDF is structured based on simple statements containing subjects (URI resources), predicates (URI properties), and objects (URI resources or literal resources). Figure 14.3 shows the relationship between nodes (subject, predicate, and object) in an RDF data graph and the TURTLE version for the same graph. The simplicity and flexibility characteristics of RDF data add the advantage to our approach to manipulate and manage the metadata required in parametric models in an unconstrained manner.

14.3.3 Data Aggregation and Processing

As demonstrated in Fig. 14.1, the workflow of our approach consists of four general steps. Data aggregation as the first step involves the collection of required data consisting of PCD as the primary source and corresponding 2D drawings and documents for enhancing the information required to be added to the model. In data processing step, building geometries are recognized utilizing the geometric features embedded in PCD. As mentioned in Sect. 14.2, in the past years or so, several approaches have been proposed for detecting building geometries in PCD with varying degree of success. In our approach, the information (the geometric data) related to detected elements is tagged by unique Identifiers like UUIDs or GUIDs before marking up elements. The markup process consists of two steps. RDF data is first generated for each identified element

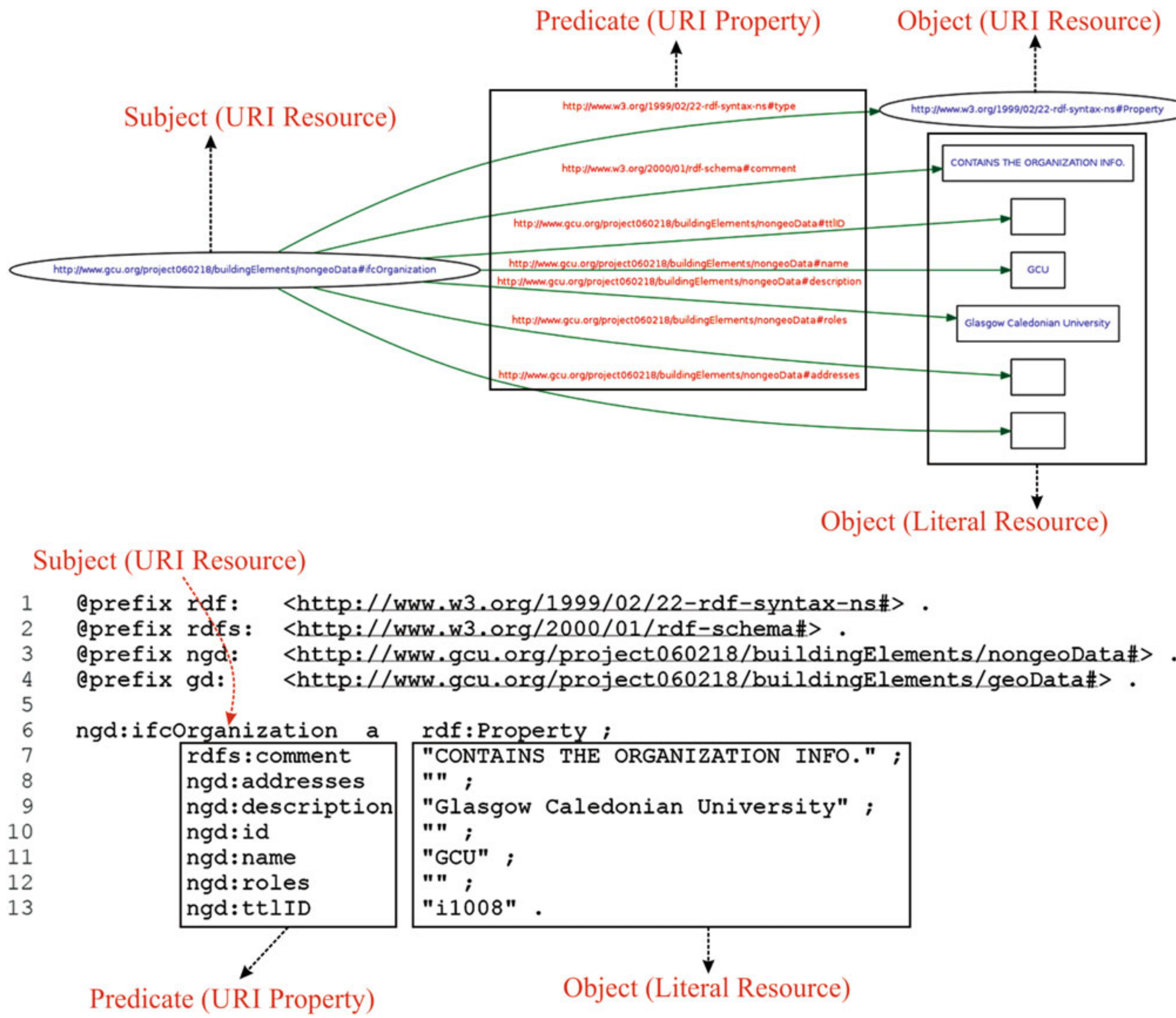

Fig. 14.3 (Top) RDF data graph, (Bottom) RDF Turtle for the same graph

separately as sub-graphs containing both geometric data (gd) and non-geometric data (ngd). Sub-graphs are then linked to the corresponding unique Identifier which links RDF to detected elements. The advantage of creating separate RDF is that the information stored in one sub-graph can be shared among different projects that contain the same information and the final corresponding RDF graph can be generated by merging the sub-graphs (Fig. 14.4). Figure 14.5 shows an RDF Turtle model generated for a wall consisting of asset information required by HES to be included in the final model and stored as linked data.

14.3.4 Data Standardization and BIM Capture

The core and challenging part of this project is the data standardization process where RDF data as a serialization needs to be translated into IFC as a data model. The translation process consists of two steps, including the extraction of required information from the generated RDF data and the generation of IFC using the extracted data. IFC is a standard and commonly used data model for the data exchange within the build projects in the construction industry. RDF model consists

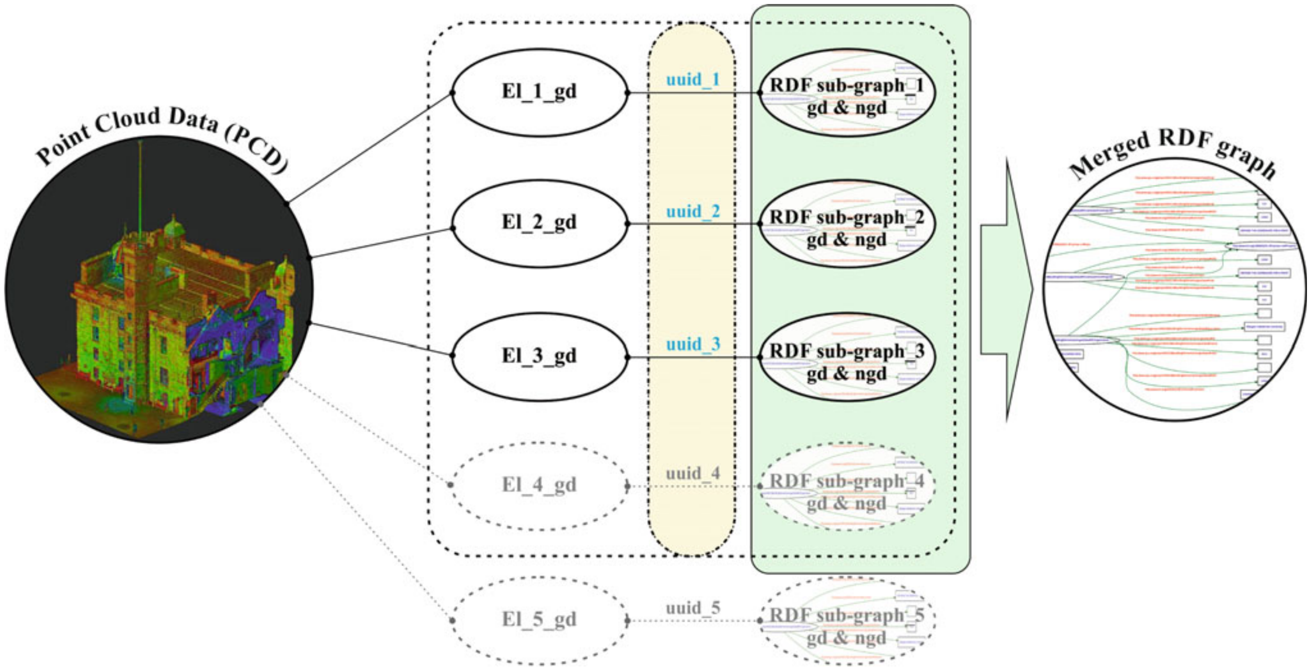

Fig. 14.4 Element mark-up process using RDF

of different types of serializations, such as RDF/XML, N3, N-Triple, and Turtle. The Turtle version of RDF as linked data is used in our approach to structure constant models based on the IFC requirements for generating parametric models. The reason for using RDF as linked data is that IFC data model has some limitations and it cannot represent some of the required asset information due to the constant structure of IFC [1, 2, 28]. In addition to that, the data for an object is represented in different locations in the IFC file, and this makes it difficult to reuse the data for other similar elements in different projects owing to the hierarchical structure of IFC data model [1, 29]. However, the use of RDF as linked data provides the opportunity to store the information and reuse it for similar objects in different projects [31]. RDF data is then generated for building elements based on a constant structure which is useful for future use in other projects if required. The other reason for using turtle format is that SPARQL query language has borrowed its structure from turtle which makes it more compatible with RDF turtle [23].

The SPARQL query language is then employed to retrieve and manipulate data that is stored in the form of RDF data. SPARQL can be used for querying either a simple RDF model (a sub-graph) or a merged model structured from several sub-graphs. An SPARQL query example is shown in Fig. 14.6 querying the sub-graph providing information regarding the organization (e.g., name, description, Identifier, etc.). The RDF model is then translated into IFC STEP by applying the information extracted from the model (query results) using SPARQL. IFC STEP entities are then generated based on the IFC requirements and the pulled data. For example, as shown in Fig. 14.5, the information related to the area of walls ShapeBase, which represented as ngd:wall 1 (subject) and gd:area (predicate) in turtle graph), is used as a planar surface to create the IfcExtrusionAreaSolid for IfcWall entity in IFC format. In the same RDF data, the ngd:pcdReference property with a UUID value is used to link the RDF Turtle to the geometric data extracted from PCD. The UUIDs are also used to represent the connection between different elements (e.g. two walls, wall opening etc.). Figure 14.7 illustrates an example of using extracted data from RDF utilizing SPARQL query for generating corresponding IFC elements. The parametric model is then generated by importing the IFC into any BIM software that supports IFC formats.

```
# filename: wall_1.ttl

@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix gd: <http://www.gcu.com/projectNum/buildingElements/geoData#> .
@prefix ngd: <http://www.gcu.com/projectNum/buildingElements/nongeoData#> .

ngd:wall_1
    rdfs:comment    "Identifies the geo and non-geo data of a wall." ;
    ngd:pcdReference    ngd:77a27972-f624-11e7-8c3f-9a214cf093ae ;
    ngd:name    "Name" ;
    ngd:idNumber    ngd:HES-ID-Number ;
    ngd:category    "Wall" ;
    ngd:function    "Ext" ;
    ngd:objectType    "Function-Category-WallThickness:TagNumber(77a27972)" ;
    ngd:constituents    "HES-Constituents" ;
    ngd:classification    "HES-Classification" ;
    ngd:drawingReference    "The reference to the drawing related to the wall_1" ;
    ngd:material    "Material" ;
    gd:location    "The centre point of object base extracted from PCD";
    gd:length    "The length of the wall extracted from PCD" ;
    gd:width    "The width of the wall extracted from PCD" ;
    gd:height    "The height of the wall extracted from PCD" ;
    gd:area    "The area of the wall base extracted from PCD" ;
    gd:volume    "The volume of the wall calculated from data extracted from PCD" ;
    gd:weight    "Weight of the object calculated from the volume and material" ;
    ngd:colour    "The colour of the object (RGB)" ;
    ngd:contactPerson    "The responsible person contact detail" ;
    gd:fireRating    "FireRating value based on the object material" ;
    gd:acousticRating    "AcousticRating value based on the object material" ;
    gd:loadBearingCapacity    "Load Bearing Capacity value" .
```

Fig. 14.5 RDF Turtle data generated for walls based on the HES required asset information

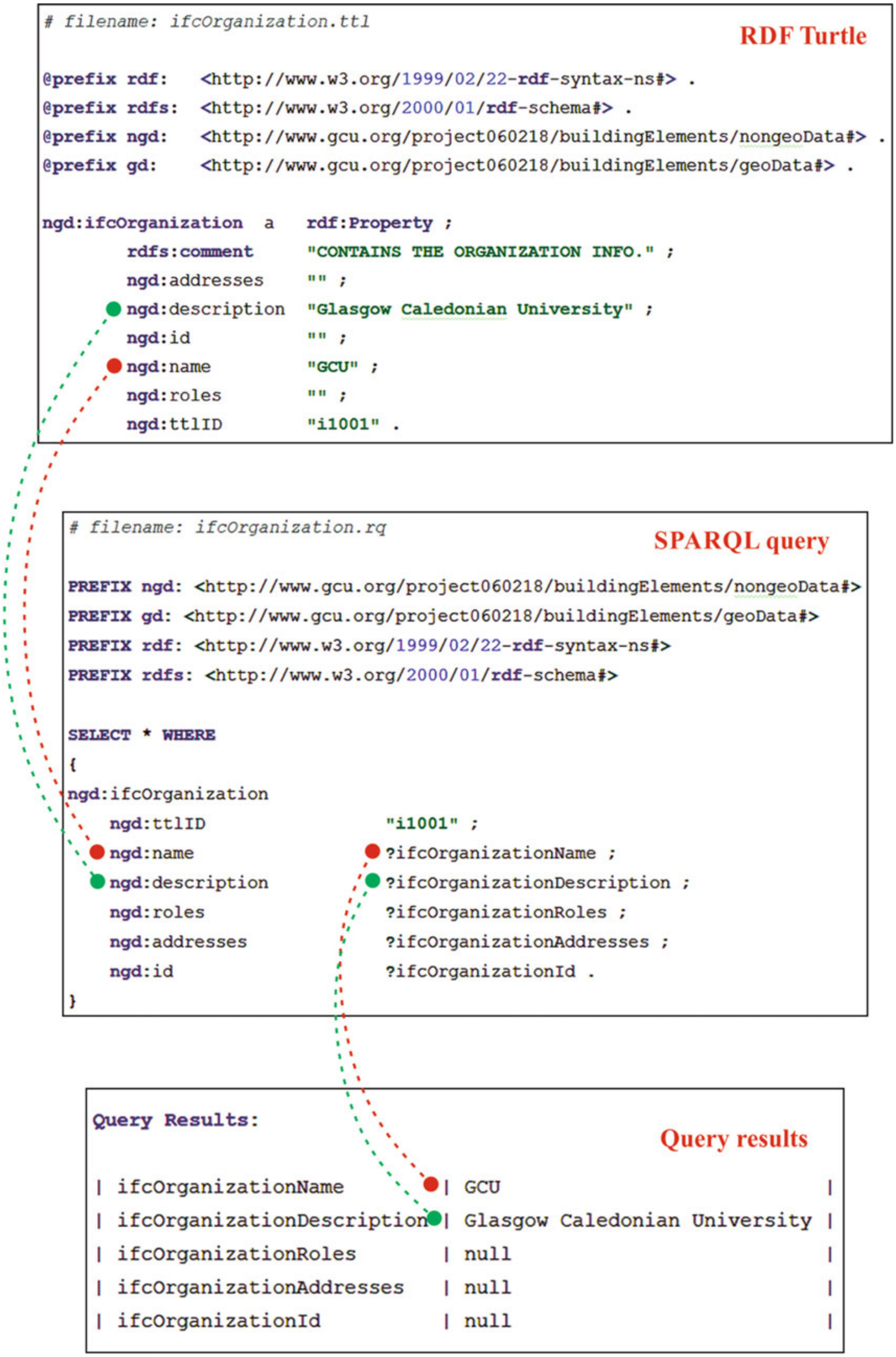

Fig. 14.6 Element markup process using RDF

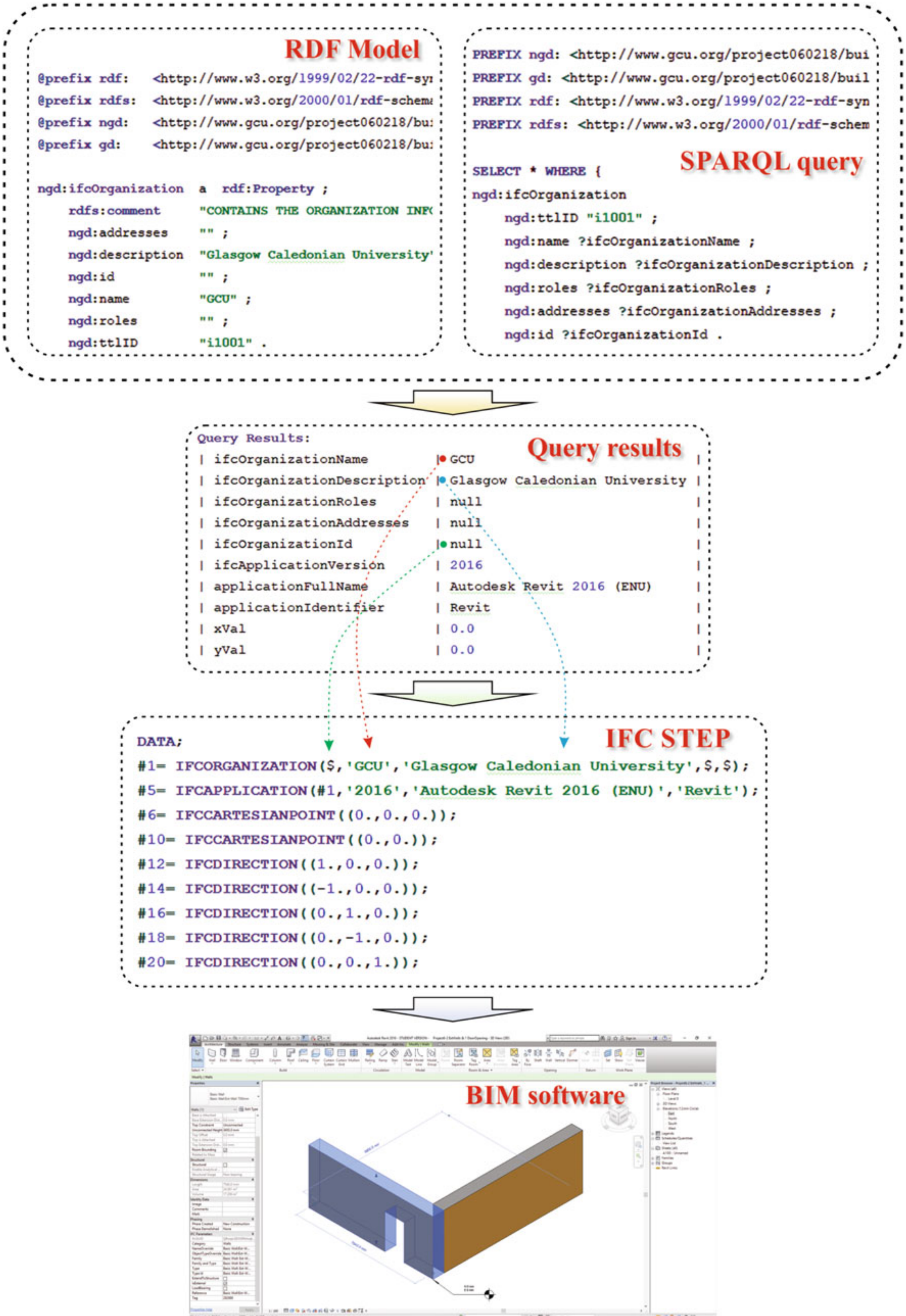

Fig. 14.7 RDF-to-IFC translation (Data standardization) and BIM capture

14.4 Conclusions

In this paper, challenges and limitations involved in generating parametric models for retro t assets, particularly historical environments, are addressed to perform a suitable framework for capturing BIMs and managing the large-scale information that needs to be appended to the model for further use during the buildings life-cycle. Several studies have been recently carried out using PCD as the main data source by declaring varying types of algorithm to identify building elements in PCD. Although some progress has been lately made to capture BIMs, a full-blown parametric model is still some way away. The fact is that a semantic-rich parametric model contains two types of information, geometric data and non-geometric data. In current practice, the identified elements, which are considered as parametric models, encompass only geometric data extracted from PCD and are represented as geometric primitives. Accordingly, non-geometric data which is required for the future use in a facility's lifespan (Facility Management), such as material, color, finish, fire rating, acoustic rating, accessibility performance, security rating, load-bearing capacity, etc., need to be added to the detected element during the BIM capture process.

According to the HES BIM projects as a case study in this project, one of the challenges is that some of the required asset information are individually added to each building component during the manual generation of the model using PCD, which is error-prone, time-consuming and laborious. The remaining information that cannot be added to the model, owing to the commercial BIM software limitations, are represented and stored in different file formats, such as documents, Excel spreadsheets, PDFs, and images. Hence, we use the concept of RDF as a Semantic Web Technology to store, share, and reuse information related to generated building objects, as a linked data, throughout the process of generating semantic parametric models. The proposed approach in this paper is currently implemented semi-automatically. The generation of RDF data for building elements is implemented manually due to the limitation of existing standard format for the data extracted from PCD. However, the process of RDF-to-IFC translation is carried out automatically by declaring constant RDF data and SPARQL queries for each category (e.g. walls, doors, windows, etc.) based on the HES BIM project requirements. The future work of this project is to implement the entire process automatically by generating RDF data based on the information captured from PCD and to structure effective, efficient, and flexible RDF data that can be utilized for all building elements and varying environments.

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References

1. Volk, R., Stengel J., Schultmann, F.: Building information modeling (BIM) for existing buildings—literature review and future needs. Autom. Constr. **38**, 109–127 (2014)
2. Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., Venugopal, M.: Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules. Autom. Constr. **29**, 183–195 (2013)
3. Gao, T., Akinci, B., Ergan, S., Garrett, J.: An approach to combine progressively captured point clouds for BIM update. Adv. Eng. Inform. **29** (4), 1001–1012 (2015)
4. Hayne, G., Kumar, B., Hare, B.: The development of a framework for a design for safety BIM tool. In: Computing in Civil and Building Engineering, pp. 49–56, Orlando (2014)
5. Dore, C., Murphy, M.: Historic building information modelling (HBIM). In: Handbook of Research on Emerging Digital Tools for Architectural Surveying, Modeling, and Representation vol. 1, pp. 239–280 (2015)
6. Barazzetti, L.: Parametric as-built model generation of complex shapes from point clouds. Adv. Eng. Inform. **30**(3), 298–311 (2016)
7. Gao, T., Ergan, S., Akinci, B., Garrett, J.: Evaluation of different features for matching point clouds to building information models. J. Comput. Civil Eng. **30**(1), 1–13 (2014)
8. Zhang, G., Vela, P., A., Karasev, P., Brilakis, I.: A sparsity-inducing optimization-based algorithm for planar patches extraction from noisy point-cloud data. Comput. Aided Civil Infrastruct. Eng. **30**(2), 85–102 (2015)
9. Quattrini, R., Malinverni, E., Clini, P., Nespeca, R., Orlietti, E.: From TLS to HBIM. High quality semantically-aware 3D modeling of complex architecture. In: The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 40, No. 5, pp. 367–374 (2015)
10. Wang, C., Cho, Y.K., Kim, C.: Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. Autom. Constr. **56**, 1–13 (2015)
11. Colomina, I., Molina, P.: Unmanned aerial systems for photogrammetry and remote sensing: a review. ISPRS J. Photogram. Remote Sens. **92**, 79–97 (2014)
12. Herraez, J., Martinez, J.C., Coll, E., Martin, M.T., Rodriguez, J.: 3D modeling by means of videogrammetry and laser scanners for reverse engineering. Measurement **87**, 216–227 (2016)

13. Bosche, F., Forster, A., Valero, E.: 3D Surveying Technologies and Applications: Point Clouds and Beyond. Heriot-Watt University, Edinburgh (2015)
14. Son, H., Kim, C.: Automatic segmentation and 3D modeling of pipelines into constituent parts from laser-scan data of the built environment. Autom. Constr. **68**, 203–211 (2016)
15. Xiong, X., Adan, A., Akinci, B., Huber, D.: Automatic creation of semantically rich 3D building models from laser scanner data. Autom. Constr. **31**, 325–337 (2013)
16. Adan, A., Huber, D.: 3D reconstruction of interior wall surfaces under occlusion and clutter. In 3D Imaging, Modeling. In: 2011 International Conference on Processing, Visualization and Transmission (3DIMPVT), 275–281, IEEE (2011)
17. Barazzetti, L., Ban, F., Brumana, R., Roncoroni, F., Previtali, M.: BIM from laser scans not just for buildings: NURBS-based parametric modeling of a medieval bridge. In: ISPRS Conference, pp. 51–56 (2016)
18. Oreni, D., Brumana, R., Della Torre, S., Ban, F., Previtali, M.: Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila). ISPRS Ann. Photogram. Remote Sens. Spat. Inf. Sci. **2**(5), 267–273 (2014)
19. Murphy, M., McGovern, E., Pavia, S.: Historic building information modelling adding intelligence to laser and image based surveys of European classical architecture. ISPRS J. Photogram. Remote Sens. **76**, 89–102 (2013)
20. Barazzetti, L., Ban, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F., Schiantarelli, G.: BIM from laser clouds and nite element analysis: combining structural analysis and geometric complexity. Int. Arch. Photogram. Remote Sens. Spat. Inf. Sci **40**(5), 345–350 (2015)
21. McGibbney, L.J., Kumar, B.: A framework for regulatory ontology construction within AEC domain. In: Ontology in the AEC Industry, pp. 193–215 (2015)
22. Quattrini, R., Pierdicca, R., Morbidoni, C.: Knowledge-based data enrichment for HBIM: exploring high-quality models using the semantic-web. J. Cult. Heritage **28**, 129–139 (2017)
23. Yu, L.: A Developers Guide to the Semantic Web. Springer Science & Business Media (2011)
24. Domingue, J., Fensel, D., Hendler, J.A. eds.: Handbook of semantic web technologies. Springer Science & Business Media, (2011)
25. Powers, S.: Practical RDF: Solving Problems With the Resource Description Framework. O'Reilly Media, Inc. (2003)
26. Logothetis, S., Delinasiou, A., Stylianidis, E.: Building information modelling for cultural heritage: a review. ISPRS Ann. Photogram. Remote Sens. Spat. Inf. Sci. **2**(5), 177–183 (2015)
27. Oreni, D., Brumana, R., Georgopoulos, A., Cuca, B.: HBIM for conservation and management of built heritage: towards a library of vaults and wooden beam floors. ISPRS Ann. Photogram. Remote Sens. Spat. Inf. Sci. **5**, 215–221 (2013)
28. Borrmann, A., Rank, E.: Specification and implementation of directional operators in a 3D spatial query language for building information models. Adv. Eng. Inform. **23**(1), 32–34 (2009)
29. Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., Van Campenhout, J.: A semantic rule checking environment for building performance checking. Autom. Constr. **20**(5), 506–518 (2011)
30. Sadeghineko, F., Kumar, B., Chan, W.: A semantic web-based approach for generating parametric models using RDF. In: Workshop of the European Group for Intelligent Computing in Engineering, pp. 361–377, Springer, Cham (2018)
31. Beetz, J., Borrmann, A.: Benefits and limitations of linked data approaches for road modeling and data exchange. In: Workshop of the European Group for Intelligent Computing in Engineering, pp. 245–261, Springer, Cham (2018)
32. Logothetis, S., Karachaliou, E., Stylianidis, E.: From OSS CAD to BIM for cultural heritage digital representation. In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 3D Virtual Reconstruction and Visualization of Complex Architectures vol. XLII-2(W3), pp. 439–445 (2017)
33. Lopez, F., Lerones, P., M., Llamas, J., Gomez-Garcia-Bermejo, J., Zalama, E.: A review of heritage building information modeling (H-BIM). Multimodal Technol. Interact. **2**(2), 1–29 (2018)

BIM Coordination Oriented to Facility Management

15

Mónica Viviana Sierra-Aparicio, José Luis Ponz-Tienda, and Juan Pablo Romero-Cortés

Abstract

BIM coordination is an iterative process that requires an accurate roadmap to adequately manage the exchange of information, overcome communication barriers, improve the decision-making environment and guarantee a successful and collaborative work throughout the project's lifecycle. Although the actual coordination practice satisfies the requirement of routing the whole systems in a proper way, it presents a lack of sequential, constructability, operation and maintenance issues. In order to contribute to the BIM coordination process knowledge, this paper introduces a coordination methodology that is based on the sequential approach and includes O&M (Operation and Maintenance) criteria. Regarding the previous idea, the project information should be organized in a coordination matrix that adds accessibility, functionality and installation requirements to each discipline. This proposal guarantees that the maintenance criteria and physical constraints are consistently meet, preserving a continuous flow and identifying wastes, delays, rework and cost overruns from the first stages of the buildings lifecycle. The suggested methodology aims to generate a more efficient coordination process which ensures that all efforts are headed in the right direction. As a result, the coordinated model will become the As-Built one.

Keywords

Building information modeling (BIM) • Coordination • Facility management

15.1 Introduction

Building Information Modeling (BIM) is the integration of technology, people and procedures with the intention of reaching a building's desired performance in terms of schedule, costs, systems disposal, sustainability, among others. The vehicle that allows this assimilation is a BIM model, defined by Azhar et al. [1] as "a 3D representation that carries all the information related to the building, including its physical and functional characteristics and project life-cycle information in a series of small objects".

A key aspect that BIM consolidation changed notably is coordination, defined as the disposal of all of the systems into the building's envelope, in a way that avoids common interferences which may result in rework and over costs. Coordination used to be a conflictive, strenuous, large and difficult chore, due among other aspects, to the lack of willingness of design consultants to reroute their systems and also to an inaccurate management of information. Although many procedures have changed with the inclusion of BIM, some authors argue that there is a general avoidance of maintenance requirements in the coordination efforts [2–4].

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To partially solve this problem, this article seeks for a strategical coordination methodology that besides integrating all systems on a harmonious way (by satisfying critical design criteria and constructability issues), also addresses maintenance concerns [2]. This means that all systems are located in a way that allows accessibility for subsequent operation and maintenance labors on the facility and improves the space management performance.

This article will chase the following sequence: first, a general overview of the state of the art of systems coordination is exposed in Sect. 15.2. In Sect. 15.3 we describe a proposal for integrating accessibility criteria faced to facility management during the coordination process. Finally, conclusions, limitations and further research are drawn.

15.2 The State of the Art of BIM Project Coordination and Facility Management

Systems coordination is mandatory between the design and construction phases of the project's life cycle. The main purpose of the coordination process is foresee on site the constructive interferences in order to reduce rework costs during the construction phase by using preliminary designs of all the systems [4]. According to a study conducted by Love et al. [5], these costs represent almost the 10% of the total construction cost. To achieve an outright coordination is fundamental an integrated design process. This means that all members of the project's team should be included from the preliminary and, while the project proceeds, they are able to make decisions that concern the effective delivery of the project delivery, in a collaborative way.

Before the adoption of the BIM collaborative procedures, the design coordination was driven by the physical overlapping of drawings (or layers), also called 2D coordination, requiring many coordination meetings to route the systems and determine which trade was making the change [4]. This was an iterative non-ending process, because all systems must satisfy several kind of constraints, and all the parties are unwilling to change their designs.

Another obstacle that design consultants, constructors, and facility managers face during the coordination process is managing the flow of information. The uninterrupted modification of the designs during coordination meetings may provoke out of date versions. Other possible obstacles include design complexity, avoidance of constructability and functionality matters, difficulties related to interference detection in depth (for example ducts), among others [4]. This occurs especially in MEP (Mechanical, Electrical and Plumbing systems) coordination.

Korman and Tatum [4] identified the importance of a methodology for the MEP coordination to avoid some of the issues stated below. In order to solve these problems, the authors improved the SCOP (Sequential Comparison Overlay Process) that is the current identification of physical interferences, by highlighting the integration of design criteria, construction experience and operation and maintenance knowledge. They also assemble some of the typical interferences between the architecture of a building and its systems, proposing a way to avoid them during the coordination process. Later, the information provided by this process, would contribute to the MEP coordination scheme using BIM.

The development of the BIM methodology supposed a significant evolution in the manner that project coordination was developed. By using BIM, all participants are able to access an updated 3D representation of the building including its systems, on a collaborative environment. In accordance with the paragraph above, Korman et al. [2] identified a huge potential of this tool and came up with an improved version of the SCOP process, calling it SCOPE (Sequential Comparison Overlay Process Evaluation Method). This improvement establishes that MEP coordination must follow a hierarchical order to shorten the rework and coordination meetings. The routing of systems should begin from the biggest and stiffest one (HVAC dry system) to the smallest and more flexible one (Control and telephone) [2].

Khanzode et al. [6] exposed a case study applying BIM coordination tools, reaching similar conclusions to the SCOPE approach. Starting with the building's envelope (architecture and structure) to its core (MEP disciplines), each system was disposed considering the physical constraints defined by the envelope and the already coordinated ones [7]. They also found out that BIM coordination follows a sequential process, instead of a Parallel one, as was commonly assumed by the literature.

Lee and Kim [7] applied both sequential and parallel coordination techniques to a pharmaceutical building with the purpose of making a comparison between productivity and flow of information. They concluded that the sequential coordination is three times faster than the parallel one because it allows the adjustment making, based on already coordinated models, so irrelevant information is ignored. On the other hand, parallel coordination tends to be a chain of circular changes, because everyone is working at the same time without enough information related to other disciplines.

In relation to FM (Facility Management), the ISO 41011:2017 [8], establish that is "an organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business". On the BIM environment, FM is considered the seventh dimension and its main target is the collection of the buildings life-cycle information for operational and maintenance mediation. Some authors believe that the mixture of relevant data, design and construction criteria may help to reduce operational costs. Kassem et al. [9], by referencing the BIM Task Group, assures that these amounts are near three times the building construction cost during the O&M phase.

Some uses of BIM in FM applications are maintenance work, space planning and management, inventory management and inspections, move and real estate portfolio management [1]. The increasing development of BIM in FM applications has encourage some Governments to conceive regulations related to building's data acquisition for Operation and Maintenance purposes, such as the United Kingdom law PAS 1192-3 [10]. However, BIM relation to FM is still a trending research topic, and there are several reports related to BIM software interoperability with FM platforms [11], information requirements for corrective maintenance or even BIM and 3D point cloud integration to track MEP components maintenance [12].

In this line, the international standard COBie (Construction Operations Building Information Exchange), arose with the idea of gathering the created data in design and construction phases of a facility, to support the operation and maintenance phases [11]. COBie is a list of assets and spaces that uses a codification system (OmniClass) to register information as the project moves forward. This tool results imperative for collecting operational documents that may bring some benefits such as reducing the detection time of abnormal conditions or even avoiding destructive testing [11].

With the aim to contribute to the body of knowledge of FM with BIM, this study exposes a proposal of a coordination methodology based on the sequential procedure, which includes FM requirements to warrant adequate spaces for all of the components of a certain room. This proposal assures the accessibility for further maintenance works. Having this in mind, the iterative process will have a double function: routing each system by satisfying physical, design and other constraints and generating an accurate model for the whole asset lifecycle [13].

15.3 The Relationships in the Buildings Lifecycle

The general BIM coordination process starts with the collection of 3D models that reflect pre-designs of all of the systems that conform a facility (all of them share an unmovable origin point in order to assure both vertical and horizontal alignment). Later on, all the files are exported to an IFC (Industry Foundation Classes) format that allows their introduction to any coordination platform. Once the files are added, the intra-discipline tests are created, with the aim of making the interference checkups, 3D model corrections and generate rules that exclude admissible interferences by following a defined coordination procedure.

Our proposal of a coordination methodology took shape with an already existing resource: a coordination matrix based on the Singapore BIM guide [14]. This five by five matrix, incorporates the main disciplines that conform a facility in the following order: Architecture (Arch), Structure (Str), Mechanical (M), Plumbing (P) and Electrical (E). This disposition is based on Lee et al.'s proposal [7], ordered by the following hierarchical criteria: coordinating from outside to inside, from large to small and from hard to soft. The main diagonal of the matrix represents the restraint of all the duplicate tests or the ones that verify interferences between each system and itself. In other words, it diagnosis clashes due to double objects, which the native software did not catch previously, or even clashes between categories associated to the same discipline (e.g. nonstructural walls and ceilings).

The tests that are over the main diagonal are a transposed version of the ones that are located under it. Giving priority to the rows, coordination starts with the building's covering, continuing with its skeleton and finishing with its inner systems. Along each iteration, one discipline is coordinated each time. In the following iterations, the other trades are modeled around it, and so on [15]. The goal is that the coordination process moves along each row and under the main diagonal, following the introduced ranking. Other aspect to take into account, especially with MEP components, is the space allocation, which is adhered to certain predefined zones for routing each system [14]. In summary, the Singapore's BIM Essential Guide for Collaborative Virtual Design and Construction coordination methodology is based in prioritizing intra and inter discipline checks.

15.4 The Inclusion of FM During the Project's Life Cycle

Several authors consider that the traditional approach of project conception and delivery, is focused merely on design and construction phases, avoiding operation and maintenance issues on important stages of a project [2–4]. As claimed by Korman and Tatum [4], due to a lack of communication between designers, constructors and operation personnel, is difficult to integrate O&M (Operation and Maintenance) knowledge on the coordination process [3], bringing difficulties such as rework, out of date information and a hindered decision making mechanism.

On the other hand, the Integrated Project Delivery (IPD) approach considers the enrollment of all the parties that are related to the project's life cycle (including the Facility Manager), since the early stages of the activity. Thus, each part is offering its experience and knowledge to warrant a single cause: adding value to the project and satisfying the client's requirements. Korman and Tatum [4] identified that each part provides different criteria: design consultants know to perform coordination and are the ones that must follow the routing rules; constructors are the ones that evaluate constructability issues and operation/maintenance managers are in charge of foreseeing how the building is going to be used.

With respect to the previously exposed ideas, the coordination matrix for an integrated focus is complete since the early stages of the project's lifecycle. Therefore, it should be an establishment of the information needed to ensure an organized operation process (minimum distances required for O&M) from the predesign phase. Moreover, in the traditional approach, the coordination matrix does not exceed two dimensions, because the architecture gives its general guidelines to all the parties and hardly integrates all of the incoming info. This lack of information management is one of the reasons why decisions are taken without conceiving the forthcoming facility's use.

The Singapore's BIM Essential Guide for Collaborative Virtual Design and Construction suggests a quality coordination review to develop beforehand the delivery of the coordinated model. This covers General, Code compliance, Constructability and Maintainability checking. In this case, Maintainability checking allows a coordination oriented thought that leads with potential accessibility difficulties and other functional types of interferences for operation and maintenance purposes. This quality review is the previous step before turning the design coordinated model into the construction one.

15.5 The FM Coordination Matrix

The FM coordination matrix, combines the pre-established guidelines in a coordination methodology that includes facility management criteria on each discipline along the iteration process. This tool improves the traditional coordination process (which already covers codes and design standards) by adding O&M knowledge, with the purpose of reaching an As-Built coordinated model.

In line with the previous approach, the suggested matrix is divided into two main regions: the first one makes reference to the traditional BIM coordination matrix (focuses mainly on the disciplines) and the second refers to the incorporation of FM. Region one is composed by zones one to three, which include duplicates control and intra and inter-discipline interferences. On the other hand, the second region covers zones four to six, which incorporate accessibility and functionality additional reviews per discipline—zones four and five—and the priorities definition among FM criteria—zone six (see Fig. 15.1).

The proposed FM coordination matrix in addition of incorporating maintenance related reviews has also other uses, related to interferences concentration (color scale) and responsible identification (see Fig. 15.2).

The "Color Scale Use" allows the identification of trends related to the combinations of systems or cells that require greater effort in terms of iterations and routing criteria, in order to guarantee the operational efficiency of the facility. This identification can contribute to a later establishment of guidelines to resolve clashes in form of an interference control sheet. Moreover, the "Responsible Use" enables an identification of the disciplines who are in charge of redirecting or accommodating, so that the system that carries the priority can satisfy the proposed design, space restrictions, connectivity and other constraints.

The following Table 15.1 describes the relationship between the previously defined zones, the identified uses and FM incorporations. This ordering of information will certainly ease the decision making environment during the coordination process, allowing an immediate recognition of those responsible and detecting the systems that require a deeper analysis. It should be noted that the information that feeds the matrix with each iteration, must be exported from the native software with the intention of speeding up the coordination process.

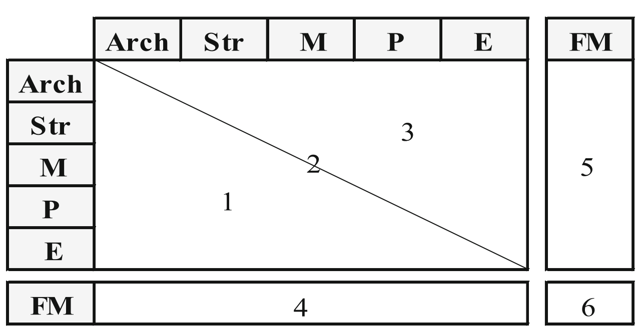

Fig. 15.1 FM coordination matrix proposal

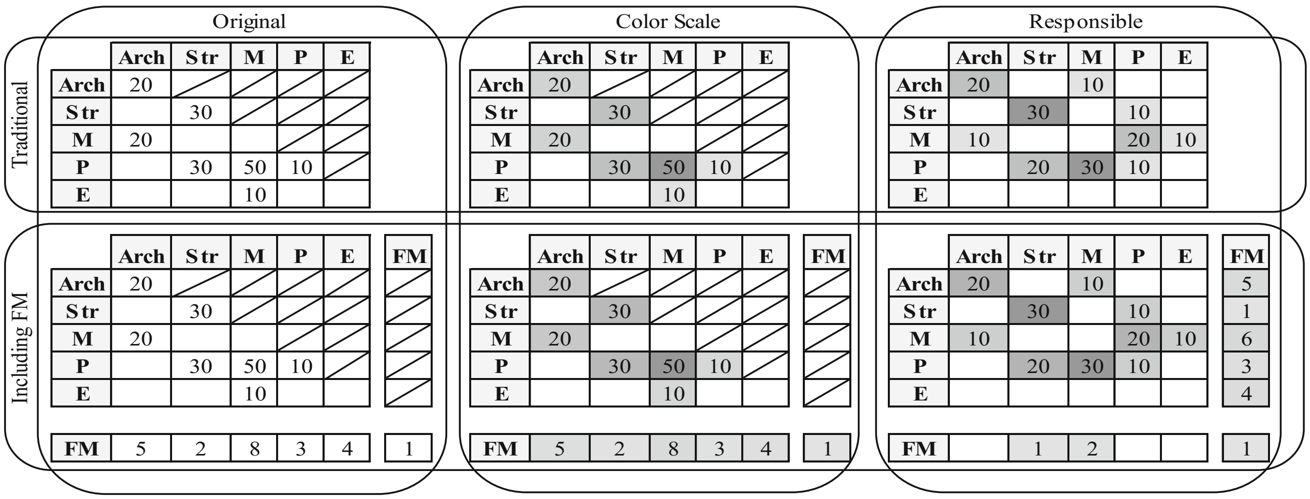

Fig. 15.2 Traditional and FM coordination matrix contrast

Table 15.1 The matrix relationship with the proposed uses

	Zone	Original	Color scale	Responsible
1	Inter-discipline interferences	Number of interferences among disciplines	Conflict zone (darkest cell)	Number of interferences solved by the trade of the rows
2	Intra-discipline interferences	Duplicate check	Critical intra-discipline system (darkest cell)	Auto corrections
3	Transposed version of 1	N/A	N/A	Number of interferences solved by the trade of the columns
4	FM criteria	FM requirements	Critical FM requirements (darkest cell)	Criteria conceded by the facility manager
5	Transposed versión of 5	N/A	N/A	FM criteria that has been solved by the trade of the rows
6	Intra-FM interferences	FM requirements	Critical FM requirements (darkest cell)	Remaining FM criteria

15.6 Results

The proposal of an FM coordination matrix is the result of the experience that has been gathered from the categorization, revision and control of the different emerging interferences, during the coordination process of some real estate projects. This iteration tracking made it possible to test the sequential coordination approach and identify its advantages in comparison with the parallel coordination methodology. One of those benefits was the gained productivity that results from the sequential approach.

After a thorough review of the literature, it was identified that the operational phase was lagging during the coordination process and this would be surely translated into over costs at the operational phase. The introduction of FM from coordination into the construction oriented model, in addition to ensuring the accessibility of the maintenance and operation personnel, allows an additional use that the Pennsylvania's BIM Project Execution Guide defines as space management and tracking [16].

15.7 Conclusions and Further Research

The research has contributed to understand the importance of including facility management in the coordination procedure. FM is introduced not as another discipline of the coordination matrix, but as a complement of each system coordination requirements. Those are related to accessibility, functionality, installation and other issues that are part of the operation and maintenance benchmark.

In this proposal, FM is not related with the code requirements or design parameters of each system because they are previously defined from the design phase. On the other hand, it reinforces the relationship between all disciplines and their systems in terms of clearance space, insulation and other attributes that mitigate operational concerns.

According to Kelly [13] "buildings are currently driven by short-term construction savings rather than operational savings". By applying an Integrated Project Delivery approach and the FM coordination matrix, both Facility Manager's experience and knowledge are included from the early stages of the buildings life cycle. This may certainly reinforce the decision making process, reducing reworks that materialize in cost overruns.

By integrating FM in the coordination procedure, there is an assurance that all the stakeholder's efforts are aligned into a unique direction: the buildings integrity during its lifecycle. Similarly, the implementation of the FM coordination matrix assures that the coordination exercise follows two main objectives: routing all the systems by satisfying design, operational and other constraints and also obtaining a model to count with before construction.

At the moment, there is a lack of knowledge related to the IFC export in terms of central and 3D separated files. This limitation is related to the management of certain properties from the native software, which may be required in the coordination procedure.

To turn into reality the introduced coordination methodology, further work regarding coordination by using a rule generator software (Solibri, Navisworks, among others) needs to be done. With the inclusion of COBie and some of the interferences and attributes identified by Korman and Tatum [3], we hope to produce an automated rule generator for clash detection. This tool will reflect the FM requirements that are part of the 4th zone of the matrix, by sending warnings when there are physical or operational interferences, till the elements involved satisfy the required restrictions.

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References

1. Azhar, S., Khalfan, M., Maqsood, T.: Building information modelling (BIM): now and beyond. Constr. Econ. Build. **12**(4), 15–28 (2015)
2. Korman, T.M., Simonian, L., Speidel, E.: Using building information modeling to improve the mechanical, electrical, and plumbing coordination process for buildings (2008)
3. Korman, T.M., Tatum, C.B.: Development of a knowledge-based system to improve mechanical, electrical, and plumbing coordination. CIFE Technical Report #129, pp. 1–162 (2001)
4. Korman, T.M., Tatum, C.B.: Using construction, operations, and maintenance knowledge to better coordinate mechanical, electrical, and plumbing systems in buildings. In: Architectural Engineering National Conference on Building Integration Solutions, pp. 1–9 (2006)
5. Love, P.E.D., Edwards, D.J., Smith, J., Walker, D.H.T.: Divergence or congruence? A path model of rework for building and civil engineering projects. J. Perform. Constr. Facil. **23**(6), 480–488 (2009)
6. Khanzode, A., Fischer, M., Reed, D.: Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project. Electron. J. Inf. Technol. Constr. **13**, 324–342 (2008)
7. Lee, G., Kim, J.W.: Parallel vs. sequential cascading MEP coordination strategies: a pharmaceutical building case study. Autom. Constr. **43**, 170–179 (2014)
8. I.O. for Standarization, "ISO 41011," 2017. [Online]. Available: https://www.iso.org/obp/ui#iso:std:68167. Accessed 20 Apr 2018
9. Kassem, M., Kelly, G., Dawood, N., Serginson, M., Lockley, S.: BIM in facilities management applications: a case study of a large university complex. Built Environ. Project Asset Manag (2015)
10. PAS 1192-3:2014, "Specification for information management for the operational phase of assets using building information modelling," 2014
11. Lavy, S., Jawadekar, S.: A Case Study of using BIM and COBie for facility management. Int. J. Facil. Manag. **5**(2), 13–27 (2014)
12. Kalasapudi, V.S., Turkan, Y., Tang, P.: Toward automated spatial change analysis of MEP components using 3D point clouds and as-designed BIM models. In: Proceedings—2014 International Conference on 3D Vision Workshops, 3DV 2014 (2015)
13. The BIM Hub: ISSUE FIVE BIM for FM, clients, owners and operators. BIM J. 62 (2018)
14. Building and Construction Authority: BIM Essential Guide for Collaborative Virtual Design and Construction, Singapore (2013)
15. Jalaei, F., Jrade, A.: A critical review of methods used to determine productivity of mechanical, electrical, and plumbing systems coordination. Constr. Res. Congr. **2014**(2008), 140–149 (2014)
16. Pennsylvania State University: Building Information Modeling Execution Planning Guide. The Computer Integrated Construction Research Group, Pennsylvania, The United States of America (2010)

16 OpenBIM Based IVE Ontology: An Ontological Approach to Improve Interoperability for Virtual Reality Applications

Anne-Solene Dris, Francois Lehericey, Valerie Gouranton, and Bruno Arnaldi

Abstract

In this paper, we propose an ontology improving the use of Building Information Modelling (BIM) models as a virtual interactive environment (IVE) generator. The result is not only the ability to create a bidirectional link between the informed 3D database and the virtual reality application, but to automatically generate object-specific functions and capabilities according to their taxonomy. We present the results based on the Risk-Hunting training application. In this context, the notions of weight, object handles and, scheduling of the construction are essential for the immersion of the future trainee and educational success.

Keywords

Building information modeling (BIM) • Ontology • Virtual and augmented reality • Interoperability

16.1 Introduction

16.1.1 AECO in France, a Sector Highly Exposed to Occupational Accidents

The Architecture, Engineering, Construction and Owner-operated (AECO) industry is the most accident- prone sector in France. In 2014, 145 construction sector employees (excluding temporary workers) died while working in France. The construction industry employed 8.6% of employees and recorded 16.3% of “accidents with stop” and 26% of deaths. As for the causes of accidents, manual handling is by far the most challenged category, accounting for more than half of all work stoppages with a rate of up to 53%. Followings are falling full on foot with 13%, falls from height with 12%, and the use of hand tools with 9%.

An economic approach to the question shows that their cost, globalized with that of occupational diseases, would amount to 1.3% of the national wealth, i.e. the theoretical equivalent of more than ten additional holidays on the calendar. These few figures illustrate the very dangerous nature of the sector and lead to an interest in the problem of accident prevention in construction.

16.1.2 Training, Essential Lever

Various reasons can help to explain the difficulties that prevention poses in this sector of activity: risk factors are of human, technical, organizational, material and often interdependent origins. Statistics show that workers benefiting from reduced

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support in the company, including posted workers, foreigners, temporary workers or apprentices, are most prone to workplace accidents. As an example, mention can be made of the INRS report [1] which stipulates that accident victims of foreign origin (non-European) are three times more numerous in the building and civil engineering sector than in other sectors, the same is true for European foreign employees. These statistics highlight the lack of training and experience of these categories of workers, especially for foreigners, but also the lack of support for temporary workers, who change their job and work environment regularly. Even in large groups such as Vinci, which for many years has been conducting a comprehensive prevention policy with the “zero accident” plan, the difference in frequency rates between employees and temporary workers is still worrying.

One of the difficulties encountered in the management of training is related to temporary workers who do not always benefit from the same level of information and knowledge related to the materials and methods of construction specific to the site on which they intervene. Recent studies demonstrate the benefits of virtual reality training [2] compared to traditional training methods. But the costs involved are still high [3] in the case of virtual reality. In both cases, the training is sequenced and does not allow the real situation, each construction project is unique. However, the work environment has a considerable impact on the perception of risk and therefore on the behavior of employees . The arrival of BIM, a working process commonly used in the construction industry, makes it possible to obtain a virtual double of the act of building.

16.1.3 Goal

The purpose of this study is to present a virtual reality training scenario generation method that allows the trainee to be immersed in the unique configuration of the site he/she is involved in.

16.2 Related Works

Overview Several reasons [?] explain the risky behaviour of the workers: the lack of knowledge of the safety rules, the lack of respect of these rules, a non-conducive environment such as high productivity targets, psychological factors, the pride of “hard leather” in male environments such as construction, lack of training, organization of the site and a sequencing of the tasks to be performed that do not take into account the needs of the workstation.

Traditional training in risk prevention/Training in virtual reality Virtual reality provides a relevant response to the act of training to perform tasks without dangers, train many people from different locations [4] at lower costs, understand abstract concepts or absolve from the language barrier (written or oral), and put into practice.

We also note that traditional training does not allow trainees to adapt to a changing environment [5] so immersion into a risk hunt in virtual reality (VR) can enrich learning.

In the particular case of risk prevention, the hazard reflex is the expected result. According to the work of JB Watson, the reflex can be conditioned by the senses and participates in the acquisition of knowledge in humans. We agree with Sutherland’s (1965) view that “the ultimate (virtual reality) device would be an environment in which the computer could control the existence of objects (and our interaction with them). The five senses can therefore be solicited simultaneously [6], which increases the interest and commitment of the participant [7] in his training thus improving the acquisition of knowledge. The limits of VR in relation to Real Education today are of a technical nature related to the use of a new technology: technical and professional skills of the developer, acceptability of interaction techniques by trainees not accustomed to video games, the orientation can be disrupted by the reduction of the field of vision and the movements whose latency can be problematic. We also remember that motion sickness can disrupt immersion in the interactive virtual environment (IVE).

16.2.1 Generate the Virtual World

Costs Building a real-world simulation tool like Risk Hunting is comparable to flight simulators [8]: expensive and long. In the field of construction, using BIM as a support to generate the IVE [9] allows more flexibility and considerable cost reduction.

Ontologies OpenBIM Based IVE, however, has its limits: the interaction and the definition of the objects on which it is possible to interact is not treated by the IFC (Industry Foundation Classes) standard. The development of an ontology meets the needs to enable the reuse [10] of knowledge of a specific area and to share a common structure of information. From the computing point of view, and more particularly knowledge engineering, the most commonly accepted definition is that of [11]: "an ontology is an explicit specification of a conceptualization of a domain". Conceptualization makes it possible to identify by an abstraction process the essential concepts referenced by the terms of the domain and the specification makes explicit the meaning associated with these concepts by associating them with a definition.

Few ontologies have been created for the construction sector; for information processing a complete study of which has been presented by Issa and Mutis [12] in the description of BIM uses and BIM objectives but also in asset management [13] and in the description of the field of action of BIM. All these researches agree on the need for a field that is digitalized to develop these ontologies.

Contribution The interaction needs of VR have not yet been formally addressed and this is the part that our research addresses by proposing a specific domain [14] ontology. Focusing on the Noy & McGuinness Seven-Step method based on Protege software, we offer a common working environment for interactive virtual reality applications whose virtual environment is derived from OpenBIM.

16.3 Proposed Solution and Results

16.3.1 Interoperability of IFC into a Virtual Environment

To interoperate BIM and VR, the first step is to read and write IFC models into a VR framework (in our case Unity3D), this include the geometries of the objects, the properties of the objects and the hierarchical structure. Reading and writing the properties of the objects and the hierarchical structure is trivial, but the geometry cannot be used as-is, we have to convert it from parametric models to triangulated meshes to be able to use it.

Furthermore we need to apply some post-processing to the loaded model to handle the constraints of VR, mainly the real-time constraint for rendering. These post-process, dedicated to VR include:

– Merging meshes: Some IFC object can be decomposed into a high number of meshes, this causes slowdown in the rendering and we merge such meshes.
– Set objects as static: Rendering can be better optimized if we know which objects are static (i.e. never move). We use the semantic of the IFC to select which objects are static (e.g. IfcWall) and which object might move (e.g. IfcDoor).
– Add collider: We need to specify which object have a collider to have physics interaction (such as walking). Having all objects act as colliders would be expensive, instead we filter objects with heir IFC classes.

Additionally, we want to make some of the IFC objects interactive (door, light button,), unfortunately not enough information is present in the IFC file to completely automatize this process. For example, the IFC class for door specify the type of door and its parameters (rotation axis,) but some design software ignore these properties. Moreover, the 3D model is stored in one part and there is no possibility to distinguish the door panel from the door frame or the door handle, this prevent to animate the door automatically. Having the possibility to tag part of the 3D model would solve this problem. To complete this process, we introduced the definition of a specific ontology.

16.3.2 The Creation of Ontologies

Several methodologies have been proposed for the construction of ontologies. These methodologies propose to use different types of information media to start the ontology such as terminology databases, technical documentation, ontologies, interview reports, questionnaires. We can cite inter alia Cyc methods [15] and SENSUS [16], the KACTUS approach [17], METHONTOLOGY methodologies [18] and On-To-Knowledge. The process of building an ontology is composed of several phases such as described in Fig. 16.1 (The life cycle of an ontology [19] (Fig. 16.2).

The Seven Steps Method proposed by Noy & McGuinness breaks down its activities as follows:

i. Determine the domain and the scope of the ontology.
ii. Consider reusing existing ontologies.
iii. Enumerate important terms of the ontology.

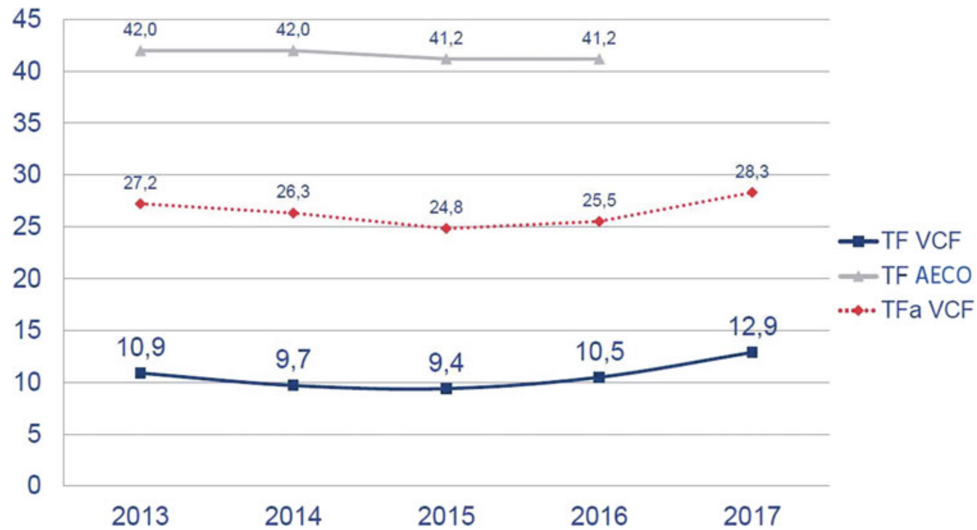

Fig. 16.1 Evolution of frequency rate (TF) = (number of accidents in first settlement/hours worked) × 1,000,000

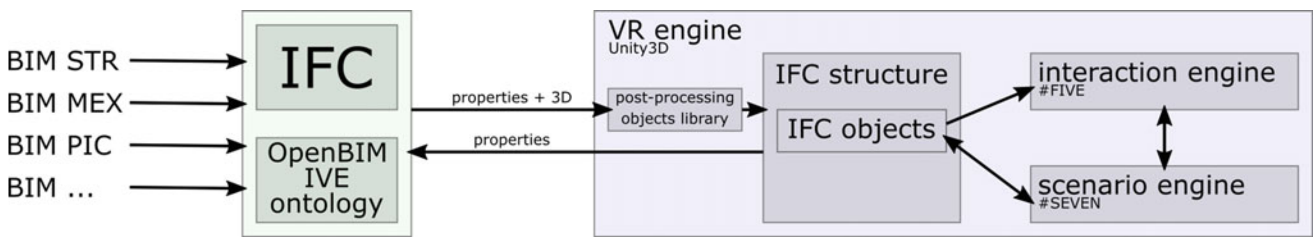

Fig. 16.2 IFC integrator Process—VR Concept Schema

iv. Define the classes and the class hierarchy.
v. Define the properties of classes—slots.
vi. Define the facets of the slots.
vii. Create instances. Steps iv to vii are repeated as many times as necessary in the ontologization process. In view of OpenBIM Based IVE ontology, the addressed domain is that of OpenBIM and interaction in virtual reality. We mainly used IFC ontologies [20] as the basis for project development. Working groups are currently collaborating to use these data and technologies to support their developments such as the buildingSMART Data Dictionary (bSDD). We will therefore evolve the model with the results of their studies. The acquisition of knowledge of the domain is the phase allowing enumeration of the main terms of the domain. For this we have studied the numerous working documents, standards and processes of the various IVE general services as well as the existing Risk Hunting Courses and their specifications.

16.3.3 OpenBIM Based IVE Ontology—Model Used

In the case of the generation of virtual reality applications, and more particularly in the context of design a training scenarios, the ontology presented in the S3PM project, OntoSPM [21] describes the procedures of individual surgery in a formal way, allowing their exploitation in the scenario engine in virtual environment called #Seven with an interaction framework called #Five. In the construction industry, a key aspect is the ability to reuse existing ontologies such as IFC ontology or Conceptual BIM ontology. The OWL family of ontology languages has been developed to unambiguously specify the properties of all ontology constructs.

We therefore implemented an OWL database integrating the concept of user interaction with #Five and #Seven. The current version of OpenBIM Based IVE Ontology contains extracts from the different ontologies used. A preliminary version is available and used in the research projects of Vinci Construction France.

16.3.4 OpenBIM Based IVE Ontology—Generation and Evaluation

The OpenBIM Based IVE has been generated by amending and reusing existing ontologies. The first source of data was IFC ontology as a structural data base of the building. We enriched it with the definition properties of Omniclass and then conceptualized the action models in virtual reality. As a first step, we have drawn up specifications for the construction industry's expectations of virtual reality technology and compared them to BIM processes on a study of twenty-four projects. This analysis allowed us to highlight primary functionalities common to each VR application using the geometric or semantic data of the BIM. These Define the concepts. Secondary features emerge depefinding on the type of application and the level of development of the BIM. As an iterative process, evaluation techniques are put in place not only during the ontology engineering process but also with end users to ensure that the result achieves the objectives set. In particular, we evaluate the number of objects reworked in the virtual environment, comparing whether it is the interaction reason (number of associated variables) or visualization (number of meshes) in order to reduce it as much as possible, goal being to achieve efficient interoperability.

On a same project: an VR application presenting the time laps of the construction, Fig. 16.3 presents the results according to the process evolution. The first study presents the results without the use of ontology, second study has been proceeded with the first version of OpenBIM Based IVE Ontology (V1), followed by version two (V2) and three (V3).

We have chosen to present the case of Risk Hunting in virtual reality since it groups together a majority of the action functionalities described by the ontologies: moving around a building model, moving objects, collaborative work, note taking and exchange with the crane operator. Moreover, it allows a direct evaluation of the ontology. More than 40 training days are conducted each year, based on two scenarios:center training or on-site training. We thus formalized these two scenarios using ontology. The shortcoming is that we have modeled a real training virtually and we envision that future trainees will want to interact differently with virtual reality than they do in a "natural" way. We thus record the unexpected movements and modalities of interaction in order to continue the enrichment process of the ontology.

16.3.5 OpenBIM Based IVE Ontology—Presentation

Four levels are Defined in the OpenBIM Based IVE Ontology:IveConcepts, IveAxiomes, IveAttributes and IveInstances. The Concepts Defines the main functions needed in VR to communicate with OpenBIM: a specific Library, systems of

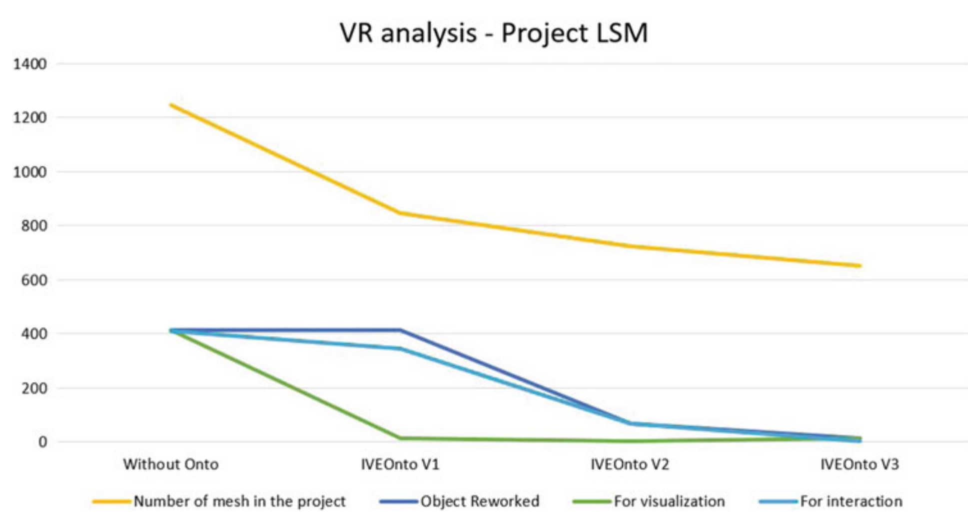

Fig. 16.3 OpenBIM based IVE Onthology—Protege

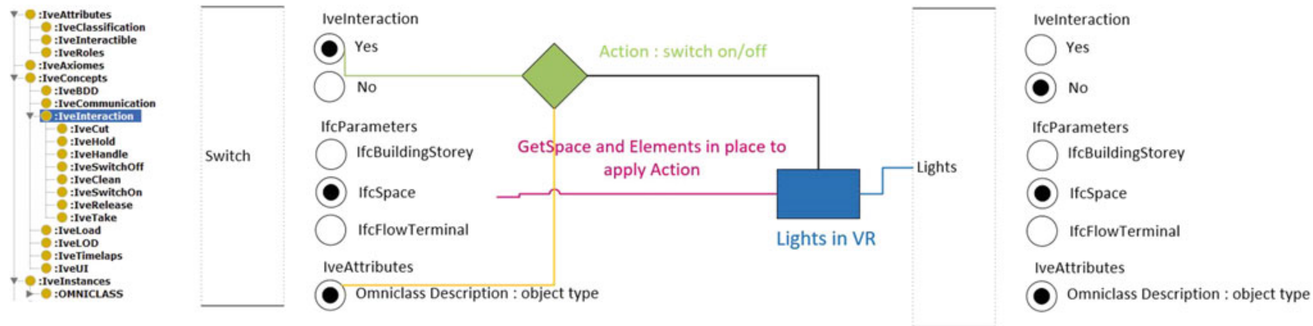

Fig. 16.4 OpenBIM based IVE Onthology—Protege

communications, the loading of les, the level of development used, the time-laps which is crucial in the construction industry and the user interfaces. Three attributes classes were necessary: classification (we used Omniclass as a basis), interaction (boolean allowing any kind of interaction) and the role of the actor in the IVE.

Based on the Omniclass table 35—Tools in order to qualify object classes, we were then able to develop the properties inherent in the interaction such as the ability to grab an object and how it can be manipulated.

Example: the interaction with a switch automatically turns on the lights in the room. These two properties have been developed with the ontology presented here (Fig. 16.4).

The evaluation phase is continued on different virtual reality applications. In our case, we chose the Risk Hunting Course because it seems to us to be one of the most complete VR applications in terms of interaction with the virtual environment: moving around a building model, moving objects, collaborative work, note taking and exchange with the crane operator.

16.3.6 OpenBIM Based IVE Ontology—Broadcasting

Our approach covers applications for visualization, navigation and interaction with building objects. The richness of the ontologies is born from their use, also to generalize our approach to other VR applications integrating perhaps the multi-users or configurators modifying the models, we plan to transpose our results on a Git deposit by getting closer to the groups BuildingSMART.

16.3.7 Design of the Application

BIM models loading. A virtual Risk Hunting Course will be more meaningful to the companions following the training if it is based on the site to which they will be transferred or on which they currently work. Starting from this principle, up to eight BIM models will be used and loaded in the game engine via the integrator.

Scenarized Interactive Environment The trainee is immerged in a virtual environment where he can move and interact (see Fig. 16.5). To address the issue of reusability of the application, we build a model of Virtual Risk Hunting to self-generate randomly possible serious errors based on the integrated IFC. Thus, depefinding on the projects, the scenario adapts to it and proposes a different set of errors for each launch. This is done by abstractly defining errors which look into the IFC ontology to find every possible instantiation of each error. From these random error, the training is guided with a scenario Defined with the #SEVEN model. Each error has a scenario fragment to handle its behaviour, these fragments are combined to make the whole scenario.

Additionally, we use the BIM Collaboration format (BCF) to handle communication between the trainee and the trainer. The trainee can use a virtual camera to take pictures while in immersion. Furthermore, the scenario itself write BCF notes on specific events to keep track of the trainee progress and errors. All these notes can be reviewed by the trainer after the training.

Questionnaire Design During our research on the benefits that virtual reality can bring compared to traditional training methods, we have been faced with the problem of lack of existing studies. The return of the experiments carried out does not make it possible to establish a concrete result. If the finding seems clear about the benefits of this technology during the training, its interest in the long term remains to be proven.

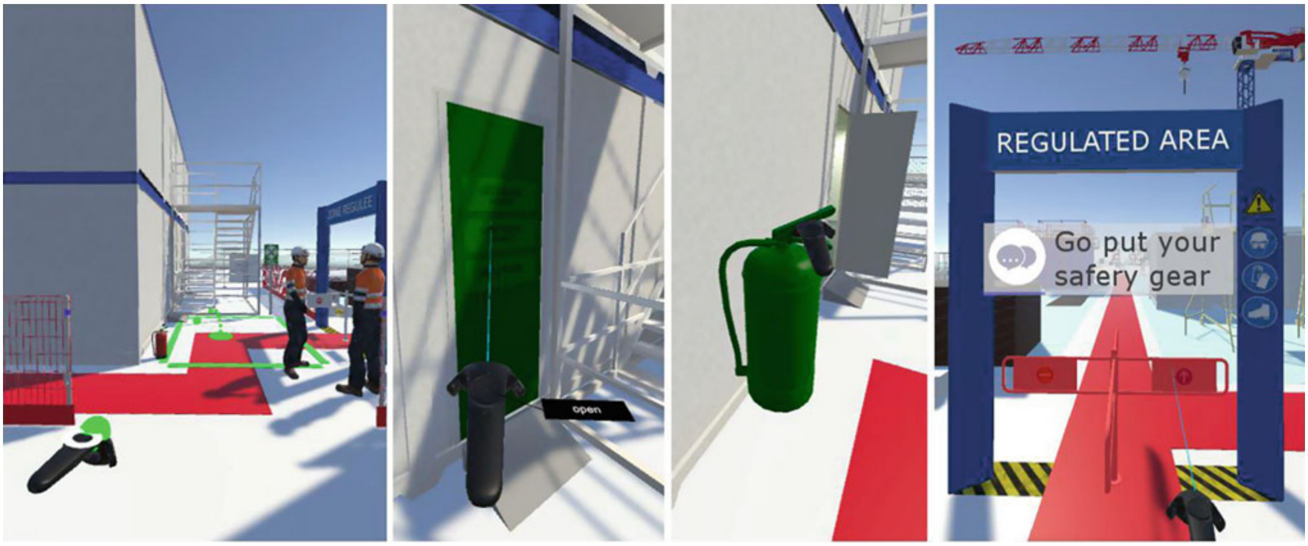

Fig. 16.5 Examples of the different ways to interact with the environment. From left to right: teleporting to a new location, remotely interacting with an object, grabbing an object and getting instructions

We therefore designed a questionnaire system based on three sheets. This test phase will be continued in the coming weeks.

16.4 Conclusion and Future Works

The various areas of AECO industry requiring the formalization of knowledge is still vast but through this study, we propose a solution improving the interoperability between virtual reality and OpenBIM, developing the works of BuildingSmart on the IFC, the bSDD, rankings and BCF in the field of virtual reality.

In the future, it will possible to reiterate the ontology construction process by studying the implementation of the error creation system and the needs of the ontology by studying the actions of trainees during their training. We are also thinking of using it on other virtual reality applications by studying the possibility of co-activity, adding stress levels according to people's roles, and qualifying men's security objects in order to make them more effectives.

References

1. National Research and Safety Institute—INRS.: Statistiques Prvention. Available at: http://www.inrs.fr/actualites/statistiques-BTP-2014.html (2014)
2. Ho, C.L., Dzeng, R.J.: Construction safety training via e-Learning: learning effectiveness and user satisfaction. Computers and Education. Elsevier Ltd, **55**(2), 858–867 (2010)
3. Gao, Y., Gonzalez, V.A., Wing Yiu, T.: Serious games versus traditional tools in construction safety training: a review, **6**(July), 653660 (2017)
4. Barot, C., Lourdeaux, D., Burkhardt, J.M., Amokrane, K., Lenne, D.: V3S: A virtual environment for risk-management training based on human-activity models. Presence: Teleoperators and Virtual Environ. **22**(1), 1–19 (2013)
5. Verna, D.: Virtual reality and tele-operation: a common framework. In: Proceedings of the 5th World Multi-Conference on Systemics, Cybernetics and Informatics (SCI) Emergent Computing and Virtual Engineering, vol. 3, pp. 499–504 (2001)
6. Fuchs, P., Moreau, G., Guitton, P. (eds.): Virtual Reality: Concepts and Technologies. CRC Press (2011)
7. Cherrett, T., et al.: Making training more cognitively effective: Making videos interactive. Br. J. Edu. Technol. **40**(6), 11241134 (2009)
8. Kozak, J.J., et al.: Transfer of training from virtual reaality. Ergonomics, 777–784 (1993)
9. Dris, A.-S., Gouranton, V., Arnaldi, B. : Integration concept and model of Industry Foundation Classes (IFC) for interactive virtual environments Integration concept and model of Industry Foundation Classes (IFC) for interactive virtual environments (2016)
10. Noy, N.F., McGuinness, D.L.: Ontology development 101: a guide to creating your first ontology. Technical report, KSL-01-05, Stanford Knowledge Systems Laboratory (2001)
11. Gruber, T. R.: Substantial revision of paper presented at the International workshop on formal ontology. Int. J. Hum. Comp. Stud. **43**, 907–928 (1993)

12. Raja, R.A., Issa, Mutis, I.: Ontology in the AEC Industry: A Decade of Research and Development in Architecture, Engineering, and Construction (2015)
13. Tibaut, A., et al.: Ontologizing the Heritage Building Domain, 10754(January) (2018)
14. Costin, A., Eastman, C.: Requirements for Ontology Development in the AECO Industry. In: LC3 2017: Volume 1—Proceedings of the Joint Conference on Computing in Construction (JC3), July 4–7, 2017, Heraklion, Greece, pp. 553–540 (2017)
15. Lenat, D., Guha, R.: Building large knowledge-based systems: Representation and inference in the cyc project. Artif. Intell. **61**(1), 41–52. doi: https://doi.org/10.1016/0004-3702(93)90092-P (1990).
16. Swartout, B. et al.: Toward Distributed Use of Large-Scale Ontologies. Proc. Tenth Workshop Knowl. Acquisition Knowl. Syst. 138–148. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Toward+Distributed+Use+of+Large-Scale+Ontologies#0 (1997)
17. Schreiber, G., Wielinga, B., Jansweijer, W.: The KACTUS view on the "O" Word. IJCAI workshop on basic ontological issues in knowledge sharing, (October 2012), 159–168. Available at: http://www.swi.psy.uva.nl (1996)
18. Gomez-Perez, A., Fernandez, M., De Vicente, A.J.: Towards a method to conceptualize domain sure, Y., Staab, S., Struder, R.: (2001) On-To-Knowl. Methodol. Handb. Ontol. 117–132. doi: https://doi.org/10.1007/978-3-540-24750-0_6 (1996)
19. Fernandez, M., Gomez-Perez, A., Juristo, N.: Methontology: From ontological art towards ontological engineering. AAAI-97 Spring Symposium on Ontological Engineering. Stanford University (1997)
20. Beetz, J., Van Leeuwen, J., De Vries, B.: IfcOWL: A case of transforming EXPRESS schemas into ontologies. Ai Edam **23**(1), 89–101 (2009)
21. Gibaud, B, et al.: OntoSPM an ontology of surgical process modeling. URL: https://medicis.univ-rennes1.fr/activities/theme1/projects/ontospm (2016)

17 BIM and Through-Life Information Management: A Systems Engineering Perspective

Yu Chen and Julie Jupp

Abstract

The digital era of construction has enabled new types of decision support for all phases of the building lifecycle. New capabilities to support the management of end-to-end service operations are emerging due to the outputs of building information modelling. Previous research has identified how the application of systems engineering activities in construction can inform the development of new methods and processes to better support a facility's life cycle. However, gaps remain in holistic systems approaches relative to how data is structured, reused and managed through-life. The paper discusses systems engineering management activities and reviews the related literature, examining the significance of these concepts in different sectors of construction. The paper identifies gaps in collaborative and progressive modelling methodologies and identifies the main challenges that industry face in adopting a systems mindset when implementing BIM on complex projects.

Keywords

Building information modelling • Information management • Lifecycle • Systems engineering • Integration

17.1 Introduction

Within the life cycle of a building asset, different groups of actors are involved in the generation and sharing of data and information throughout the design, construction and operations and maintenance (O&M) phases [1]. The fragmented nature of both the construction and facilities management (FM) industries leads to the inefficient exchange and low reuse of building asset information [1, 2]. During the past decade with the rise in computing power, more effective utilization of building asset information has improved globally [3]. Building Information Modelling (BIM) is widely regarded as the foundation of the fourth industrial revolution [3]; BIM is defined as "a new approach to design, construction, and facilities management, in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format" [4]. The implementation of BIM in design and construction phases brings with it evident benefits in terms of cost and schedule control [5], which are quite marginal in perspective of the gains to be made in the O&M of an asset's service life [6]. Many issues relate to the management of the flow of digital building information [7]; where for example, problems manifest in the management of the vast amounts of data and information generated during design and construction phases, some of which is not valuable to the operational phase of the asset [8].

To capitalize fully on the potential of BIM to help optimize the flow of digital information and process activities, it is necessary to define a structuring concept linking BIM models, BIM uses, related information flows in the project together, with workflows linked with user profile information [9, 10]. Previous researchers have identified how the application of

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systems engineering (SE) activities in construction have significant potential to structure the flow of data and information as well as process activities [11, 12], "where integration is important to ensure that parts, components, units, subassemblies, subsystems and systems work together as a whole" [13], and are able to serve different business processes across the organization. SE is a multidiscipline approach and means to enable the realization of successful systems in complex environments [14]. It emphasizes the importance of the traceability of the requirements of end users, operators, maintainers, suppliers, etc. However, whilst SE provides a robust set of methods (e.g., information requirements management [3], configuration management [15, 16] and change management [17, 18]), gaps remain in how these methods translate to the complex nature of construction projects, where challenges surround the way data is structured, verified, reused and managed over the life cycle of a building asset [1, 3, 19, 20]. Recent initiatives to develop BIM Standards (e.g., PAS 1192 and ISO/DIS 19650) have sought to address these issues. However, an understanding of how SE methods and processes can be used to implement collaborative methodologies beyond these high-level guidelines is currently lacking.

Against this backcloth, this paper presents a literature review of those BIM related initiatives in recent construction domain research aimed at overcoming the gaps in collaborative progressive modelling methodologies and the challenges of information management throughout the building asset lifecycle. The paper introduces systems engineering management activities and enablers before reviewing related literature and discussing the relevance of these concepts to the application of BIM in construction. The paper then identifies specific gaps in model progression methodologies and reveals where the challenges lie for the industry in developing a systems mindset to the implementation of BIM on complex projects.

17.2 Background

With increasing uptake of digital construction technologies, a greater understanding of the through-life information management capabilities relative to the required backbone infrastructure, data structures, cloud provisioning services, and enterprise architectures are beginning to grow. A major challenge for both the physical and digital asset life cycle is "the existence of various data format standards, few practice standards and no lifecycle information standards" [21]. Although efforts have been made to ensure the data standards from various domains are interoperable, it is still difficult to determine "what data and context are required for each phase of the product lifecycle" [21].

Over the last three decades, the complex, discrete manufacturing industries, such as aerospace and shipbuilding, have made significant progress in productivity increases and management efficiencies. This is in large part due to a more seamless integration of systems enabled by SE capabilities and Product Lifecycle Management (PLM) platforms [9, 21, 22]. This improvement, however, has not been achieved in the design, delivery and operations of building assets [9]. Given the increasingly cyber-physical and digital nature of the construction and FM industries in the last decade, it is expected that the SE approaches developed in other sectors have significant potential to inform approaches to information integration across the building asset's life cycle [9, 11, 13].

In the past decade, the adoption of SE in the construction industry has gained an increasing interest both in practice and in academia [1, 13, 23–25]. In practice, organizations in civil engineering have long realized the value of SE methods in terms of making projects manageable and better suited to customer requirements [23]. The International Council on Systems Engineering (INCOSE) Infrastructure Working Group, for example, is exploring the use of SE in civil engineering. Also in the Netherlands, ProRail [23] published the third version of a general SE guideline for civil engineering that addresses three levels—sector, organizational, and project—targeting different user groups based on the experience gained through the application of SE methods.

Some notable previous research works have been dedicated to the study of adopting SE approaches in construction projects [1, 13, 24, 25]. Whyte [13] provides a comprehensive review of system integration research in the delivery and operation of infrastructure and suggest future directions for research on systems integration within civil infrastructure. Whyte [13] highlights the potential of combining "data-sets and model-based systems engineering, BIM and performance-based models" and using "new forms of data analytics to reveal new patterns" [13]. A chief concern that raised by the translation of SE in the built environment is the reliance on a single source of data and the potential for errors and significant failures in the absence of robust processes for data verification and validation throughout the project life cycle [13]. Hoeber and Alsem [1] presented a way of working that utilizes open-standard BIM, SE ontologies, object libraries and an Information Delivery Manual to support information management throughout the life cycle of infrastructures assets. However, further evaluation and extension case studies are needed to measure the benefits of the approach in a quantitate way. Mata et al. [24] developed a Systems of Systems model along the SE concepts and Systems Modeling Language (SysML) to evaluate the sustainability performance of infrastructure projects. De Graaf et al. [25, 26] assessed the level of SE applications in six construction projects of the Dutch Water Board based on the SE process model developed by the U.S. Department of Defense (DoD). This growing body of literature signals the case for understanding SE methods relative to the unique context and requirements of designing, delivering and operating complex building assets.

Although the application of SE approaches in complex horizontal infrastructures (e.g., rail projects) has been explored during the last decade, there are few documented cases of the use of SE methodology in the complex vertical building sectors (e.g. smart/intelligent building, hospital). The main barriers lie on the unique industry structure and supply chain [2, 9]. Taking the aerospace industry as an example, the industry's structure is globalized and consolidated, with only a few large firms dominating the industry [2, 9]. Conversely, the construction industry is a localized and highly fragmented industry, with many small firms permeating the industry, make through-life information management challenging during the delivery phases of complex building projects [2, 9].

17.3 Systems Engineering Management Activities and Enablers

The most common and accepted definition of SE was proposed by INCOSE: "SE is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirement, and then proceeding with design synthesis and system validation while considering the complete problem." [14]. Systems Engineering Management (SEM), as a branch of SE, is the application of scientific, engineering, and managerial efforts to address *operational needs and client requirements*, to transform said need into system configuration and performance parameters, and to integrate related technical parameters and managerial factors to meet performance objectives [15]. SEM processes and toolsets are therefore essential to supporting SE implementations and achieving its benefits [27].

In the past decade, construction industry initiatives are increasing efforts to develop model-based information management methods. For example, in preparation for the BIM Mandate in 2016 in the UK, the British Standard Institute published the PAS[1] 1192-2: 2013 and later PAS 1192-3: 2014. PAS 1192-2 specifies an "information management process to support BIM Level 2 in the capital/delivery phase of projects" [28]. In contrast, PAS 1192-3 focuses on "the operational phase of assets irrespective of whether these were commissioned through major works, acquired through transfer of ownership or already existed in an asset portfolio" [29]. Both Standards introduce new concepts and system-based processes to BIM implementation.

The following section discusses the role of SE in BIM deployment and examines the SEM activities and enablers that have the potential to establish a systems-based approach to more effective management of building information throughout the life of an asset. Accordingly, equivalent BIM initiatives in the construction industry are compared with SE methods to highlight significant gaps in BIM methodology.

17.3.1 Systems Engineering Management Activities

According to the DoD [30], SEM is achieved via the integration of three activities: (1) development phasing, (2) life cycle integration, and (3) systems engineering process.

Development phasing. Development phasing aims to control the design process and define design baselines that govern each level of development [30]. The SE process is applicable at each level (or phase) of system development, one level at a time, to produce the corresponding requirement descriptions of each level, known as "configuration baselines" [30]. Thus, configuration management (CM) under an SE approach involves five distinct activities: CM Planning and Management, Configuration Identification, Configuration Control, Configuration Status Accounting, and Configuration Verification and Auditing [31]. During system decomposition and definition, requirements, functions, and objects (R/F/O) are verified with higher-level R/F/O before then being validated against client expectations [32]. The components of a system are then integrated and recomposed into the product. System components are therefore verified with corresponding R/F/O at each level with ongoing validation [27, 32]. Verification and validation (V&V) are not treated as separate phases but are integrated activities executed continuously throughout the SE process [32].

[1]Publicly Available Specification.

In a BIM-enabled construction context, to date there has been no equivalent structured approach to CM developed as a way to systematically managing system decomposition and definition, requirements, functions, and objects; nor as a way to manage change throughout the asset lifecycle in order to maintain building system integrity. The main challenges of implementing CM in construction surround difficulties in structuring and coordinating the execution CM activities across the project enterprise and in accordance with the building system hierarchy. In terms of V&V, there are reasonable levels of maturity in model auditing, design coordination, and associated quality assurance processes across the detailed design and construction documentation phases. However, the preparation of a holistic approach to a V&V plan in early project stages is often overlooked [26].

Life cycle integration. Life cycle integration involves the customer and stakeholders in the design process, ensuring that the design is viable and aligns with the customer's requirement throughout the life of the system or asset [30]. It requires the early involvement of all stakeholders to identify and document their needs and requirements which is also known as project planning [30]. In subsequent stages, the project must be monitored and controlled carefully to ensure alignment with stakeholders requirements [22].

Similar defined processes can be identified in the construction industry. To meet the challenge of defining *what information* is required, *from whom* and at *what level of detail* several industry specifications have addressed the definition of modelled objects and information embedded within them at the project preparation and brief phase [33], with examples of BIM guidelines and execution templates common in most countries. These guidelines and templates are normally targeted at supporting the development of the BIM execution plan (BEP), also known as a BIM management plan (BMP) [34]. Within these plans, the model element table (MET) is designed to identify information requirements of the project at an early stage [34]. It summarizes the list of model elements but also "indicates the level of development (LOD) to which each model element author (MEA) is required to develop model element content before the conclusion of each phase" [35]. The BIM model is then developed according to the requirements defined in the MET [34]. To support this process, progressive model development methodologies and protocols [34], such as UK's PAS1192-2 [28], Canada's AEC protocol [36] and the USA's LOD specification [37] have been developed.

Systems Engineering Process. The specification of the Systems Engineering Process, or SEP, lies at the heart of all SEM activities. It aims to provide a structured but flexible process that "transforms needs and requirements into a set of system product and process descriptions, generate information for project decision-makers, and provide input for the next level of development" [30]. Based on the SEM model by the U.S. DoD [30], de Graaf et al. [26] propose a SEP framework to analyze the implementation of SE in an engineering consulting firm in the civil engineering sector. The engineering consulting firm studied recognized the significance of SE in relation to their daily practices, and in 2010 made the decision to implement SE in its business more prominently to professionalize and improve the quality of processes and its products, whilst reducing failure costs [26]. Figure 17.1 shows the ten SE elements implemented by the firm; between "input" and "output" there are three core SE activities—*requirements analysis*, *functional analysis and allocation*, and *design synthesis* —and six feedback elements—*requirement loop, design loop, design verification and validation, specification verification and validation* [25, 26].

Requirements analysis (activity 1) is aimed at translating client needs and demands (process inputs) into specific, measurable, acceptable, realistic, and time-bound requirements [25]. A verification and validation (V&V) plan linking to requirements is normally shaped by the project team [26]. Function analysis and allocation (activity 2) supports the derivation of functions from requirements, composing functional architecture, converting functions into solution free objects, and allocating requirement to functions/objects [26]. In design synthesis (activity 3), several design alternatives are developed based on the "solution neutral" objects and only one of them is selected [25]. During this activity, a key objective is for the decision-making process to be recorded and traceable [25]. Feedback loops and interactions (activities 4–9) between core SE activities ensure the correct linkages among them as well as the continuous updating, checking and documentation of the design so as to maintain consistency with the last iteration's developments and insights [25].

Whilst there are limited case studies of the application of SEP in a civil engineering context, in the wider construction industry there are no documented examples. Whilst not explicitly recognized as a SEP, PAS 1192-3 proposes a model-based information management process map of the asset life cycle (see Fig. 17.2). The process map is comprised of the specification of a Common Data Environment (CDE) based on BS 1192 and ISO/TS 8000 and illustrates the links between the data and information generated using the CDE as the single source of asset information [29]. This process provides a comprehensive overview of data and information flows throughout the asset life cycle. However, it is an information flow instead of an activity-based or task-based description of processes which generate, verify, update, and validate information.

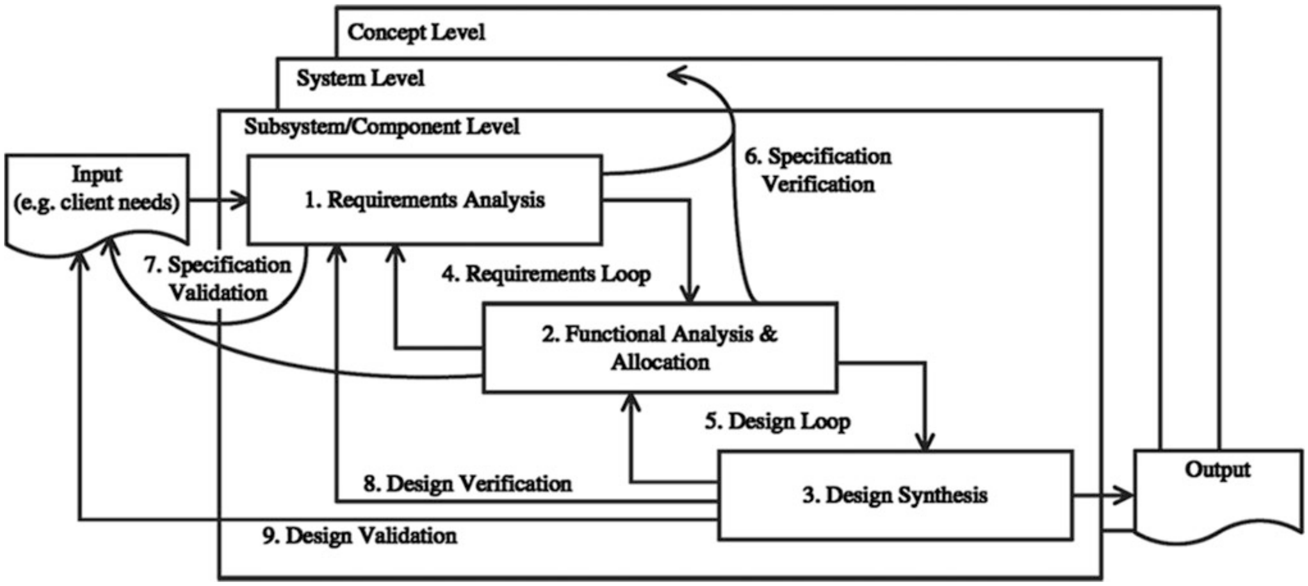

Fig. 17.1 The SEP in the civil engineering industry based on U.S. DoD [25]

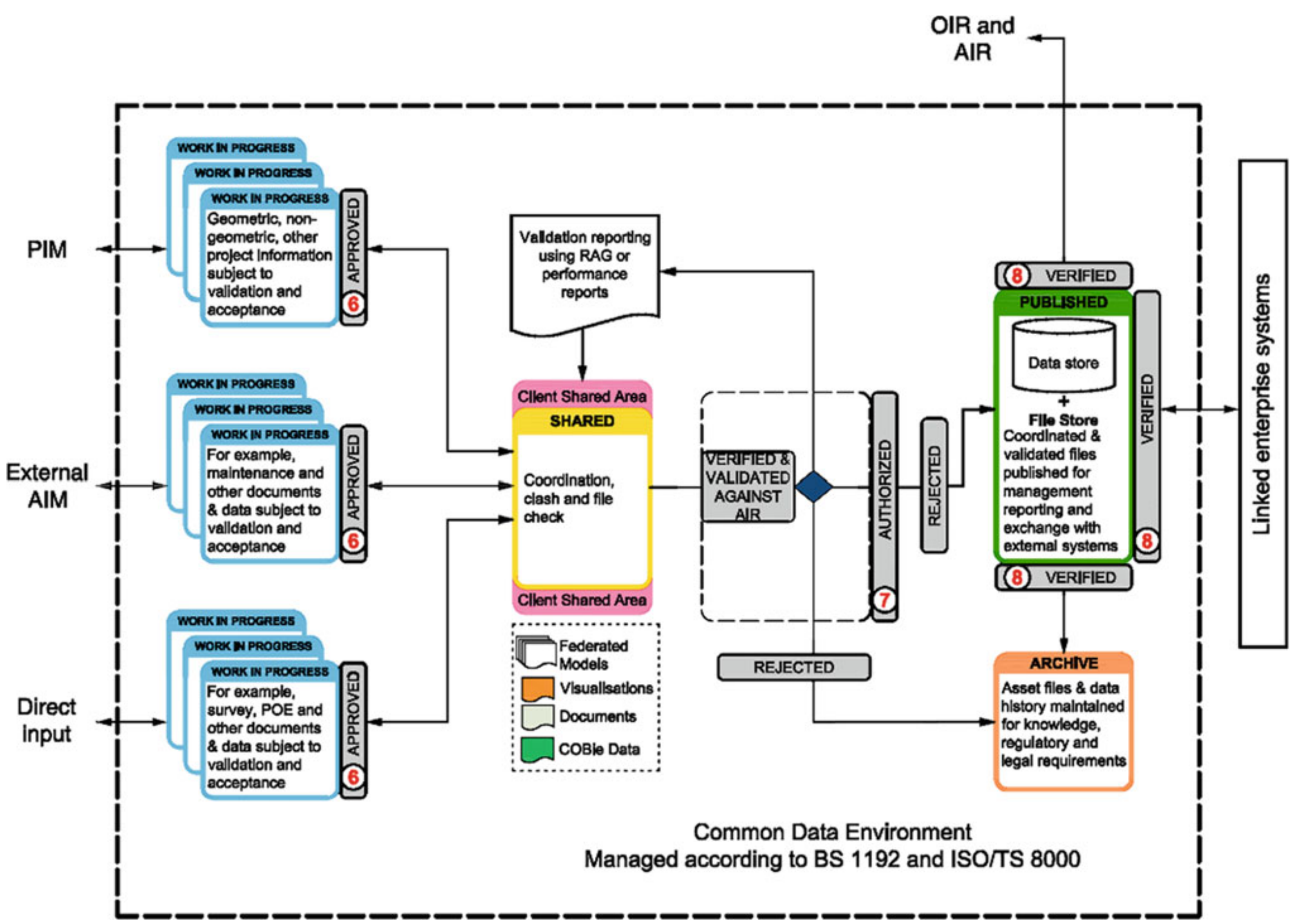

Fig. 17.2 Information process mapping within CDE [29]

17.4 Systems Engineering Management Enablers

To implement SEM activities and realize the benefits of systems thinking, supporting enablers including management and collaboration structures and toolsets have been developed and refined over the years in complex manufacturing sectors. Locatelli et al. [27] identify seven enablers underpinning SEM activities. Here we explore their connection to comparable BIM concepts and initiatives; where gaps are identified we discuss the potential application of SE and SEM activities.

Integrated Product Teams. Achieving life cycle integration requires the simultaneous consideration of all life cycle needs and requirements at the early stage. It has been long known that complex system integration can be greatly enhanced through the early involvement of interdisciplinary teams, also known as integrated product teams (IPTs) [30]. The IPTs normally consist of all stakeholders who will influence project success, such as customers, clients, end-users, contractors, sub-contractors, and suppliers [27].

Similar concepts in construction are represented in frameworks supporting Integrated Project Team (IPT) and Integrated Project Delivery (IPD). The AIA's[2] IPD guideline recognizes the value of an integrated team as the lifeblood of IPD [38]. Similarly, ACIF[3] and APCC[4] in Australia have developed guidelines supporting project team integration [39]. The OGC in the UK has also proposed guidelines for IPT in perspective of team working and partnering [40]. The composition of integrated project team normally consists of all stakeholders.

Systems Integration Process. The purpose of systems integration processes are to achieve the "system-of-interest" by progressively combining system components in alignment with system requirements using an "integration strategy" [14]. Activities include defining an integration strategy, scheduling integration, assembling system elements, validating and verifying information flow across interfaces at each level of assembly, and recording integration information [14]. The continuous engagement of the IPT is essential to realize the potential of any systems integration process, ensuring the improvement of information flows, coordination, situation visibility, rework reductions and the lowering of participant frustration [41].

In a construction context, Davies and Mackenzie [42] explored the implementation of systems integration for the London Olympics. The research-based project was aimed at managing the complexity of multiple large complex projects by decomposing each into different levels of systems integration with clearly-defined interfaces and buffers between levels and subsystems. Davies and Mackenzie identified the most challenging aspects of systems integration as establishing processes to maintain stability while responding dynamically to uncertain and changing conditions [42], a perennial problem common to most large, complex construction projects.

SE Management Plan. The SE Management Plan is the top-level plan for managing the SE effort [14]. The SE Management Plan defines "how the project will be organized, structured, and conducted and how the total engineering process will be controlled to provide a system that meets stakeholder requirements" [14].

In a construction context, a comparable BIM related initiative is the BEP/BMP discussed above in the "Life cycle integration" section. A well-conceived and documented BEP/BMP developed at the early stage of the project with input and buy-in from all stakeholders can structure the total architectural and engineering design as well as the construction process. The BEP/BMP can be used to control how the design and progressive modelling of the facility will be structured across the design and construction phases of project delivery, providing a document that specifies *what information* is needed, *from whom* and at *what level of detail* meets stakeholder requirements. However, the quality and consistency of BEP/BMP vary widely, especially with regards to the specification of workflows, model use, model responsibilities, and model-based information exchange [43].

Requirements Management. Requirements management in SEP involves the capture, analysis, and tracking of system requirements using defined workflows and supporting technologies [27]. Requirements management tools support rigorous documentation and version control, relationships between multiple requirements, and traceability of each requirement [27]. One widely adopted requirement management software is IBM Rational DOORS. As a multi-platform and enterprise-wide tool, it is designed to capture, link, trace, analyze, and manage a wide range of diverse textual and graphical information to ensure a project's compliance to specified requirements and standards [44].

The use of requirements management workflows and technologies are not wide-spread in the construction industry and appear to be more common in the civil engineering and infrastructure sectors. Within these sectors, requirements

[2]The American Institute of Architects.
[3]The Australian Construction Industry Forum.
[4]The Australasian Procurement and Construction Council Inc.

management tools such as IBM Rational DOORS are relatively common. In the healthcare sector of construction case studies of BIM projects have also reported the use of planning and data management tools software such as dRofus, which have some requirements management capabilities in relation to the architectural design using a bidirectional link between dRofus and the 3D modelling software (e.g., Autodesk Revit and Graphisoft's ArchiCAD). dRofus provides a cloud-based platform and enables a data-centric approach to managing requirements relative to BIM outputs. In this way, client requirements can be captured and the traceability of any changes to the architectural model can be supported. The facility standards of multiple projects can also be managed using the dRofus tool [45]. However, the interactions between multiple dependent requirements remain independent, and links to the model to automate traceability are rare. Further, the use of a Requirements Traceability Matrix (RTM) [27] is typically not systematically applied across the project team in a continuous or integrated way.

Model-based Systems Engineering. Model-based systems engineering (MBSE) is "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [46]. MBSE is aimed at replacing a document-centric approach with a model-centric approach via its full integration with SEP [46]. To reduce the miscommunication and foster the adoption of standard MBSE, SysML was developed as a standard modelling language for the unification of different modelling languages currently used in SE [27, 46]. A common data environment or a central data repository is also required. For example, 3DExperience and TeamCenter are two commonly used platforms supporting SEM activities in complex manufacturing sectors, and are designed to support the management of design and development activities in a single environment [47, 48].

In construction, single environments and enterprise platforms across the supply network are less common. The use of a CDE is growing. Software platforms such as Bentley's, ProjectWise provides a collaborative project environment, where its information management capabilities were developed explicitly for the construction industry [49]. Importantly IFC Standards, developed since the early 1990s, have also provided an open and standardized data model to enable interoperability between BIM software applications. IFC schema supports model-based interoperability [34], and like the SysML standard modelling language provides the means to translate different modelling formats. As a subset of the IFC schema, Model View Definition (MVD) is aimed to define parameters progress [34] and the Information delivery manual (IDM) concept was designed to facilitate interoperability, promote digital collaboration, and provide a basis of high-quality information exchange. However, MVD and IDM are still at an early stage of maturity.

Simulation and Analysis. Simulation and analysis are implemented at both the sub-system level (discipline-specific) and the systems level (multiple-discipline). It is therefore seen as essential to the design of multidisciplinary systems [27]. It enables the achievement of optimal system performance by closely linking the components of different disciplines, supporting the assessment and forecast of the dynamic status of a system and its components [27, 50].

In a model-based construction context, simulation and analyses are primarily undertaken at a discipline level before multiple discipline models are federated. Once federated, the main goal of analysis is the implementation of design coordination and quality assurance processes based on assessments of object interferences using clash detection toolsets. 4D and 5D simulation and analysis methods can be utilized for schedule planning and cost estimation. However, most 3D simulation and analyses methods are siloed activities, making it difficult to assess the dynamic status of the whole design.

Trade-off Analysis. The trade-off analysis is used to support decisions throughout SE process solving conflicts and satisfying both stakeholder requirements and constraints. The goals of trade-off analysis include achieving balanced requirement baselines, selecting the right functional architecture, and identifying the best design solution [27].

In the construction domain, trade-off analysis is known as "Cost/Benefits Analysis", and primarily involves the budget, schedule and quality objectives at the project level [27]. Cost/benefits analyses are most relevant during value engineering (VE) exercises. VE has become a standard practice in construction projects. However, VE is not always fully understood or well executed. Software applications to support collaboration during VE exercises and their outcomes provide a means to record decisions and quantities of elements, track proposed changes, and create an audit trail for later verification. The recent development of cloud-based model data management platforms to support VE provide the ability to access model information, and understand the elements, quantities, and costs being discussed. Yet, these tools encompass only a visual engine to view the model and do not provide the ability to simulate alternative scenarios to explore trade-offs between decision criteria and their impacts.

17.5 Discussion

As discussed in previous sub-sections, the overview of where BIM initiatives are concentrated or partially developed in terms of defined process and protocol, and technological initiatives is illustrated in Table 17.1. The three statuses including ● = growing maturity, ◘ = limited instances, and ○ = an evident gap in BIM processes protocols or technologies. The three statuses reflect the level of development of BIM related initiatives in construction. The ● status means that there are industry level or organizational level standards, guidelines or protocols developed but are as yet unproven across all sectors of the industry; e.g. ISO standards and PAS standards. ◘ status means that there are associated organizational level protocols and documentation reported by researchers in industry case studies. The ○ status means that there are no case studies or relevant industry or organizational documentation.

As a summary of the discussion of the literature presented in Sect. 17.3, Table 17.1 highlights a number of gaps and areas for applying SE approaches and SEM activities to achieve a more integrated approach to design, project delivery and structured information management throughout the life of the project and facility. The importance of project planning is emphasized in the publication of the recent ISO BIM Standards 19650. Despite the increased effort in construction on the development and implementation of process and data standards, a holistic systems approach is lacking. Accordingly, initiatives and guidelines present a fragmented approach to BIM implementation and industry confusion still surrounds methods to support greater levels of data and information quality and accuracy in project delivery. A key example highlighting deficiencies in current BIM implementation methods lies in SE approaches to development phasing specifying tightly couple configuration management activities and software applications for verification and validation activities. However, the linkages between building system decomposition and definition and the verification of requirements, functions, and objects together with their validation against client expectations are largely missing in the construction domain's approach to BIM implementation.

While the ● status represented in Table 17.1 represents growing maturity in some areas, the limited instances ◘ and number of gaps ○ outweigh the patchy development of a methodology to implement BIM to realize the value of building information throughout the life of the project and asset. Key areas for research to address include integrated approaches to (i) development phasing with specific emphasis on configuration management, (ii) a comparable systems engineering

Table 17.1 Systems engineering approaches versus BIM related initiatives

SE approaches		BIM methods, tools and initiatives	
		Process and protocols	Technologies
SEM activities			
Development phasing	Verification	●	●
	Validation	◘	◘
	Configuration management	○	○
Life-cycle integration	Project planning	●	○
	Project monitoring and control	●	◘
Systems engineering process	Requirement analysis Functional analysis and allocation Design synthesis, verification, and validation System analysis and control	◘ ◘ ◘ ○	◘ ○ ○ ○
SEM Enablers			
People	Integrated product teams	●	◘
Process and protocol	Systems integration process	○	○
	SE management plan	◘	○
	Requirements management	◘	◘
Technology	MBSE	◘	●
	Simulation and analysis	○	◘
	Trade-off analysis	○	○

Note ● growing maturity; ◘ limited instances; ○ gap process with particular need to address deficiencies in system analysis and control, and (iii) system management enablers including systems integration processes, requirements management, and trade-off analysis.

17.6 Conclusion

The work presented in this paper is an initial step in a larger research effort to understand the role and better utilize SE and SEM methods to support building information management through-life. Based on the review of current BIM practices and initiatives, a degree of disparate and fragmented approaches to BIM is evident across the different development phases. Gaps in a more systematic approach to BIM implementation and through-life information management are identified. Gaps relate to development phasing, lack of systemic approaches to product and process integration, and system management enablers. However, these gaps reflect a non-exhaustive review of current BIM standards, protocols, processes and documented case studies. Findings are therefore limited. Moreover, the interrelationships of the gaps identified are essential before proffering conclusions. Further, the level of maturity at an organizational level is difficult to estimate due to human factors and variations in BIM competencies. Industry perspectives of both SE, SEM, and BIM are therefore essential to extend this research. Current work is focused on undertaking a more detailed review and comparison of SE, SEM and BIM methods and enablers.

References

1. Hoeber, H., Alsem, D.: Life-cycle information management using open-standard BIM. Eng. Constr. Archit. Manag. **23**, 696–708 (2016). https://doi.org/10.1108/ECAM-01-2016-0023
2. Green, S.D., Newcombe, R., Fernie, S., Weller, S.: Learning Across Business Sectors: Knowledge Sharing Between Aerospace and Construction. The University of Reading, Reading (2004)
3. Whyte, J.K., Hartmann, T.: How digitizing building information transforms the built environment. Build. Res. Inf. **45**, 591–595 (2017). https://doi.org/10.1080/09613218.2017.1324726
4. Eastman, C., Eastman, C.M., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Wiley (2011)
5. Barlish, K., Sullivan, K.: How to measure the benefits of BIM—A case study approach. Autom. Constr. **24**, 149–159 (2012). https://doi.org/10.1016/j.autcon.2012.02.008
6. Love, P.E., Matthews, J., Simpson, I., Hill, A., Olatunji, O.A.: A benefits realization management building information modeling framework for asset owners. Autom. Constr. **37**, 1–10 (2014). https://doi.org/10.1016/j.autcon.2013.09.007
7. Jupp, J.R., Awad, R.: BIM-FM and information requirements management: missing links in the AEC and FM interface. In: Product Lifecycle Management and the Industry of the Future. Springer, Cham, pp. 311–323. (2017) https://doi.org/10.1007/978-3-319-72905-3_28
8. Anderson, A., Marsters, A., Dossick, C.S., Neff, G.: Construction to operations exchange: challenges of implementing COBie and BIM in a large owner organization. In: Construction Research Congress 2012: Construction Challenges in a Flat World, pp. 688–697. (2012) https://doi.org/10.1061/9780784412329.070
9. Jupp, J.R.: Cross industry learning: a comparative study of product lifecycle management and building information modelling. Int. J. Prod. Lifecycle Manag. **9**, 258–284 (2016). https://doi.org/10.1504/IJPLM.2016.080502
10. Boton, C., Rivest, L., Forgues, D., Jupp, J.: Comparing PLM and BIM from the product structure standpoint. In: IFIP International Conference on Product Lifecycle Management. Springer, Cham, pp. 443–453 (2016). https://doi.org/10.1007/978-3-319-54660-5_40
11. Blockley, D.I., Godfrey, P.: Doing it Differently: Systems for Rethinking Construction. Thomas Telford (2000)
12. Aslaksen, E.W., Delamare, M., Fehon, K., Godau, R., Knott, A., Kouassi, A., De Liefde, J.: Guide for the application of systems engineering in large infrastructure projects. INCOSE Infrastruct Work Group San Diego (2012)
13. Whyte, J.: The future of systems integration within civil infrastructure: a review and directions for research. In: INCOSE International Symposium, vol. 26, pp. 1541–1555 (2016) https://doi.org/10.1002/j.2334-5837.2016.00244.x
14. INCOSE.: Systems Engineering Handbook. A Guide for System Life Cycle Processes and Activities, v.3. INCOSE, Seattle, WA, USA (2006)
15. Sage, A.P., Rouse, W.B.: Handbook of Systems Engineering and Management. Wiley (2009)
16. Lindkvist, C., Stasis, A., Whyte, J.: Configuration Management in Complex Engineering Projects. Procedia CIRP **11**, 173–176 (2013). https://doi.org/10.1016/j.procir.2013.07.046
17. Morris, P.W.: The Management of Projects. Thomas Telford (1997)
18. Whyte, J., Stasis, A., Lindkvist, C.: Managing change in the delivery of complex projects: configuration management, asset information and 'big data'. Int. J. Proj. Manag. **34**, 339–351 (2016). https://doi.org/10.1016/j.ijproman.2015.02.006
19. Xu, X., Ma, L., Ding, L.: A Framework for BIM-Enabled life-cycle information management of construction project. Int. J. Adv. Robot. Syst. **11**, 126 (2014). https://doi.org/10.5772/58445
20. Zadeh, P.A., Wang, G., Cavka, H.B., Staub-French, S., Pottinger, R.: Information Quality Assessment for Facility Management. Adv. Eng. Inform. **33**, 181–205 (2017). https://doi.org/10.1016/j.aei.2017.06.003
21. Hedberg, T., Feeney, A.B., Helu, M., Camelio, J.A.: Toward a lifecycle information framework and technology in manufacturing. J. Comput. Inf. Sci. Eng. **17**, 021010 (2017). https://doi.org/10.1115/1.4034132

22. Lemberger, I.D., Erasmus, L.D.: Systems engineering management process maturity of South African manufacturing organisations. In: Management of Engineering and Technology (PICMET), 2014 Portland International Conference. IEEE, pp. 2371–2380 (2014)
23. ProRail, Rijkswaterstaat, Bouwend-Nederland, ONRI (2013) Guideline Systems Engineering for Public Works and Water Management, Version 3
24. Matar, M., Osman, H., Georgy, M., Abou-Zeid, A., El-Said, M.: A systems engineering approach for realizing sustainability in infrastructure projects. HBRC. J. **13**, 190–201 (2017). https://doi.org/10.1016/j.hbrcj.2015.04.005
25. de Graaf, R.S., Vromen, R.M., Boes, J.: Applying systems engineering in the civil engineering industry: an analysis of systems engineering projects of a Dutch water board. Civ. Eng. Environ. Syst. **34**, 144–161 (2017). https://doi.org/10.1080/10286608.2017.1362399
26. de Graaf, R.S., Voordijk, H., den Heuvel, L.: Implementing systems engineering in the civil engineering consulting firm: an evaluation. Syst. Eng. **19**, 44–58 (2016). https://doi.org/10.1002/sys.21336
27. Locatelli, G., Mancini, M., Romano, E.: Systems engineering to improve the governance in complex project environments. Int. J. Proj. Manag. **32**, 1395–1410 (2014). https://doi.org/10.1016/j.ijproman.2013.10.007
28. BSI (2013) PAS 1192-2: 2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling. The British Standards Institution
29. BSI (2014) PAS 1192-3: 2014 Specification for information management for the operational phase of assets using building information modelling. The British Standards Institution
30. Defense Acquisition University: Systems engineering fundamentals. Fort Belvoir, VA., USA (2001)
31. Xu, Y., Malisetty, M.K., Round, M.: Configuration management in aerospace industry. Procedia. CIRP. **11**, 183–186 (2013). https://doi.org/10.1016/j.procir.2013.07.052
32. FHWA: Systems Engineering for Intelligent Transportation Systems (2007)
33. Bolpagni, M., Ciribini, A.L.: The information modeling and the progression of data-driven projects. In: CIB world building congress. pp. 296–307 (2016)
34. Boton, C., Rivest, L., Forgues, D., Jupp, J.: A comparison of shipbuilding and construction industries from the product structure standpoint. Int. J. Prod. Lifecycle Manag. 11–2 (2018)
35. AIA: E202-2008 Building Information Modeling Protocol Exhibit. American Institute of Architects, Washington, DC (2008)
36. AEC (CAN) (September) BIM Protocol—Implementing Canadian BIM Standards for the Architectural, Engineering and Construction Industry Based on International Collaboration, V 2. CanBIM, Toronto
37. BIMForum (2015) Level of Development Specification. For Building Information Model, V 2015
38. AIA (2007) Integrated Project Delivery: A Guide. Version 1
39. ACIF, APCC (2014) Project Team Integration Workbook
40. OGC: Achieving Excellence Guide 5 - The Integrated Project Team (2007)
41. Browning, T.R.: Designing System Development Projects for Organizational Integration. Syst. Eng. **2**(4), 217–225 (1999)
42. Davies, A., Mackenzie, I.: Project complexity and systems integration: constructing the London 2012 Olympics and Paralympics Games. Int. J. Proj. Manag. **32**, 773–790 (2014). https://doi.org/10.1016/j.ijproman.2013.10.004
43. McArthur, J.J., Sun, X.: Best practices for BIM execution plan development for a public-private partnership design-build-finance-operate-maintain project. WIT Trans. Built. Environ. **149**, 119–130 (2015)
44. IBM Rational DOORS. https://au.mathworks.com/products/connections/product_detail/ibm-rational-doors.html. Accessed 27 Apr 2018
45. Product | dRofus. http://www.drofus.no/en/product.html. Accessed 27 Apr 2018
46. INCOSE T.: Systems Engineering Vision 2020. INCOSE-TP-2004-004-02), http://www.incose.org/ProductsPubs/pdf/SEVision2020_20071003_v2_03.pdf (2007)
47. What is Teamcenter? (or, Teamcenter explained)—Tata Technologies PLM Solutions. http://blog.myigetit.com/2016/08/17/what-is-teamcenter-or-teamcenter-explained/. Accessed 27 Apr 2018
48. DEXPERIENCE® Platform - Dassault Systèmes®. https://www.3ds.com/products-services/3dexperience/. Accessed 27 Apr 2018
49. ECS - ProjectWise. http://www.cadsolutions.com.au/projectwise.shtml?gclid=CjwKCAjwlIvXBRBjEiwATWAQIuTS3gvvdiuIopJk_VMP8Qd7gi9DT1o-294NovliMyI0e96bSebV2xoC4p0QAvD_BwE#. Accessed 27 Apr 2018
50. Sinha, R., Paredis, C.J., Liang, V.-C., Khosla, P.K.: Modeling and simulation methods for design of engineering systems. J. Comput. Inf. Sci. Eng. **1**, 84–91 (2001). https://doi.org/10.1115/1.1344877

18 A Lean Design Management Process Based on Planning the Level of Detail in BIM-Based Design

Petteri Uusitalo, Olli Seppänen, Antti Peltokorpi, and Hylton Olivieri

Abstract

Few construction companies apply the available lean tools and processes in an integrated manner when managing design. Additionally, various lean design management -tools and -processes have each their own strengths and optimal phases in project when to apply them. Earlier approaches in lean design management have not explicitly included level of detail of BIM-models in connection with planning methods in an appropriate manner. For example, the Last Planner System (LPS) is a planning and control system that uses collaborative social methods to get task dependencies and commitments from project stakeholders, but it does not provide any guidance what those tasks should be in a BIM-based process. On the other hand, location-based methods such as Location-based Management System and takt planning have provided guidance for scheduling production by using (LPS). Thus, by combining information from various sources we were able to define a location-based design management process using the concept of level of detail that can be integrated with LPS. The level of detail definition must start from the end-user of the information in each stage of the construction project. The model was co-created and validated in focus group meetings with design and construction companies. In future research we will run case-studies to test the model in real-life settings.

Keywords

Level of detail • Lean design management • BIM • Last planner system

18.1 Introduction

Lean design management (LDM) has contributed in achieving remarkable results related to adding customer value, reducing project cost and increasing collaboration among project parties (e.g. [1–3]. Various LDM-tools and -processes each have their own strengths and optimal phases in project when to apply them [4]. However, few construction companies apply the available lean tools and processes in an integrated manner and much greater benefits could be gained by combining the tools and processes to exploit the synergies between the various tools [5]. In this paper we look at LDM process from construction project perspective assuming early involvement in BIM-based design. The authors of this paper are aware of LDM's technical and social aspects, however, this paper focuses on technical side of both LDM and information flow.

The goal of this study is to propose a process for design management by applying optimal lean tools and processes for managing BIM-based design. The process aims to eliminate production delays caused by missing or incorrect design, as well as minimizing the rework required from the design team caused by excessive level of detail too early in the process [6]. The project's production strategy determines the milestones which are the basis for scheduling Level of Detail (LOD) of

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information. Each LOD is based on information requirements for various end uses of design: permit process, procurement, prefabrication or installation. The planning of LOD needs to be pull-based process pulling from a location-based production schedule.

18.2 Background

18.2.1 Lean Design Management

Lean construction and lean thinking in design management have been studied for several decades [3, 7]. Lean design management is a collection of lean methods, tools and social processes that can be used to facilitate design [5]. Lean principles promote a structured means to improve the entire system. Lean in design management reduces waste and improves value and information flow [8].

The information in design management process adds value when it is transparent and flowing [8]. A superb tool for improving information flow and transparency is the Dialogue Matrix (DM). DM promotes common understanding and facilitates dialogue especially in meetings between project party. The matrix identifies preconditions for design tasks and supports the pull logic. DM is structured to record questions from team members to other team members. Answers to those questions are systematically tracked in the matrix [9].

Another system to manage design as well as production is the Last Planner System (LPS). LPS is a well-known, collaborative, commitment-based, mainly social process, that integrates (1) *should*—setting milestones and strategy as well as specifying handoffs and identifying operational conflicts, (2) *can*—making work ready and re-planning when needed, (3) *will*—making promises in weekly work planning, and (4) *did*—measuring success with PPC (plan percent complete) and acting on reasons for task failure [10]. The four levels of LPS scheduling are also called, master schedule, reversed phase schedule, look-ahead schedule and weekly schedule.

LPS uses the collaborative social methods in reverse phase scheduling (also called pull planning) to get task dependencies and commitments from project stakeholders [11], but it does not provide any guidance what those tasks should be in a BIM-based process. On the other hand location-based methods such as Location-based Management System (LBMS) (e.g. [12]) and takt planning (e.g. [13, 14]) have provided more structure for scheduling production by using LPS. In takt planning, takt refers to the regularity or intervals of tasks performed. Hopp and Spearman [15] defined Takt as the unit of time within which a product must be produced to match the rate at which that particular product is needed. In other words, balancing the supply rate to match the demand rate. Originally Takt time was developed for manufacturing, but since it has been applied in construction production, the results have been promising (e.g. [16]).

18.2.2 Level of Detail in BIM-Based Design

BIMForum, the US chapter of buildingSMART international, has promoted reference standards of LOD (Level of Development) for the construction industry to yield. Earlier approaches in LDM have not explicitly included LOD of BIM-models in connection with planning methods. LOD is a process where building information models and the complexity of their components progress from the lowest level of conceptual representation to the highest level of detail based on component's use, for example for fabrication or installation needs [5, 17, 18]. However, determining an appropriate LOD for each element is only part of the solution, and so far it has been considered in isolation with limited connection to design schedules. The total time spent in modeling increases vastly when going from LOD to another [18]. If changes occur, those hours spent developing the model in too much detail ahead of the actual demand would be considered waste.

Another system to manage detailed design is a method called Location-based Design Management (LBDM). In LBDM detailed design is done in production determined clusters and is managed by location. LPS is used to manage design hand-offs. LPS pull scheduling is implemented so that milestones are formed by every location and a location-based production schedule is driving the design so that modelling and document production is using the same locations as construction and they are sequenced in the order of construction [5]. However, the method did not consider explicitly the level of detail of information. We argue that the combination of these two technical approaches could be a powerful way to enhance design management in a BIM-based project.

18.3 Method

The method is design science research where we attack a real world problem [19], which was identified as the poor connection between production and design schedules. The process was developed by combining earlier research and best practices related to BIM scheduling processes. The developed solution artifact is a lean design management process, which was validated in a focus group meeting. Focus group discussion is a sound method of collecting group of professionals with similar experience from the same field as well as unravel their shared views and understandings of the subject at hand [20]. The focus group participants were invited from 13 Finnish design and construction companies. Each member of the focus group held a managerial position. The feedback and the general consensus of the focus group related to design management process helped the authors to validate and refine the technical and social parts of the process.

To get oriented in current status of design management in Finland, the research team conducted eight semi-structured interviews for construction professionals from several Finnish construction companies. Each of the interviews was recorded and the average length of interviews was 50 min. Before every interview, the interviewees were briefed on the purpose of the study.

18.4 Current Design Management Processes and Challenges in Finland

The interviews revealed the following details about design management practices in Finnish construction industry: (1) LPS is extensively used in construction companies, (2) LOD specifications are known at the end of project, but forecasting when those specifications are needed in middle of project is hard. (3) Designers are frustrated at the current process where constructors demand too detailed design too early in the project. (4) Constructors are aware that they demand too much information too early in the project. (5) Designers question constructors early design demands. (6) Design demands are generally divided into work packages for procurement reasons but there is no common understanding among project stakeholders of what information is required for each procurement package.

18.5 LDM Overall Process

Technical system of the proposed LDM overall process is based on Last Planner's four phase scheduling. Different techniques and tools are used on different levels and they link to production schedule differently. The developed process is a combination of LOD, LPS, BIM, LBMS, LBDM and Takt scheduling. The novelty of the LDM Overall process is in scheduling LOD of building information models using location-based methods and then using LOD to implement LPS. Table 18.1 presents the main components and sources of the LDM Overall process.

Master design schedule. At this level, the design schedule is integrated with its equivalent counterpart—master schedule of production. Master design schedule is based on controlling the LOD of information and BIM models as well as linking the design schedule to production demands. Building permit, procurement, pre-fabrication and installation are associated with individual information demands. Those information demands need to be defined at the beginning of the project. Some of the systems and information demands can be location-based, in which case their demand-times are defined by locations.

Table 18.1 LDM overall process and its main components

Scheduling phase/component	Description	Original source
Master design schedule	Linking the production schedule to information needs and milestones based on project teams decisions and production strategy	LPS + LOD (BIM) + LBMS/TAKT + LBDM
Phase design schedule	Collaborative pull plan meetings	LPS + LOD (BIM)
Look-ahead schedule	Combination of look-ahead scheduling and DM	LPS + DM
Weekly schedule	Weekly meetings for the project team	LPS
Measuring success	PPC	LPS

The LOD requirement is presented in numbers as a function of time. The adjusted examples are stemming from the BIMForums LOD Specifications [21]. LOD 350 contains information demanded by installation and that information must be ready before the first task, related to that particular system, starts. LOD 325 contains information demanded by pre-fabrication and that is scheduled with a delay from LOD 350. LOD 325 is a coordinated and clash-free model. LOD 300 is a model where model-elements are flawless and their position accurately defined. In LOD 290 all the necessary model elements and their accurate geometry is in the model, but the elements are not yet positioned as accurately as required for LOD 300. LOD 200 contains preliminary designs. Each LOD and the documentation related for that particular LOD is attached to the master design schedule. The idea is to schedule the demand for information and coordinating that demand to construction process.

In order to tie this idea to a location-based schedule (such as takt or LBMS schedule), the following issues should be defined: (1) what information is demanded and when, (2) what information can be developed by locations, and (3) what information is developed by systems. Here, the information is mainly referring to BIM-based information, however information may also be presented in other forms than BIM. To each transition, from one LOD to another, a responsible organization is needed. An example would be an interface between a trade partner and a designer.

Figure 18.1 presents an example of linking design tasks to production tasks that are location-based in a takt or LBMS schedule. The example here is a design and manufacturing of pre-cast concrete elements and installing them from floors 2 to 6. The information needs are different in each phase. For example installer requires more detailed design in installation phase than pre-cast company for making a bid in procurement phase. Before yellow area (LOD 290) is pre-planning. Procurement-level information (LOD300) is developed during the yellow area. Both of these areas are designed system-based (the LOD milestone happens at the same time for each milestone). Design for prefabrication (LOD 350, blue area), can continue location-based and the design can become a part of takt train at this point. By the time installation starts in the first red square the design must contain all necessary information for installation (LOD 400). Each LOD milestone is used as a phase scheduling milestone, and the lower part of the schedule can contain design tasks that are not location-based but have dependencies with the location-based design tasks—red arrow lines indicate examples of dependencies between other tasks.

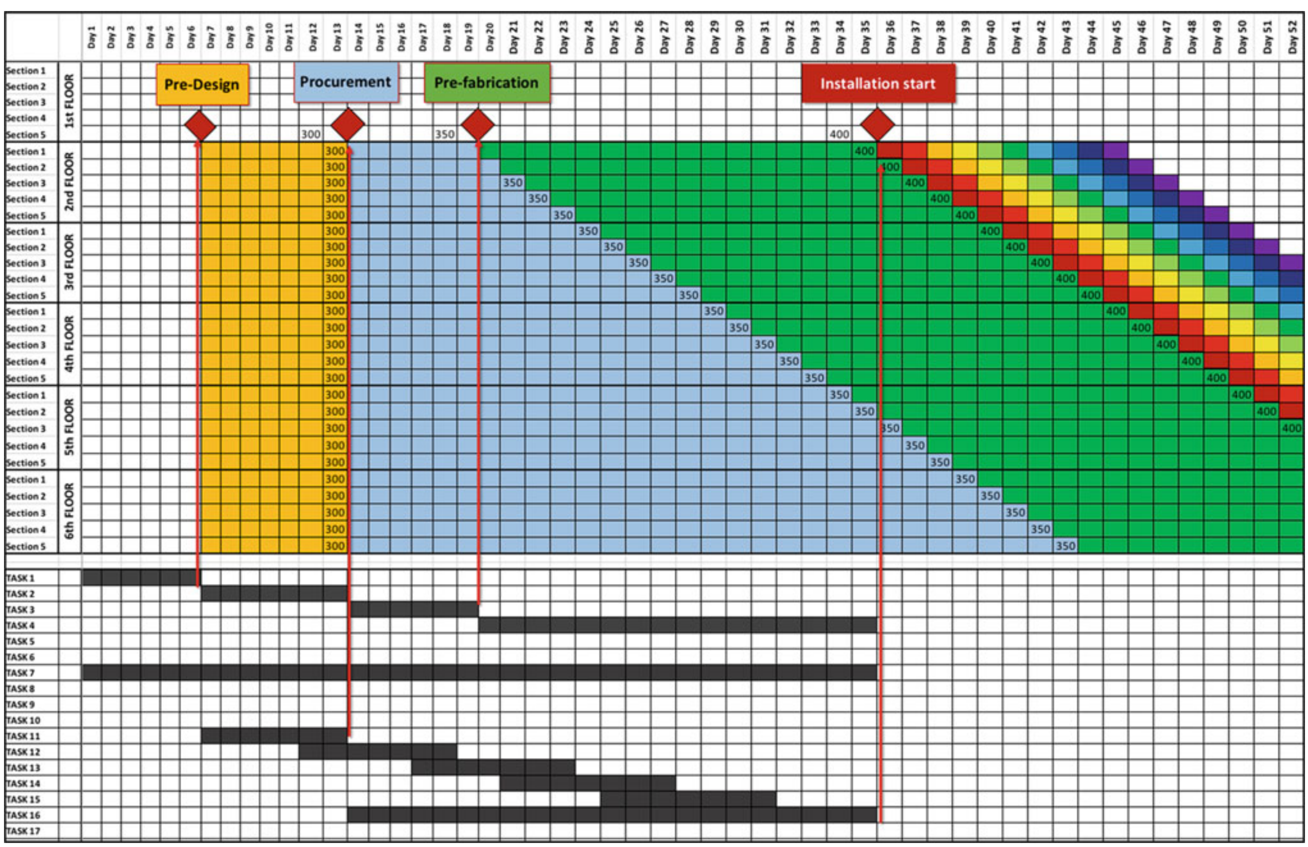

Fig. 18.1 Linking the design LOD's with the production takt time. Vertical axis presents locations and horizontal axis presents time

Phase design schedule. The basis of phase design schedule is performed as a standard LPS reversed phase schedule. LOD-demands from master design schedule act as milestones. These milestones are either one system or several interconnected systems, such as structural frame work, interior finishes and HVAC coordinating. Reversed phase schedule is performed by starting to pull from finished product. Project team consist of general contractor, trade partners and the designers.

First, the project team needs confirmation about mutual agreement of the final result of the phase (e.g. [22]). The final result embodies of what information demands are needed at the end of the phase. Second, start from the end and move towards the beginning. When placing a post-it note, the person requests information from the other project party. The focus is to progress based on information demands rather than listing each party's design tasks. The objective of this procedure is to delete unnecessary tasks. The results from these unnecessary tasks are not demanded by anyone.

A complementing tool to resolve task dependencies, would be Design Structure Matrix (DSM). DSM is a tool where tasks are defined, their relation and information need from other tasks, and from that information an optimal task sequence is indicated in the matrix [23, 24]. Although DSM and LPS have overlapping properties, and the fact that DSM is more technical tool and lacking the social aspects of LPS, the use of both tools would add to information flow inside the project.

Project team needs to resolve if each location where takt time work starts counts as a milestone. This resolution depends on the decision made on the master design schedule level—what parts of the design is performed location-based. Similar to production, the phase schedules of each similar milestone are likely to be very similar, so pull scheduling could focus in detail on just one milestone and then the team can determine any differences between locations that would necessitate variations from the template phase schedule.

Look-ahead design schedule. The basis of this phase conducts standard LPS look-ahead scheduling. The overall process adds more structured way of tackling emerging obstacles by combining the use of DM into this phase. All the questions, asked from other project party, are then documented using DM. Answers to those questions will turn into tasks for the answering party. Generally questions are equivalent to obstacles in LPS's backlogs.

Validation. Authors of this paper presented the LDM Overall process in the focus group meeting for validation. The focus group shared couple of concerns. The first concern was how the Overall process would operate with different project contract types where level of detail requirements for different phases are very different (e.g. fixed price requires almost completed design at procurement). The solution would be to have a project-based specification of LOD requirements at each step. The second concern was how to choose those design tasks that should be scheduled location-based and how to choose those design tasks that should be dealt based on a system. This is an open research question which can be addressed in future research. In general, all the focus group participants were ready to accept the concepts and liked the schedules simplicity and the visual performance. The model conceptually answers the requirements. However, implementing a full design schedule is required in future research in order to understand its usability in practice.

18.6 Conclusion

Good best practices were found from case-projects, interviews and earlier research, but each one only solved a part of the problem. By combining information from various sources we were able to define a location-based design management process using the concept of LOD that can be integrated with location-based methods and LPS. The LOD definition must start from the end-user of the information in each stage of the construction project. For example, to start procurement we do not need final positions of each building information model element, but we need a way to estimate the quantity of work and risks to come up with the price estimate. For pre-fabrication we need fully coordinated building information model to ensure that the pre-fabricated parts fit without field rework. For installation the BIM-based design must include all the necessary details required by the workers. Design for pre-fabrication and installation can be location-based and can be pulled by production schedule.

The overall design schedule is partially activity-based and partially location-based. The LPS is used to elaborate the design schedule and get to the level of commitment of individual designers and verify starting data requirements and required decisions for each design task. In this way the process involves several stakeholders: the owner, architect, engineers, and the general contractor as well as trade contractors. The model for LDM Overall process was co-created and validated in focus group meeting with engineering and construction companies. In future research we will run case-studies to test the model in real-life settings.

Related to the design management challenges revealed from the interviews of Finnish construction professionals, the LDM Overall process argues to invalidate them. Since LPS is already extensively used in Finland it would be fruitful to intensify design management to collaboratively manage the timing and the level of details and designs in a project. If every project party would commit to their task, there would be no need for constructor to demand too detailed design too early in project. The LDM Overall process steers the project stakeholders to thoroughly, and in a structured way, discuss upfront about the information need and its interdependency with building information models related to each procurement package, thus increasing common understanding among the project team. The Overall method also has a potential for removing waste in current BIM modelling process by scheduling accurate LOD of building information models based on pull from production demands. When committing to the scheduled LOD-based milestones, project team has the potential to decrease the need for modelers to advance their models into too detailed level based on assumptions thus facing the risk of possible remodeling when changes occur.

References

1. Boukendour, S., Hughes, W.: Collaborative incentive contracts: stimulating competitive behaviour without competition. Construction Management and Economics **32**(3), 279–289 (2014)
2. Pishdad-Bozorgi, P.: Case studies on the role of Integrated Project Delivery (IPD) approach on the establishment and promotion of trust. Int. J. Constr. Educ. Res. **13**(2), 102–124 (2017)
3. Tilley, P.A. (2005), "Lean design management: a new paradigm for managing the design and documentation process to improve quality?", In Proceedings of the 13th International Group for Lean Construction Conference, Sydney, Australia, pp. 283–295
4. Franco, J.V., Picchi, F.A. : Lean design in building projects: guiding principles and exploratory collection of good practices. In Proceedings of the 24th annual conference of the International Group for Lean Construction, Boston, MA, USA, pp. 113–122 (2016)
5. Uusitalo, P., Olivieri, H., Seppänen, O., Pikas, E., Peltokorpi, A. : Review of lean design management: processes, methods and technologies. In: Proceedings of the 25th Annual Conference of the International Group for Lean Construction, Heraklion, Greece, pp. 571–578 (2017)
6. Said, H.M., Reginato, J.: Impact of design changes on virtual design and construction performance for electrical contractors. J. Constr. Eng. Manag. **144**(1) (2017)
7. Koskela, L., Ballard, G. and Tanhuanpää, V.P. (1997), Towards lean design management. In: Proceedings of the 5th annual conference of the International Group for Lean Construction, Gold Coast, Australia, 13p
8. Reifi, El, Emmitt, S.: Perceptions of lean design management. Archit. Eng. Des. Manag. **9**(3), 195–208 (2013)
9. Bølviken, T., Gullbrekken, B., Nyseth, K.: Collaborative Design Management. In: Proceedings of the 18th Annual Conference of the International Group for Lean Construction. Haifa, Israel (2010)
10. Ballard, H. G.: The last planner system of production control. Ph.D. Dissertation, Civil Engineering, The University of Birmingham, Birmingham, 192 pp (2000)
11. Kerosuo, H., Mäki, T., Codinhoto, R., Koskela, L., Miettinen, R.: In time at last—Adaption of last planner tools for the design phase of a building project. In: Proceedings of the 20th Annual Conference of the International Group for Lean Construction. San Diego, CA (2012)
12. Seppänen, O., Modrich, R., Ballard, G.: Integration of last planner system and location-based management system. In: Proceedings of the 23rd Annual Conference of the International Group for Lean Construction. Perth, Australia, pp. 29–31 (2015)
13. Frandson, A.G., Seppänen, O., Tommelein, I.D.: Comparison between location based management and takt time planning. In: Proceedings of the 23rd Annual Conference of the International Group for Lean Construction (pp. 28–31). Perth: IGLC (2015)
14. Seppänen, O.: A comparison of takt time and LBMS planning methods. In: Proceedings of the 22nd Annual Conference of the International Group for Lean Construction. Oslo, Norway, 25–27 Jun 2014, pp. 23–27 (2014)
15. Hopp, W.J., Spearman, M.L.: Shop Floor Control, p. 495. Factory Physics, Waveland Press, Long Grove, IL (2008)
16. Frandson, A.G., Tommelein, I.D.: Takt time planning of interiors on a Pre-Cast hospital project. In: Proceedings of the 24th Annual Conference of the International Group for Lean Construction. Boston, MA, USA, 20–22 Jul 2016 (2016)
17. Abou-Ibrahim, H., Hamzeh, F.: Enabling lean design management: an LOD based framework. Lean Constr. J. 12–24 (2016)
18. Leite, F., Akcamete, A., Akinci, B., Atasoy, G., Kiziltas, S.: Analysis of modeling effort and impact of different levels of detail in building information models. Autom. Constr. **20**(5), 601–609 (2011)
19. Hevner, A., Chatterjee, S.: Design science research in information systems. Design research in information systems, pp. 9–22. Springer, US (2010)
20. Hennink, M.M.: Focus Group Discussions. Oxford University Press, Oxford, UK (2013)
21. BIMForum: 2017 Version of the Level Of Development Specification. http://bimforum.org/wp-content/uploads/2017/11/LOD-Spec-2017-Part-I-2017-11-07-1.pdf (2017). Accessed 3 Dec 2017
22. Tsao, C., Hammons, G.: Learning to see simplicity within a complex project through the lens of Pull Planning. In: Proceedings of the 22nd Annual Conference of the International Group for Lean Construction, Oslo, Norway, 25–27 Jun 2014, pp. 751–762 (2014)
23. Huovila, P., Koskela, L., Lautanala, M., Pietiläinen, K., Tanhuanpää, V.: Use of the design structure matrix in construction. Lean Constr. 417–425 (1997)
24. Steward, D.V.: The design structure system: a method for managing the design of complex systems. In: IEEE Transactions on Engineering Management, **EM-28**(3), 71–74, (1981)

Part II

Cyber-Human-Systems

19 The BIMbot: A Cognitive Assistant in the BIM Room

Ivan Mutis, Adithya Ramachandran, and Marc Gil Martinez

Abstract

Today, collaborative environment method is of with widespread use among project stakeholders. They benefit project planning in a variety of ways, including by enabling team members to build stronger relationships, enhance communication, and perform efficient planning, to name several. The collaboration occurs in sessions that immerse stakeholders in an environment commonly referred to as a BIM room—a shared space that enables project stakeholders, such as architects, general contractors, structural and MEP trades, and other specialized knowledge actors, to physically or virtually meet and to establish constant presence. The BIM room is a medium for stakeholders (BIM-room participants) to more accurately and efficiently make informed decisions on end to end construction problems. This project is aimed at investigating the use of information technology as a mediating mechanism to facilitate sharing meanings of expressions and to assist stakeholders in effectively finding relevant information that connects to their intent in the BIM-room. This research proposes the creation and implementation of a cognitive assistant to project stakeholders: BIMbot. The BIMbot is an agent that will have the ability to simulate a conversation or a messaging exchange with a present actor. From the actor-BIM-bot exchange and having an order, command, or request, BIMbot will carry common functions for the actors within the BIM room like retrieve the current version of family-objects of the BIM; load, filter, and view section(s) of interest; automate object placement; etc. BIMbot is designed to produce significantly more efficient interaction of collaborative meetings in the BIM room.

Keywords

Cognitive intelligent agent • BIM room • Pre-design phase • Generative models

19.1 Introduction

When Building Information Modelling (BIM) was first introduced, few could have imagined the large impact that this term would reach in the years that followed. BIM has gone from being a barely known academic development to capturing the attention of the whole architecture, engineering and construction (AEC) industries [1] (1). But beyond technology, BIM unfolds a whole new set of design and construction capabilities with regard to traditional practices (2). These workflows encourage all project stakeholders to collaborate from initial design stages, creating changes in roles and relationships amongst them. Therefore, BIM can be better understood as a process towards innovative practices rather than a mere set of tools and technologies. Today, designers and construction stakeholders from several disciplines are required to collaborate together in temporary teams [2]. The communication and collaboration is key from the early stage normally called pre-design phase, where the design team can set new relationships faster. This exchange is described in Fig. 19.1. Then, BIM aids an integrated design and construction procedure that needs to be supported by Integrated Project Delivery (IPD). Its methods consist of carrying out early collaboration amongst the stakeholders who are involved in the project. The logical

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way of thinking would lead us to claim that the teams are more confident when computer tools embrace coordination and collaboration [2]. Nevertheless, the principal proposition in the academic and professional literature on BIM are seriously concerned on issues involving the creation, exchange and management of data; shared geometries and software interoperability, which are valuable for getting teams to work in shared computing environments. In this paper, our attention is focused on the dialogue and conversations that constitute collaboration, especially those in technologically supported environments. Dossick and Neff [3] carried out a study to conclude that clean technology, although highly contributes to a better project documentation, planning, scheduling and also providing the project with data-rich, object based intelligent and parametric digital representations of the facility, still brings a lot of inefficiencies with the dynamic and those "messy" activities needed to support problem-solving [2].

This is where our approach takes part in the BIM process. An artificial cognitive assistant called BIMBot, a cognitive assistant that approaches to the requirements of messy talk since it has been created as an active and interacting tool. The idea is to incorporate this artificial assistant to the team members of the collaboration team. We hypothesize that this tool will fulfill our goal to reduce the inefficiencies in the pre-design process, since the stakeholders will be able to shorten the actions of the conversations by interacting with the cognitive agent which will rapidly respond to queries and actions, by retrieving those tasks in order to survey require tasks as a result of that messy talk.

To implement a cognitive assistant, a qualitative research method will be carried out to obtain the correct data. This is performed since we want to understand meanings of different stages, tools, and opertaions of the BIM process. Also, we wish to collect information through describing and understanding experience, ideas and beliefs of BIM experts that can add value to our collected data. To develop inferences and collect data, we review a myriad of research papers, BIM magazines, BIM standards and other experiences that we can find in the web. Reviewing papers will certainly point us in the right direction to arrive on the right inferences but it will not help us in gathering the data we need for this research. This is because no real conversations (data) in huge volumes are recorded in research papers. As mentioned, pre-design phase is studied and focused on the clashes/interferences phase. In Table 19.1 is described the most frequent ones in BIM room. So once the BIM software detects those interferences, the BIM participants involved in the BIM meetings, usually resort to solving interferences verbally. It is the verbal conversations during the pred-design phase that act as data for BIMBot. Therefore, by providing this data to the BIMbot, the final solution will enable to support another similar discussion in the near future, either in the same team or another project. As a validation, we will propose to set up an innovative experience in

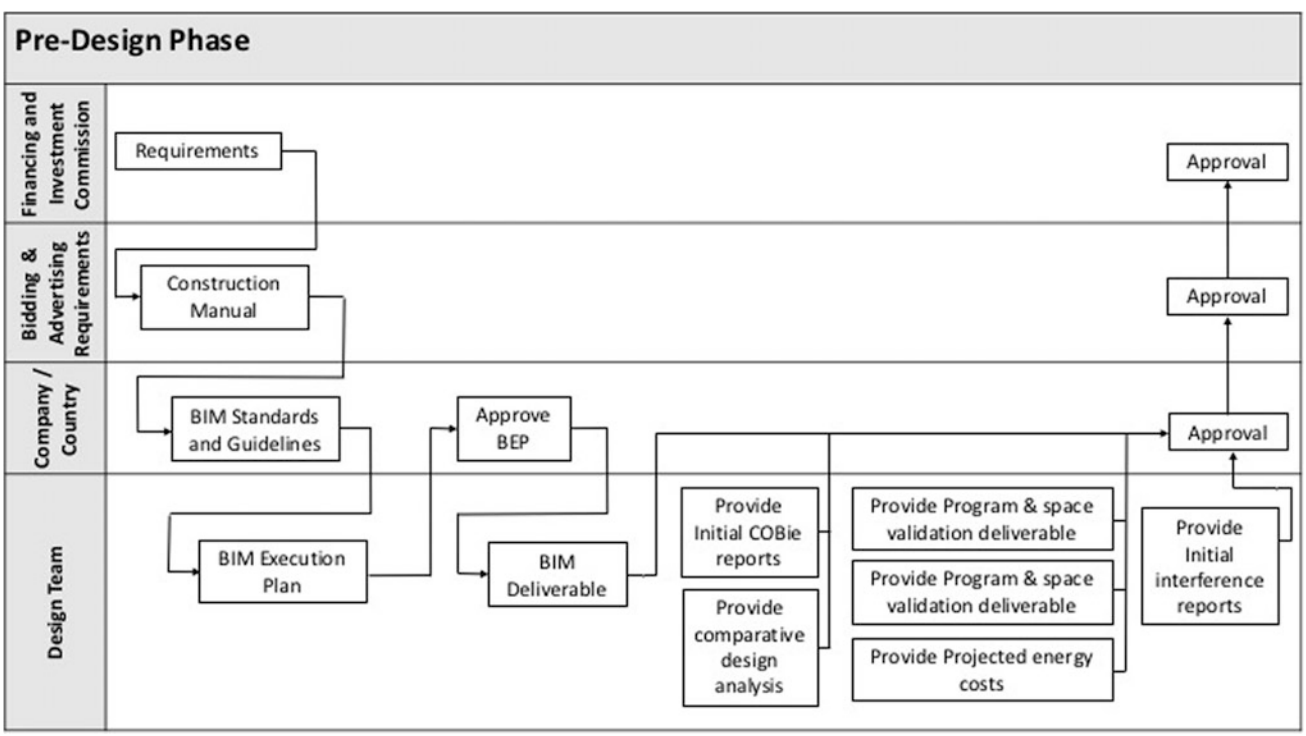

Fig. 19.1 Based on Georgia Tech BIM requirements for architects, engineers and contractors

Table 19.1 Level two interferences. Georgia Tech

Casework	Electrical fixtures, devices, conduit, raceways, homeruns, cable trays, piping systems and accessories
Furnishings	Electrical fixtures, devices
Structure (columns, beams, Framing, etc.)	Specialty equipment, electrical equipment, fixtures, devices, conduit, raceways, homeruns, cable trays, piping systems and accessories
Ductwork and piping	Floors, specialty equipment, electrical equipment, fixtures, devices

the BIM room, so that we will carry out a selection of a design team to work closely with our BIMbot. Thus, they will be able to check the ability of this cognitive assistant and see whether or not it is a useful tool to incorporate in a regular BIM room. So that, it will let the assistant find the most relevant information from any other conversation. The cognitive assistant that we have developed is currently capable of retrieving information on desired models. This prototype is the first version of many to follow in the aim of achieving our final goal which is elaborated in Sect. 19.5.

19.2 Related Work

The construction of a project is a complex process that involves activities of various nature carefully organized in time and space. If building information modelling wanted to represent the building process in all its depth, it would have to integrate the work of engineers, architects, contractors and all disciplines involved. This was the main reason why BIM software titles started to develop own versions focused on a certain area of the AEC industry. Several research papers have been focused on the collaboration and coordination among the actors involved in a construction project. This collaboration is carried out in a natural environment called BIM room [4], which is a unique virtual place, accessible and operable from the internet. The main purpose is to manage the BIM model, the information that the BIM generates (graphic and non-graphic), the evolutionary processes of the project, the roles of the agents involved and their communications in a structured and directional way towards the achievement of the project's objectives [5].

The CDE (Common Data Environment) [2] provides a collaborative environment where teams can share their work and files for the Information Management process. The CDE could consist of more than one system configured to meet the requirements defined in BS 1192: 2007 (United Kingdom). This document presents the management process within the CDE necessary to facilitate the delivery of the necessary project information. As it is a unique environment where different disciplines, interests and collaborative actions converge, this system should facilitate interoperability between the different software platforms and be based on standard formats of free access.

Researchers quickly realized about the lack of efficiency on the BIM room and studied the integration of technology into the collaboration by using ethnographic observation and one-on-one interviews with project participant [3]. They also introduce the concept of Messy talk, which is defined as the interstitial dialogue between and after formally organized agenda items. Finally, it is understood that although technology is a useful tool that contributes to a better project documentation, planning, scheduling and also providing the project with data-rich, object based intelligent and parametric digital representations of the facility, still brings a lot of inefficiencies with the dynamic and those "messy" activities needed to support problem-solving [2]. Thus, an artificial cognitive agent to develop and enhance this task is needed if it is created taking into account the previous work conclusions.

19.3 Methodology

This section highlights the reason for choosing to implement our cognitive assistant in Pre-design phase (Sect. 19.3.1) and the architecture of our cognitive assistant (Sect. 19.3.2).

19.3.1 Pre-design Phase

The collaboration begins in the pre-design phase, where stakeholders are involved in an environment commonly named BIM-room. Project stakeholders are architects, general contractors, structural and MEP trades, among other specialized knowledge actors, who physically or virtually share the same space to establish constant presence. In this phase, it is discussed several issues and clashes that may occur among all the stakeholders, who communicate during the sessions through a conversationally verbal exchange. Nevertheless, this communication is not yet well supported by BIM technology, as indicated by Dossick and Neff in their paper [3], that still needs to be adapted to the concept of "messy talk" carried out in the pre-design phase. Thus, based on the lack of efficiency in the discussion phase, where drawings or notes are still used instead of technology, BIMbot will indeed serve as a tool to put technology and collaboration together. Therefore, our first approach is carried out in the pre-design phase, firstly starting on the clashes and interference discussions, as it is explained and illustrated below.

19.3.1.1 Conflicts/Interferences at the Pre-design Phase

The first step of our approach is to get familiarized with the current practices of IPD and the clashes or interferences that normally arise among the design team in the pre-design phase. IPD, is a project delivery method distinguished by early collaboration between cross-functional teams through all phases of design, fabrication, and construction. By entering this type of contractual agreement, teams are able to collaboratively harnesses the talents and insights of all participants to optimize project results, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction. The entire process, from concept to construction, is defined by early substantive engagement by all key stakeholders.

In this process three levels of interferences were identified [6]. In the first level are the ones considered critical to the design process. These interferences have been assigned the highest priority and should be rectified within the model as soon as possible. In the second level are those which are considered important to the design and construction process [6]. These interferences have been assigned the greater priority and should be rectified during project meetings during design. Lastly, the interferences that belong to the third level are reported interferences that, while are considered important to the correctness of the model, will generally be changing on a regular basis throughout the design and construction process. These interferences have been assigned a lower level of priority but should be rectified before the phase submission of the models [6]. Thus, we conducted an analysis of the second level of interferences since they are marked as the greatest priority. The most frequent clashes cases are found in Table 19.1, where each row works independently and means that normally the elements in the first column get in conflict with the elements of the second. With this analysis, the aim of providing data in a Q&A format to the BIMbot will be achieved.

19.3.2 Cognitive Agent—BIMBot's Architecture

Rule based models are easy to create but they do not work well as they function purely on pattern matching. If there are no patterns found to a given query, then Rule based bots do not generate a response. In addition, as pattern matching functions on rules (like first order logic rules), it becomes a tedious task to write rules to cover all scenarios [7]. As this was seen difficult, introduction of Machine Learning paved way to create intelligent bots. The bots are called intelligent as they have the capability to learn from data or previous conversation. There are two type of models that make use of Machine Learning and exploit its advantages. (1) Retrieval-based models, (2) Generative models. Retrieval-based models do not create any new responses. These models generally select a response from a pool of responses based on the question it received. On the other hand, Generative models are more intelligent. They can create their own responses based on the question they receive. Generative models learn the structure of sentences through training. Generative models require huge amount of data for training purposes. If these models are trained, they tend to outperform Retrieval based models when it comes to seeing queries that have not been seen before [7]. Currently, majority of the research is on Generative models using Deep learning techniques. This is because Deep learning architectures like Sequence to Sequence are apt for text generation. Inspired from the success of generative models, we have created our cognitive agent using a generative model along with a rule-based model which runs on pattern matching [8, 9]. The upcoming sections will elaborate on four major components of BIMBot's architecture: (1) Corpus (2) Neural Machine Translation(NMT) (3) Rule-based Model (4) NLP Engine (Fig. 19.2).

19.3.2.1 Corpus

One of BIMBot's important component is Corpus, which is a collection of texts/data in an unstructured format. It is pivotal for the architecture as it acts as a source of training data for BIMBot. There are two steps involved in building the right corpus for our cognitive agent. The first one was gathering data for the Corpus and the last one being, cleaning the gathered data.

The first step is to source data for training purposes and they are as follows: (1) Cornell Movie Corpus, (2) Reddit and (3) BIM room conversations (from different Civil companies). The reason to aggregate data from three different sources is to have both open domain knowledge (general knowledge) and to have closed domain knowledge (BIM related knowledge).

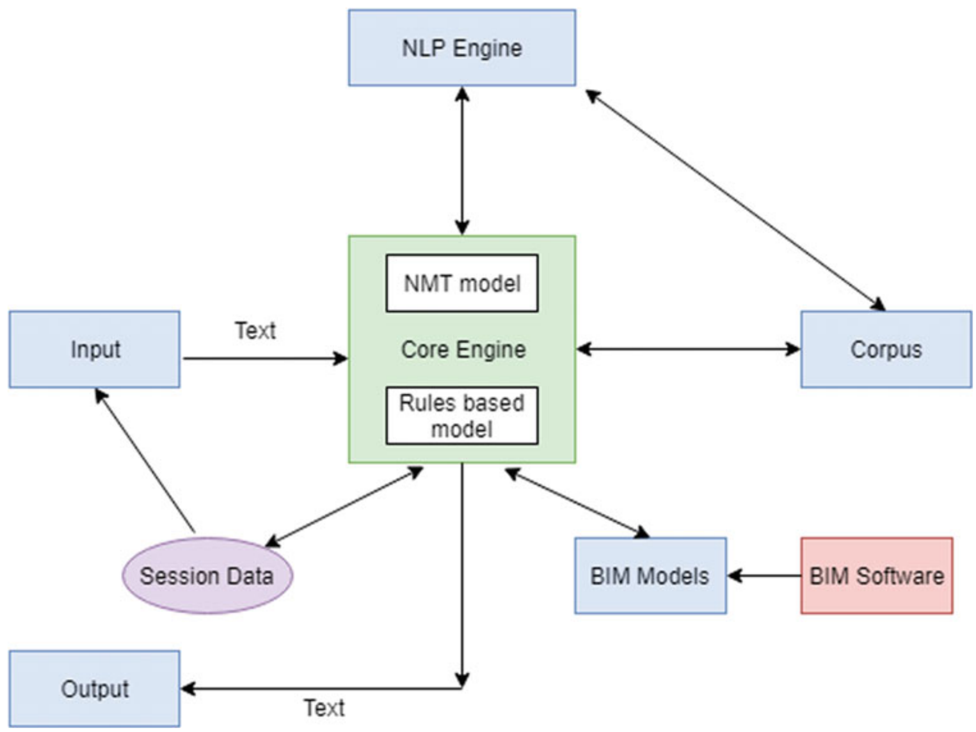

Fig. 19.2 BimBot's architecture

Table 19.2 Cleaned data—Question/Answer format

Question	Answer
I cannot ignore the verdict of my council	Surely you can do anything you want
Can I go out to play?	After you are done with your work

Moving to the last step of our two-step process, the data when first gathered is usually unstructured. A thorough cleaning of data is done before the data is used for training the cognitive agent. The cleaning process happened in two steps. The first step was to structure the sentences in Question/Answer format as described in Table 19.2. Separate python scripts were written for reddit dataset and Movie Cornell Dataset to structure the data. Following this step, we identified profane words in the structured data. Sentences with such words (profane words) led us to truncate the Question/Answer pair. This was done to ensure that the cognitive agent responded in a polite, patient manner and not otherwise.

The BIM room conversations were acquired in two formats: (1) Text format and (2) Audio Format. We converted the audio format to text by using IBM Watson's speech to text web application. After converting the audio clips to text, we aggregated the data from both the formats to manually structure them in Question/Answer format. This was done manually because the quantity of data was low and we wanted to carefully handle sensitive information, should there be any.

19.3.2.2 Neural Machine Translation - Generative Model

For this research purpose, we have implemented BIMBot, our cognitive agent, through Neural Machine Translation (NMT) which falls under the umbrella of sequence to sequence models [10, 11]. Neural Machine Translation is also known as encoder-decoder architecture. Though Neural Machine Translation model differ in terms of architecture, we have gone with the natural choice of implementing BIMBot's encoder and decoder using Recurrent Neural Network (RNN) [12]. Usually, encoders and decoders are implemented using RNNs. Humans have persistence when it comes to thoughts and thinking. When humans make decisions, it is usually based on their previous thoughts. Conventional Neural Networks don't function like the humans do and this is a major drawback. With the introduction of Recurrent Neural Networks(RNN), this issue is addressed. RNNs have loops enabling them to hold information.

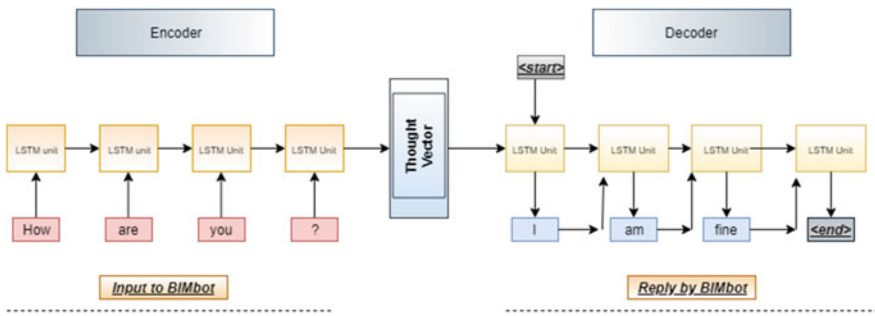

Fig. 19.3 Sequence to sequence model

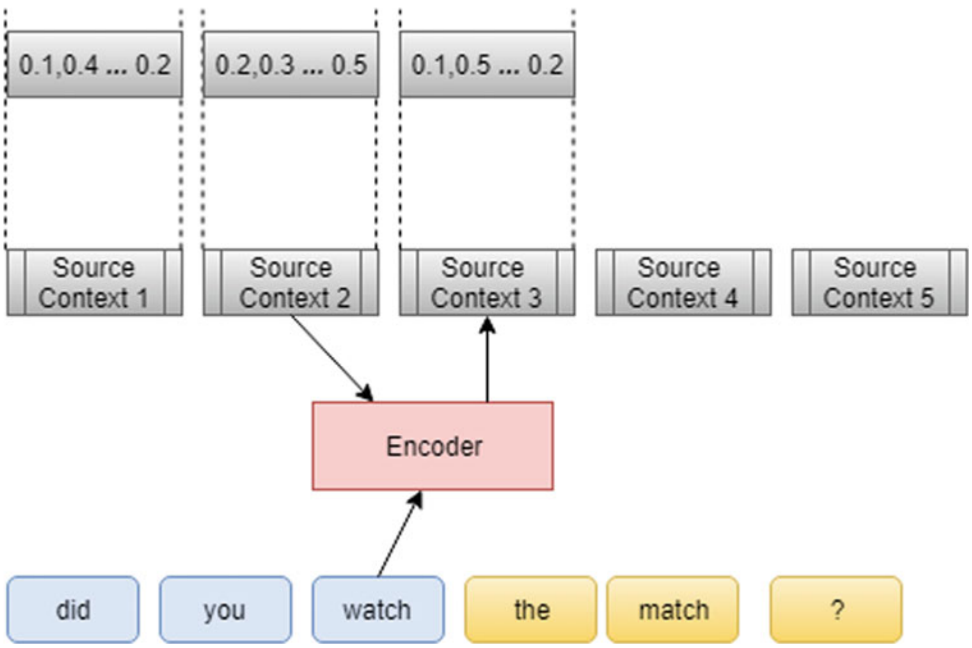

Fig. 19.4 Encoder phase

RNN models vary in terms of (1) "directionality—unidirectional or bidirectional", (2) "depth—single or multi-layer" and (3) "type—a Long Short-term Memory (LSTM), or a gated recurrent unit (GRU)" [13]. For our research, keeping long term dependencies in thoughts, we have opted for an RNN model which is bi-directional, multi layered and has LSTM units. Long term dependencies are important because, as the context/conversation between actors and BIMBot increases, BIMBot should understand the context to generate appropriate responses [14–16] (Fig. 19.3).

The NMT system of BIMBot reads the source sentence with the help of an encoder to build what is called a thought vector as explained in [13]. The thought vector is a "sequence of numbers that represents the sentence meaning". This thought vector is then processed by a decoder to produce the correct response.

Decomposing this learning process, there are two phases involved: (1) Encoder and (2) Decoder. In the Encoder phase (Fig. 19.4), the source sentence from the Corpus is sent to the Encoder to generate "Source Context using the present word and the previous Source Context". The Source Context represents the words in numbers. Each word has a Source Context which is associated with a series of numbers as illustrated in Fig. 19.4. The representation of numbers to a word is done with the help of an embedding layer. The embedding layer is built on words from the Vocabulary file across higher dimensions (Sect. 19.3.3.4). Words that have similar/common property are found to be on the same dimension of space. For example, parts of speech of words can be found on the same dimension while gender can be found on another dimension.

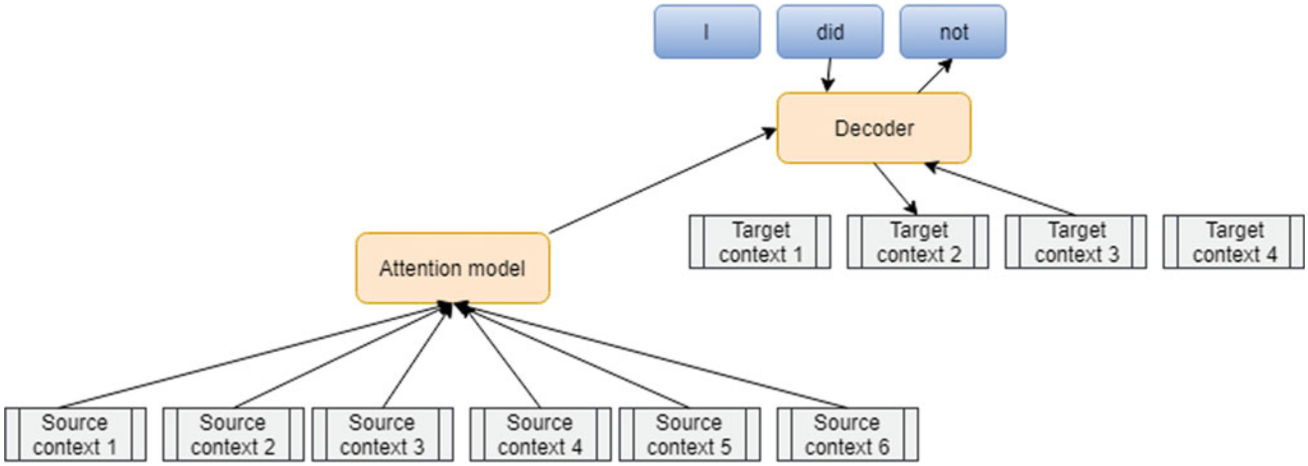

Fig. 19.5 Decoder phase

The target words/responses are generated in the second phase of this process. This is achieved with the help of Target Context, Source Context and the previously generated word (Fig. 19.5). The Target Context contains the status of text generation while the Source Context along with the Attention Model contains the representation of source sentence. The Attention Model calculates attention weights as described in [17] for the Source Context. This representation is called as memory.

At each time step, the Target Context is used to select which part of the memory must be read. This then enables the NMT model to concentrate on the required memory to create appropriate response. The text generation stops when the decoder uses an End-Of-Statement tag [18].

19.3.2.3 Rules-Based Model

The rules-based model is an elaborate text-generation engine which looks for patterns in the input text from the actors "which can serve as hooks to be manipulated and recombined into its responses" [19].

BIMBot offers features like searching IFC models and retrieving IFC mode properties. To have such features, it is necessary to include a rule-based model. Using pattern matching, appropriate rule scripts (majorly based on first order logic) are triggered/called to retrieve properties from IFCxml files. We have created our own version of the IFCxml which replicates the standard IFCxml files. This is done because, IFCxml files cannot be accessed outside BIM software environment. In addition, this provides the capability of addition/deletion of properties at will. Our version of the IFCxml files sit in BIM models which will be accessed by BIMBot on demand to retrieve a model's property/properties.

19.3.2.4 Natural Language Processing(NLP) Engine

The NLP engine consists of tokenizer which splits the texts/data from Corpus into words [20]. The tokenizer helps to create the vocabulary file which is used by BIMBot's core engine during its learning/inference phase.

19.4 Implementation and Experimentation

In our experimental setup, there are two major phases. The first phase being, training, is when our core engine gets trained using the training data from Corpus. The final phase, Inference or testing, is when we test how BIMBot fares against unseen input.

19.4.1 Training

In Sect. 19.3.2.2, we have elaborated on the learning methodology practiced by our cognitive agent to learn one example. Training is the process of repeating the aforementioned procedure for all the conversations in the Corpus.

To train the cognitive agent, we concentrated on two major aspects: (1) Training Data (2) Epoch. The duration/learning will depend on both the aspects. For the cognitive agent to learn diverse topics it is necessary to provide huge volumes of

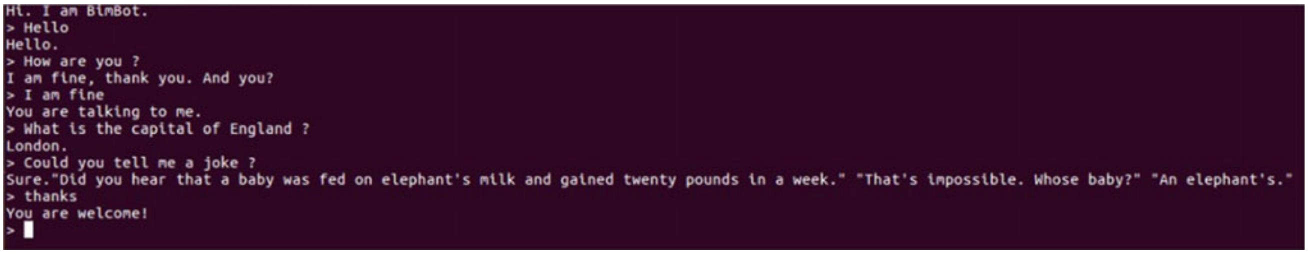

Fig. 19.6 General converstions with BIMBot

data. For the purpose of this experiment, we have gathered around 300,000 pairs of conversations. For the cognitive agent to have a good learning rate, it is necessary to provide the correct number of epochs. An epoch is a forward pass and backward pass of all training data. The cognitive agent could be trained more by increasing the number of epochs, but it is also necessary that we do not overfit/underfit the data by having high/low epochs. We trained our cognitive agent for 36 h on a Nvidia P5000 GPU to create the base model.

19.4.2 Inferences (Results)

After training BIMBot, we were able to get responses for unseen source sentences. This process is called inference. Bimbot is required to understand the semantics of the sentence to gauge if the sentences are general conversations or pertaining to BIM models. BIMBot will understand the semantics and act accordingly as seen in Figs. 19.6 and 19.7.

Currently, there are no standard metrics like precision and recall quantifying the performance of text generation tasks like cognitive agents. This is because, there are far too many ways of responding to a particular question. For such tasks, evaluation is usually done manually. But for our research purpose, we are considering three important metrics: (1) User Engagement, (2) Speed and (3) Functionality.

(1) User Engagement: Cognitive Assistants should be able to initiate conversations and respond to users' requests by keeping the conversations coherent. BIMBot has the capability to keep the conversation coherent up to four questions/responses. When the 5th question/response is provided, our cognitive agent finds it difficult to cduomprehend the question. Therefore, it renders an answer that does not relate to the question. A possible counter to this issue could be changing the NMT's model parameters as discussed in [21].

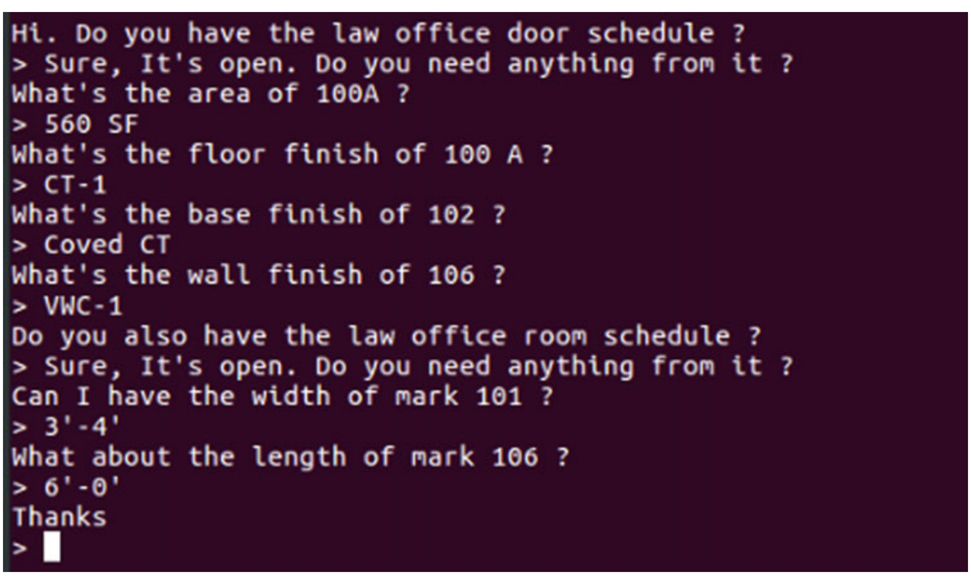

Fig. 19.7 BIM related conversations with BIMBot

(2) Speed: One of the prime reasons to use a cognitive agent is to interact with users for getting desired information instantly. Our Cognitive Assistant is fast and can respond to a user's request in milliseconds.
(3) Functionality: Cognitive Agents should be designed to offer good functionalities to users. BIMBot is designed to retrieve properties from IFCxml models and search if IFC models are found or not. These functionalities help users to easily find the information they are looking for. An example of this is illustrated in Fig. 19.6.

19.5 Conclusion and Future Work

In this paper, we have presented how a cognitive agent could be implemented in the Pre-design phases to increase the efficiency of BIM tasks. Using our agent, architects/engineers work with BIM models in easier fashion by retrieving properties that they desire with ease.

In the future, we would like to venture two interesting paths. The first one of which being, deploying our cognitive agent during a BIM meeting to check the productivity and efficiency it brings about during the Pre-design phase. The second path is to rollout the next version of our cognitive agent which will be an upgrade from the current version. The next version will carry better features like detecting clashes and a better NLP engine with syntactic/semantic analyzer.

References

1. Anon, (n.d.). What is BIM?/NBS. [online] Available at: https://www.thenbs.com/knowledge/what-is-building-information-modelling-bim. Accessed 2018
2. Dossick, C.S., Anderson, A., Azari, R., Iorio, J., Neff, G., Taylor, J.E.: Messy talk in virtual teams: achieving knowledge synthesis through shared visualizations. J. Manag. Eng. **31**(1), A4014003 (2015)
3. Dossick, C., Neff, G.: Messy talk and clean technology: communication, problem solving and collaboration using building information modelling. Eng. Proj. Organ. J. **1**(2), 83–93 (2011)
4. Merschbrock, C., ErikMunkvold, B.: Effective digital collaboration in the construction industry—A case study of BIM deployment in a hospital construction project (2018)
5. Addor, M., Santos, E.: BIM design coordination room infrastructure: assessment of communication activities. In: Computing in Civil and Building Engineering (2014), (2018)
6. Georgia Tech BIM Requirements and Guidelines for Architects, Engineers and Contractors., 1st ed., pp. 1–39. Atlanta, Georgia Institute of Technology (2011)
7. Jack, C.: CHATBOT: Architecture, Design, and Development (2017)
8. Vinyals, O., Quoc, V. Le.: A Neural Conversational Model (2015)
9. Alom, M.Z., Taha, T.M., Yakopcic, C., Westberg, S., Hasan, M., Van Esesn, B.C., Awwal, A.A.S., Asari, V.K. :The History Began from AlexNet: A Comprehensive Survey on Deep Learning Approaches (2018)
10. Wu, Y., Schuster, M., Chen, Z., Le, Q.V., Norouzi, M. : Google's Neural Machine Translation System: Bridging the Gap between Human and Machine Translation (2016)
11. Sutskever, I., Vinyals, O., Le, Q.V.: Sequence to Sequence Learning with Neural Networks (2014)
12. Cho, K., Merrienboer, B.V., Bahdanau, D., Bengio, Y. : On the properties of neural machine translation: encoder-decoder approaches. Comp. Sci. (2014a)
13. Google's NMT Documentation—https://github.com/tensorflow/nmt
14. Lipton, Z.C., Berkowitz, J., Elkan, C.: A Critical Review of Recurrent Neural Networks for Sequence Learning (2015)
15. Karpathy, A. : The Unreasonable Effectiveness of Recurrent Neural Networks. http://karpathy.github.io/2015/05/21/rnn-effectiveness/
16. Ramamoorthy, S.: Chatbots with Seq2Seq. Retrieved from http://suriyadeepan.github.io/2016-06-28-easy-seq2seq/
17. Bahdanau, D., Cho, K., Bengio, Y.: Neural Machine Translation by Jointly Learning to Align and Translate (2014)
18. Sennrich, R., Haddow, B., Birch, A.: Neural Machine Translation of Rare Words with Subword Units (2016)
19. Veizenbaum, J.: ELIZA—A Computer Program For the Study of Natural Language Communication Between Man And Machine (1966)
20. Bird, S., Klein, E., Loper, E. : Analyzing text with Natural Language Toolkit
21. Liu, F., Lu, H., Neubig, G. : Handling Homographs in Neural Machine Translation (2018)
22. Yoon, S., Kim, S., Choi, J., Keum, D., Jo, C.: A proposal for using BIM model created in design to construction phase—Case Study on preconstruction adopting BIM. J. KIBIM **5**(4), 1–10 (2015)
23. Shafiq, M., Matthews, J., Lockley, S. : A study of BIM collaboration requirements and available features in existing model collaboration systems. In: International Council for Research and Innovation in Building and Construction (2013)

20 Perceived Productivity Effects of Mobile ICT in Construction Projects

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Abstract

The increased affordability of mobile devices, wider network coverage, and better mobile applications have changed the ways communication and information transfer take place in the construction industry in both developed and developing countries. While considerable research has been conducted on the extent of usage of mobile information and communication technologies (mobile ICT) and development of prototype applications in the context of construction projects, less attention has been paid on examining the perceptions of construction management (CM) professionals regarding implications of using mobile ICT. The present study identified different ways in which the use of mobile ICT translates into better productivity in construction projects. A questionnaire survey conducted across the Indian construction industry revealed that the use of mobile ICT improves construction productivity due to four factors: (1) improved communication and information flow, (2) better project execution, (3) improved access to data, and (4) proper defect management. While attributes related to communication and access to information received high rankings, the respondents perceived that the use of mobile ICT has low positive influence on attributes such as cost savings, speed of construction, sustainability, and construction errors.

Keywords

Information and communication technology (ICT) • Mobile ICT • Construction productivity

20.1 Introduction

The construction sector is heterogeneous, highly fragmented, closely regulated, and project-oriented [1]. It attracts a wide variety of people from different cultural and professional backgrounds to work together. Consequently, proper communication between various parties assumes enormous importance in construction projects. Moreover, the success of many information-intensive construction processes is heavily dependent on the timely availability of accurate data [2]. However, the temporary nature of project organizations makes communication a very complex process in construction projects [3].

Construction management (CM) professionals are highly mobile and usually spend considerable time traveling between sites and offices. Since construction projects involve mainly fieldwork, communication and access to information has been problematic and slow [4]. Communication through fixed telephones and exchange of paper-based mails is asynchronous in nature which causes time delays. Moreover, the fixed telephone interactions confine the users to a specific location [5].

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On the other hand, CM professionals require on-demand access to information to resolve issues on sites [6]. A clear understanding of on-site information about work tasks and construction resources, and the real-time project data are prerequisites to take right decisions [7, 8]. To achieve this, many construction organizations have adopted mobile information and communication technologies (mobile ICT) during the last few years.

The use of mobile ICT such as smartphones, tablets, mobile applications, wireless connectivity, and cloud computing presents an excellent opportunity to facilitate instant communication and information transfer in construction projects [9]. Due to increased network coverage and advanced software and hardware platforms, mobile devices have become ubiquitous ICT [10]. It is estimated that the number of smartphone users will increase from the 2.6 billion recorded in 2014 to 6.1 billion by 2020 with 70% of the world's population using smartphones and 90% covered by mobile broadband networks [11]. In India, the number of smartphone users have grown to 340 million [12].

Due to this unprecedented growth in the use of mobile ICT, the ways in which communication and information transfer take place nowadays have changed considerably [13]. However, unlike other industries, the implications of these technologies for productivity have not been explored in sufficient depth within the context of the construction industry. This study was conducted to identify the perceived effects of the use of mobile ICT on construction productivity.

20.2 Literature Review

The adoption of mobile ICT presents an excellent opportunity to bring drastic changes in the use of data, information, and knowledge in the construction industry [14]. These technologies can enable CM professionals to access computing and communication functionalities seamlessly regardless of space and time [15]. As a result, smartphones and tablets have become an integral part of day-to-day construction processes. These technologies accelerate fieldwork to improve productivity and allow for less management inefficiencies [16]. In addition, allowing workers to access information from any location can help to overcome the inconvenience of travelling back and forth between the construction site and office. Moreover, these technologies could assist CM professionals in efficient management of remote construction projects [17].

Mobile ICT can facilitate access to unlimited information on the internet, instant correspondence using various applications, and collaboration between different teams using technologies such as audio and video conferencing [18]. Their successful implementation can result in faster decision making, cost savings, reduced project delivery time and reduced impact of the physical dispersion of construction professionals [19]. Therefore, it has potential to improve the field work, on-site information management, and productivity significantly in construction projects [4, 20, 21].

Furthermore, cloud storage provides access to data and other computational services via the Internet [22]. The advantage of cloud services is that documents can be updated easily and processed simultaneously by many users and the new content can be made available immediately [23, 24]. It significantly overcomes the limited processing power and storage capacity of mobile devices by providing a separate computing and data storage resource [25].

Although mobile ICT are becoming more popular in the construction industry, very few studies have been undertaken to examine the implications of the use of mobile ICT for construction productivity from CM professionals' perspectives [26]. There is a need to develop a better understanding of perceived effects of the use of these technologies on construction productivity, especially in the context of developing countries such as India where the uptake of mobile ICT is still low. Consequently, the present study examines various attributes and factors associated with the use of mobile ICT that improve productivity in construction projects.

20.3 Research Methodology

An initial questionnaire was developed based on literature review. The questions were divided into five parts and covered different facets of mobile ICT usage. The first and third sections have been reported in the current paper. The first part of the questionnaire consisted of questions on personal and professional attributes of the respondents. The third part had questions on positive implications of the use of mobile ICT for productivity in construction projects. Whereas, the remaining three parts of the questionnaire covered the extent of mobile ICT usage in construction projects, negative implications of the use of mobile ICT for productivity, and limitations of mobile ICT. The initial questionnaire was administered to six CM professionals who had an average eight years of experience of using mobile ICT in construction projects. The feedback received from the participants brought attention to few mistakes committed in the self-administered questionnaire. As a result, some changes in the layout and language were performed to make sure that the members of the population interpret the questions correctly. The questionnaire was tested again after corrections in the initial questionnaire by a different group of four experienced CM professionals [27].

The final questionnaire was administered online. The organizations or respondents accounted for the sample survey comprised of the members of the Construction Industry Development Council (CIDC). The CIDC was set up in 1996 by the Planning Commission, Government of India, jointly with the Indian construction industry to take up activities for the development of the Indian construction industry [28]. It is a consortium of construction companies, construction equipment manufacturers, technology providers, and research institutions. Since most of the key organizations in the Indian construction industry are also the members of CIDC, the authors considered CIDC as a credible source for collecting data. It had 117 members at the time of data collection. Of these, 62 organizations who directly undertake construction projects of different nature were chosen as the population for this study. For ensuring the accuracy of the chosen sample representing the entire population, Eqs. (20.1) and (20.2) were used to decide the sample size [29].

$$SS = \frac{Z^2 \times P \times (1 - P)}{C^2} \tag{20.1}$$

where SS represents the sample size for the survey; Z represents the confidence level (1.96 for 95% confidence level); P represents the percentage of selecting a choice, expressed as decimal (0.5 used for sample size needed); and C represents the confidence interval i.e. 0.5. The Eq. (20.1) gives the value of SS as 384.

Correction for finite population:

$$New\,SS = \frac{\mathrm{SS}}{\left(1 + \frac{\mathrm{SS}_{-1}}{\mathrm{pop}}\right)} \tag{20.2}$$

where pop represents 62 construction firms that were members of CIDC. Using Eq. (20.2), the new sample size turned out to be 53 organisations. Moreover, nine other construction companies who were not in the CIDC list were also found suitable for collecting data and thereby, included in the sample. The anonymous questionnaire was finally sent to CIDC member organizations and other companies and after a continuous follow-up for 6 months, a total of 119 questionnaires were received from 61 organizations. However, 14 responses were discarded due to incomplete information. Finally, 105 completed survey responses received from 54 construction organizations were used for further analysis. Table 20.1 shows the details of participants. The data represents a good mix of respondents and organizations with distinct characteristics.

Initially obtained in terms of a five-point Likert scale in which 1 represents strong disagreement and 5 represents strong agreement, responses were stored and analysed using the *Statistical Package for Social Sciences* (SPSS) *version 25* software program. Each of the attributes affecting the use of mobile ICT was ranked based on mean values. The highest mean value indicates the most critical attribute with rank 1, the next most critical attribute with rank 2 and so on. If the mean value is equal, the attribute with lower standard deviation received the higher ranking.

The Cronbach's alpha, α, was calculated to check the scale reliability. The value of α was 0.889, which indicates good reliability of the questionnaire [30]. All the diagonal values in anti-image correlation matrix were greater than 0.5 and hence all the attributes were considered suitable for factor analysis. In the next step, exploratory factor analysis (EFA) was performed for data reduction purposes. The factors extracted using principal component analysis were orthogonal and contained many overlapping attributes across various factors. Therefore, a principal axis factor analysis was conducted on 23 items with oblique rotation. The Kaiser–Meyer–Olkin measure verified the sampling adequacy for the analysis, KMO = 0.814, which is well above the acceptable limit of 0.5 [31]. For analyzing the multivariate normality and correlations between the factors, the Bartlett's test of sphericity was conducted. The value of significance obtained was 0.000 (<0.005) which further represented the suitability of data for factor analysis. Four factors had eigenvalues over Kaiser's criterion of 1 and in combination explained 46.88% of the variance. The scree plot also showed the inflexion point that justified retaining four factors.

Table 20.1 Respondents' profile

Characteristics	Categories	Number of respondents	% of total
Experience (in years)	Less than 5 years	59	56.19
	6–10	26	24.76
	11–15	9	8.57
	Over 15 years	11	10.47
Sector	Residential projects	19	18.10
	Commercial projects	21	20.00
	Industrial projects	26	24.76
	Infrastructure projects	39	37.14
Job title	Site engineer	29	27.62
	Planner	33	31.43
	Construction manager	10	9.52
	Project manager	19	18.10
	Executive	14	13.33
Years of mobile ICT usage in construction projects	Less than 1 year	9	8.57
	Between 1–3 years	27	25.71
	Between 3–5 years	22	20.95
	Between 5–10 years	34	32.38
	More than 10 years	13	12.38
Respondent's company turnover, 2016–2017 (in million INR)	Less than 100,000	44	41.90
	10,0001–500,000	29	27.62
	Above 500,000	32	30.48

20.4 Results and Discussions

Table 20.2 shows the ranking of different attributes based on their mean and standard deviation values. Whereas, Table 20.3 shows the factor loadings after rotation. Due to space limitations, the identified factors have been discussed briefly.

Table 20.2 demonstrates that the use of mobile ICT results in increased construction productivity mainly due to improved communication and better access to information. The respondents perceived that the use of mobile ICT has relatively less positive influence on cost savings, speed of construction, sustainability, and construction errors, as reflected by their relatively low mean values or rankings.

20.4.1 Improved Communication and Information Flow

This factor includes nine attributes that explain improvements in communication and information transfer due to the use of mobile ICT in construction projects. The use of mobile ICT not only improves communication within a team but also between different project teams. Previous studies have also found that the use of ICT in the construction projects results in improved coordination, collaboration and communication processes and faster decision making [32, 33]. By allowing seamless and effective transmission of information, these technologies eliminate the kinds of errors and delays that are inherent in manual approaches [4]. Using built-in cameras, photos and videos from the construction site can be shared with other project team members for an informed discussion [26]. Consequently, the time taken in planning or resolving an issue is reduced considerably which improves construction productivity.

Table 20.2 Ranking of attributes

Rank	Attributes	Mean	Standard deviation
1	Instant flow of information	4.39	0.596
2	Instant access to information	4.33	0.645
3	Improved communication between different teams	4.29	0.600
4	Improved communication within the team	4.29	0.661
5	Better reporting between site and office staff	4.21	0.583
6	Instant accessibility	4.18	0.585
7	Simplified exchange of information	4.14	0.657
8	Access to meteorological data (rain, temperature etc.)	4.13	0.636
9	Ability to capture more data	4.12	0.646
10	Less paperwork	4.11	0.870
11	Increased work flexibility	4.03	0.596
12	Instant inspection reports	4.01	0.612
13	Availability of relevant data on cloud for remote access	3.97	0.713
14	Better response to contractual provisions (e.g. notice of delay within 24 h)	3.97	0.727
15	Faster decision-making process	3.93	0.858
16	Instant clarification/correction in drawings	3.89	0.788
17	Improves working relationship between teams	3.86	0.713
18	Better material management	3.75	0.806
19	Better defect management	3.72	0.753
20	Cost savings	3.59	0.840
21	Increased speed of construction	3.46	0.832
22	Improved sustainability or reduced waste generation	3.43	0.908
23	Less construction errors	3.41	0.817

20.4.2 Better Project Execution

This factor has seven attributes that represent the improvements in execution of project due to the use of mobile ICT by CM professionals. The improper management of materials, drawing errors, and rework have been identified as major causes of poor productivity in construction projects [34]. The respondents also perceived that the use of mobile ICT improves response to contractual provisions by reducing construction errors and providing instant clarifications and updates. Previous studies have found that the construction costs can be reduced by up to 25% through efficient transfer of information between the construction teams [35]. Moreover, these technologies have potential to result in shorter completion time of tasks [36].

20.4.3 Improved Access to Data

The first attribute highlights the benefits offered by mobile ICT in accessing meteorological data which could help in better planning of construction activities. Since most of construction work is carried out in an open environment, the timely information on adverse weather conditions could reduce its negative impacts on productivity. Similarly, the use of mobile ICT can facilitate access to data from anywhere at any time using cloud-based applications. This shift from traditional paper-based to digital-based data management improves productivity in construction projects [26].

20.4.4 Proper Defect Management

This factor explains a variance of 5.212% and has two attributes. The less waiting time between inspection and the report saves considerable amount of time and thereby, results in better management of construction defects. Moreover, the

Table 20.3 Factor profile of attributes associated with the use of mobile ICT

Serial number	Details of factors and attributes	Factor loading	Variance explained (%)
1.0	**Improved communication and information flow**	–	16.370
1.1	Improved communication within the team	0.791	
1.2	Improved communication between different teams	0.771	
1.3	Improves working relationship between teams	0.618	
1.4	Simplified exchange of information	0.563	
1.5	Faster decision-making process	0.544	
1.6	Better reporting between site and office staff	0.531	
1.7	Instant accessibility	0.460	
1.8	Less paperwork	0.441	
1.9	Instant flow of information	0.425	
2.0	**Better project execution**	–	15.733
2.1	Improved sustainability or reduced waste generation	0.805	
2.2	Better material management	0.780	
2.3	Cost savings	0.741	
2.4	Less construction errors	0.581	
2.5	Increased speed of construction	0.570	
2.6	Better response to contractual provisions (e.g. notice of delay within 24 h)	0.539	
2.7	Instant clarification/correction in drawings	0.454	
3.0	**Improved access to data**	–	9.561
3.1	Access to meteorological data (rain, temperature etc.)	0.636	
3.2	Availability of data on cloud for remote access	0.597	
3.3	Increased work flexibility	0.486	
3.4	Instant access to information	0.452	
3.5	Ability to capture more data	0.407	
4.0	**Proper defect management**	–	5.212
4.1	Better defect management	0.672	
4.2	Instant inspection reports	0.476	

information is readily available to make an informed decision rather than a judgement call which eliminates the delays inherent in manual approaches [26]. Using a defect management software, information on construction defects can be promptly recorded and shared.

20.5 Conclusion

Given current popularity of mobile ICT, research into examining the implications of these technologies for construction productivity is highly warranted. The aim of this research was to examine the ways through which the use of mobile ICT improves construction productivity from the perspective of CM professionals. The findings of this study are expected to increase the use of these technologies in construction projects, especially in developing construction markets such as India where construction organizations show reluctance in the uptake of ICT.

The factor analysis highlighted that mobile ICT improves productivity in construction projects by improving communication and information flow, project execution, access to data, and defect management. The questionnaire survey further revealed that the impact of mobile ICT in improving communication and information transfer is perceived as more important compared to its role in improving performance of construction projects in terms of cost, schedule, and sustainability. It seems that the potential impacts of mobile ICT usage on cost and schedule performance of construction projects are yet to be realized in the Indian construction industry. Considering positive implications of the use of mobile ICT for construction productivity, it is put forth that construction organizations should invest more in these technologies.

The findings of this study must be considered within the context of its limitations. The data for this study was gathered only from CM professionals working in the Indian construction industry. More research is needed to devise measures to enhance the potential applications of these technologies in improving cost, schedule, safety, and sustainability in construction projects. However, despite these limitations, the findings highlight the main benefits associated with the use of mobile ICT in construction projects.

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References

1. Dainty, A., Moore, D., Murray, M.: Communication in Construction—Theory and Practice. Taylor & Francis, Oxon (2006)
2. Haas, C.T., Tucker, R.L., Saidi, K.S., Balli, N.A.: The value of handheld computers in construction. A report of Centre for Construction Industry Studies, the University of Texas, US (2002)
3. Kaplan, A.M., Haenlein, M.: Users of the world, unite! The challenges and opportunities of Social Media. Bus. Horiz. **53**(1), 59–68 (2010)
4. Son, H., Park, Y., Kim, C., Chou, J.S.: Toward an understanding of construction professionals' acceptance of mobile computing devices in South Korea: an extension of the technology acceptance model'. Autom. Constr. **28**, 82–90 (2012)
5. Wiredu, G.O.: Mobile Computer Usability: An Organizational Personality Perspective. Springer, Berlin Heidelberg, Heidelberg (2014)
6. Ballan, S., El-Diraby, T.E.: A value map for communication systems in construction. J. Inf. Tech. Constr. **16**(44), 745–760 (2011)
7. Kim, C., Park, T., Lim, H., Kim, H.: On-site construction management using mobile computing technology. Autom. Constr. **35**, 415–423 (2013)
8. Ferrada, X., Sepúlveda, M., Serpell, A., Núñez, D., Neyem, A.: A lessons-learned mobile system for construction companies: motivation and design. Procedia Eng. **85**, 157–165 (2014)
9. Disterer, G., Kleiner, C.: BYOD bring your own device. Procedia Tech. **9**, 43–53 (2013)
10. Yadav, K., Naik, V., Singh, A., Singh, P., Kumaraguru, P., Chandra, U.: Challenges and novelties while using mobile phones as ICT devices for Indian masses: short paper. In: Proceedings of the 4th ACM Workshop on Networked Systems for Developing Regions, ACM, pp. 10–11 (2010)
11. Ericsson.: https://www.ericsson.com/news/1925907. Accessed 21 Mar 2018
12. eMarketer.: https://www.statista.com/statistics/274658/forecast-of-mobile-phone-users-in-india/. Accessed 21 Mar 2018
13. Bresnahan, T., Yin, P.: Adoption of new information and communications technologies in the workplace today. Innovation Policy Econ. **40**, 95–124 (2017)
14. Williams, T., Bernold, L., Lu, H.: Adoption patterns of advanced information technologies in the construction industries of the United States and Korea. J. Constr. Eng. Manag. **133**(10), 780–790 (2007)
15. Anumba, C.J., Wang, X.: Mobile and pervasive computing in construction: an introduction. In: Anumba, C.J., Wang, X. (eds.) Mobile and Pervasive Computing in Construction, 1st edn. John Wiley & Sons Ltd., UK (2012)
16. Sattineni, A., Schmidt, T.: Implementation of mobile devices on jobsites in the construction industry. Procedia Eng. **123**, 488–495 (2015)
17. Sidawi, B., Alsudairi, A.: The potentials of and barriers to the utilization of advanced computer systems in remote construction projects: case of the Kingdom of Saudi Arabia. Vis. Eng. **2**(3), 1–11 (2014)
18. Sun, M., Howard, R.: Understanding IT in Construction. Spon Press, Taylor & Francis, London (2004)
19. Aziz, Z., Anumba, C.J., Ruikar, D., Carillo, P., Bouchlaghem, D.: Intelligent wireless web services for construction—A review of the enabling technologies. Autom. Constr. **15**(2), 113–123 (2006)
20. Chen, Y., Kamara, J.M.: Using mobile computing for construction site information management. Eng., Constr. Archit. Manag. **15**(1), 7–20 (2008)
21. Venkatraman, S., Yoong, P.: Role of mobile technology in the construction industry-A case study. Int. J. Bus. Inf. Syst. **4**(2), 195–209 (2009)
22. Arayici, Y., Aouad, G.: Computer integrated construction: an approach to requirements engineering. Eng. Constr. Archit. Manag. **12**(2), 194–215 (2005)
23. Varkonyi, V.: Debunking the Myths about BIM in the 'Cloud'. AEC bytes, 1–4 (2011)
24. Williams, T.P.: Applying handheld computers in the construction industry. Pract. Periodical Struct. Des. Constr **8**(4), 226–231 (2003)
25. Eric, N., Jang, J.W.: Design study on cloudlet and mobile devices communication based on distance. Information, International Information Institute (Tokyo) 19(5), 1425–1430 (2016)
26. Hasan, A., Elmualim, A., Rameezdeen, R., Baroudi, B., Marshall, A.: An exploratory study on the impact of mobile ICT on productivity in construction projects. Built Environ. Proj. Asset Manag. **8**(3), 320–332 (2018)
27. Saris, W.E., Gallhofer, I.N.: Design, evaluation, and analysis of questionnaires for survey research, 2nd edn. John Wiley & Sons, NJ (2014)
28. CIDC. http://www.cidc.in/new/aboutus.html. Accessed 21 Mar 2018
29. Ayyub, B.M., McCuen, R.H.: Probability, statistics, and reliability for engineers and scientists. CRC Press, US (2011)
30. Kline, P.: The handbook of psychological testing, 2nd edn. Routledge, London (1999)
31. Field, A.: Discovering statistics using IBM SPSS statistics, 4th edn. Sage, London (2013)

32. Mohamed, S., Stewart, R.A.: An empirical investigation of users' perceptions of web-based communication on a construction project. Autom. Constr. **12**(1), 43–53 (2003)
33. Lee, S.K., Yu, J.H.: Success model of project management information system in construction. Automat. Constr. **25**, 82–93 (2012)
34. Hasan, A., Baroudi, B., Elmualim, A., Rameezdeen, R.: Factors affecting construction productivity: a 30 year systematic review. Engineering, Construction and Architectural Management. **25**(7), 916–937 (2018)
35. Bowden, S.: Application of mobile IT in construction. PhD Dissertation, Department of Civil & Building Engineering, University of Loughborough, UK (2005)
36. Yang, L.R.: Exploring the links between technology usage and project outcomes. Constr. Manag. Econ. **25**(10), 1041–1051 (2007)

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21 Mobile EEG-Based Workers' Stress Recognition by Applying Deep Neural Network

Houtan Jebelli, Mohammad Mahdi Khalili, and SangHyun Lee

Abstract

A large number of construction workers are struggling with high stress associated with their perilous job sites. Excessive occupational stress can cause serious job difficulties by negatively impacting workers' productivity, safety, and health. The first step to decrease the adverse outcomes of this work-related stress is to measure workers' stress and detect the factors causing stress among workers. Various self-assessment instruments (e.g., a stress assessment questionnaire) have been used to assess workers' perceived stress. However, these methods are compromised by several drawbacks that limit their use in the field. Firstly, these methods interrupt workers ongoing tasks. Secondly, these methods are subject to a high degree of bias, which can lead to inconsistent results. The authors' earlier work attempted to address the limitations of these subjective methods by applying different machine learning methods (e.g., Supervised Learning algorithms) to identify the pattern of workers' brain waves that is acquired from a wearable Electroencephalography (EEG) device, while exposed to different stressors. This research thus attempts to improve the stress recognition accuracy of the previous algorithms by developing an EEG-based stress recognition framework by applying two Deep Learning Neural Networks (DNN) structures: a convolutional deep learning neural network (deep CNN) and a Fully Connected Deep Neural Network. Results of the optimum DNN configuration yielded a maximum of 86.62% accuracy using EEG signals in recognizing workers' stress, which is at least six percent more accurate when compared with previous handcraft feature-based stress recognition methods. Detecting workers' stress with a high accuracy in the field will lead to enhancing workers' safety, productivity, and health by early detection and mitigation of stressors at construction sites.

Keywords

Brain waves • Workers' stress • Wearable electroencephalography (EEG) • Convolutional deep neural network • Fully connected deep neural network • Occupational stress • Workers' productivity • Health • Safety

21.1 Introduction

With 68% of construction workers suffering from high mental stress as a result of working in the industry, construction work is one of the most stressful occupations [1]. Workplace stress is strongly associated with workers' productivity, health, and safety behavior [2]. Therefore, it is critical to measure and characterize construction workers' stress levels in the field, which can not only reduce their injuries, accidents, and errors but also improve their productivity and job satisfaction.

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Various instruments to measure workers' stress have been used, but they either rely on imprecise memory and reconstruction of feelings in the past (e.g., stress assessment questionnaires) [3] or interfere with workers' ongoing work (e.g., biochemical measurement), which limits their use in the field. One of the most reliable ways to assess stress is to examine the reflection of various stressors on brain activity [4, 5]. To measure this reflection, an Electroencephalogram (EEG) has frequently been used in clinical diagnosis and biomedical research [4–7]. In spite of the fact that EEG holds promise as a means to assess individuals' stress in the clinical domain, using traditional EEG devices to assess construction workers' EEG signals while working on a construction site is impractical due to the wired connections and complicated settings of these devices.

Due to recent technological advancements, wearable and wireless biosensors are readily available and have demonstrated a great potential to be used at construction sites to improve workers' safety, well-being, and health [8–21]. Wearable technology offers a less invasive method for assessing construction workers' stress using their EEG signals, which remain independent of workers' imprecise memories. Quite recently, the authors' applied different signal processing and machine-learning techniques (e.g., Supervised Learning algorithms) to recognize construction workers' stress by extracting a handcraft feature from EEG [19]. This research seeks to improve the stress recognition accuracy of the current frameworks by proposing a Deep Learning based stress recognition. In this research, the authors examine two classes of Deep Neural Network (DNN) architectures models. First, a convolutional neural network (CNN) was trained to recognize workers stress based on their EEG signals. CNN was selected due to its high performance in Deep Learning based classification task. Then, the authors developed a Fully Connected Deep Neural Network, based on the EEG signals that were collected at real construction sites.

To examine the performance of the proposed Deep Learning based stress recognition framework, the authors collected EEG signals from 10 construction workers while performing different tasks in the field. Workers' stress-related hormone (cortisol), which is a reliable method to assess human stress [22], was measured using a saliva sample. Workers' cortisol level was used to label different construction tasks as low or high stress. Recognizing workers' stress with high accuracy is expected to improve the conditions of construction sites and workers' well-being through the detection and mitigation of the stressors at construction sites.

21.2 EEG-Based Stress Recognition by Applying Deep Learning

Figure 21.1 illustrates the overview of the proposed framework to recognize workers' stress using their brain waves. As the first step, the workers' brain waves were collected from 14 different locations of their scalp using a wearable EEG headset, which was fit into their safety hard hat. As mentioned earlier, workers' cortisol level was measured as a ground truth to be used to label workers' stress. Then, as the second step, a signal processing framework that was proposed by authors' previous work [23] was applied to enhance the quality of the EEG signal by reducing signal noises and artifacts. As the last step, two DNN structures (a Fully Connected Deep Neural Network and a Convolutional Neural Network) were applied to recognize workers' stress.

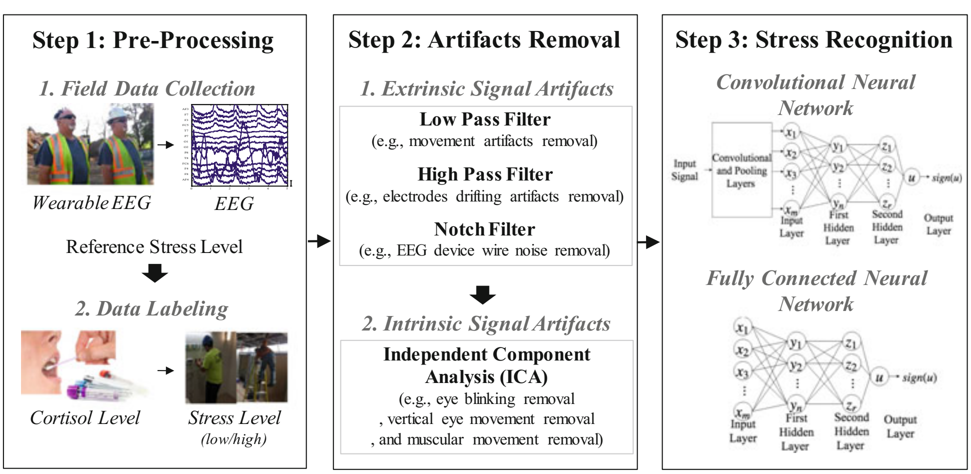

Fig. 21.1 The overview of a Deep Neural Network (DNN)-based stress recognition framework using the EEG signals collected in the field

21.2.1 EEG Signal Pre-processing: Artifacts Removal

A large number of external and internal sources can contaminate the quality of EEG signals [24]. In this regard, EEG signal artifacts can be divided into two groups: intrinsic signals artifacts, that come from the body itself (e.g., vertical eye movement, eye blinking) [24], and extrinsic signal artifacts, that come from external factors (e.g., movement, respiration, and use of muscles) [25–27]. EEG signal artifacts are more significant while collecting data at construction sites, due to the noisy sites environment and frequent body movement of the workers. Therefore, it is essential to reduce EEG signal artifacts before analyzing data. To reduce EEG signal artifacts, the authors previously developed an EEG signal processing framework, which acquires high-quality EEG signals by removing the most common EEG signal artifacts from the EEG recorded using a wearable EEG device at the construction site [23]. The proposed framework in the authors' former work, reduces both extrinsic and intrinsic artifacts in EEG signals. To reduce extrinsic artifacts from the EEG signals recorded in the real construction sites a 60 Hz low-pass filter, a 0.5 Hz high-pass filter, and a notch filter with the cutoff frequency of 60 Hz were applied. To reduce intrinsic artifacts, the authors applied an independent component analysis (ICA). ICA is a computational method that has been commonly used in EEG research to remove intrinsic signal artifacts [28–30]. ICA detects and removes the artifactual components from the EEG signal [31] by separating the original signal into multiple components [25].

21.2.2 Fully Connected Deep Neural Network

A Fully Connected Deep Neural networks can be interpreted as a complex function which gets an input data, $x = [x_1, x_2, \ldots, x_m]$ (e.g., EEG signals across different channels) and predicts the label of the data as an output (e.g., different stress levels). Network layers and neurons make the structure of a Fully Connected Deep Neural networks. The first hidden layer comprises of n neurons and n hidden variables $(y_1, y_2, \ldots, y_n)$. Each edge between neuron x_i and y_j is associated with a weight value represented by α_{ij}. The hidden variables $(y_1, y_2, \ldots, y_n)$ are calculated based on Eq. 21.1.

$$y_j = f\left(\sum_{i=1}^{m} \alpha_{ij} x_i\right) j = 1, 2, \ldots, n, i = 1, 2, \ldots, m \tag{21.1}$$

where $f(.)$ is an arbitrary function and usually is taken to be the sigmoid function. Similarly, the second hidden layer has r neurons and r hidden variables $(z_1, z_2, \ldots, z_r)$. Let β_{ij} denote the weight value between neuron y_i and z_j. Then, hidden variables of the second hidden layer are calculated using Eq. 21.2.

$$z_j = f\left(\sum_{i=1}^{n} \beta_{ij} y_i\right) j = 1, 2, \ldots, r \tag{21.2}$$

Finally, the output u, which represents the predicted label (low or high stress) is calculated using Eq. 21.4.

$$u = f\left(\sum_{i=1}^{r} \gamma_i z_i\right) \tag{21.3}$$

where, γ_i is the weight value of neuron z_i and output u. After observing output u, if $u \geq 0$, we predict the label of the input data as 1 (high stress), otherwise the predicted label is -1 (low stress). In other words, the predicted label is $sign(u)$. For training a neural network, the authors applied a backpropagation algorithm [32] to find optimal weight values α_{ij} and β_{ij} and γ_i based on the training data. Fully Connected Deep Neural Network in this research was modeled off-line using a custom developed software based on the Neural Network Toolbox provided by MATLAB. A MATLAB version 8.1.0.604 program was used for all of the computations.

21.2.3 Deep Convolutional Neural Network

In addition to a Fully Connected Deep Neural Network, the authors explored the capability of a Deep Convolutional Neural Networks (CNN) to recognize workers' stress using their EEG signals. Convolutional and pooling layers are two essential

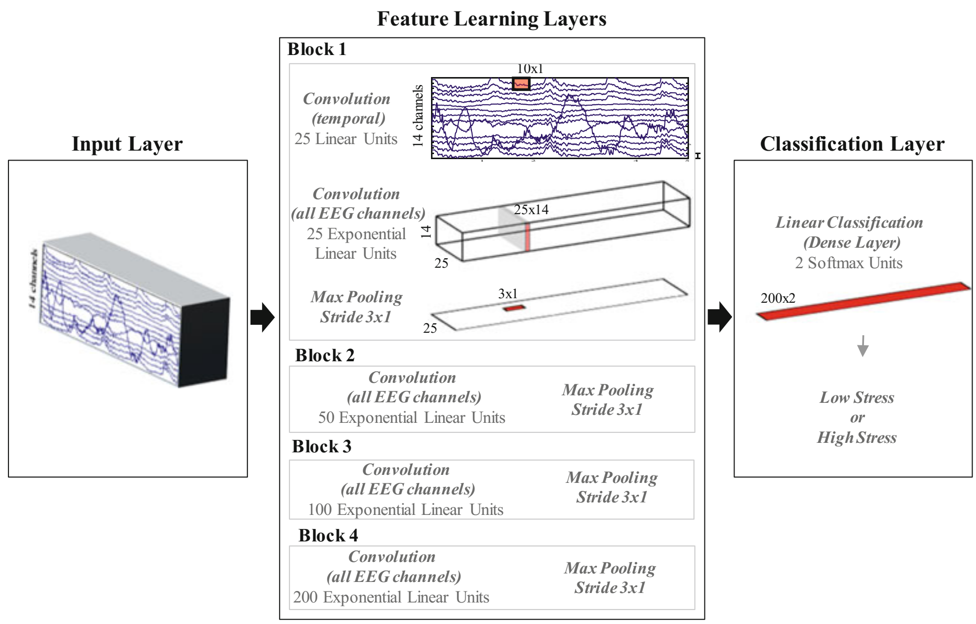

Fig. 21.2 Deep Convolutional Neural Network architecture to recognize construction workers' stress level based on their EEG signals

types of layers that create the structure of a CNN. Convolutional layers extract the patterns of different blocks of the data around each window of the input signal. Then, pooling layers aim to reduce the risk of model overfitting and the computational cost and time of the model by decreasing the spatial size of the output of convolutional layers. Each convolution layer calculates the convolution of its input with a bunch of filters. Each filter defined as a $p \times q$ matrix. The convolution between input signal I and filter F is calculated using Eq. 21.4.

$$O[m,n] = (I * F)[m,n] = \sum_{i=1}^{p} \sum_{j=1}^{q} I[m-i, n-j] \cdot F[i,j] \tag{21.4}$$

where, O is the convolution of I and F. I is the input signals (different EEG channels) and F is a filter. Notice that if $m - i \leq 0$ or $n - j \leq 0$, then $I[m-i, n-j] = 0$.

To learn complex EEG signal patterns, four blocks of the consecutive convolutional and pooling layers were used. Then, to classify the learned patterns, a softmax layer was added after convolutional and pooling layers. A fully connected network was used as the classification layer. The fully connected neural network tries to find the best classifier using extracted features by convolutional and pooling layers. In other words, convolutional and pooling layers helps classifier to extract features from neighboring pixels. On the contrary, the softmax layer considers input data (all EGG channels) without emphasis on the patterns existing among neighbor pixels and data points. Figure 21.2 shows the architecture of the developed Deep CNN in this research. The network was modeled off-line using a custom developed software based on an open source library (Keras-toolbox) provided by Python. A Python version 2.7.11 program was used for all of the computations.

21.3 Experimental Setting

To examine the performance of the proposed Deep Learning-based stress recognition framework to recognize workers' stress while exposed to different stressors at actual construction sites, the authors' visited four different construction sites and recorded 10 construction workers' brain waves using a wearable EEG headset. Subjects reported no mental disorders or history of epilepsy that could affect their brain waves. Subjects' were asked to perform same tasks under low stress conditions (e.g., working on the ground level and working right after taking a break) (Fig. 21.3a) and high stress conditions (e.g., working at the top of a ladder, working in confined space, and continuous work without taking a break) (Fig. 21.3b). Before starting the data collection, all the subjects were informed of the purpose and procedure of the data collection.

Fig. 21.3 EEG data collection in field: **a** Low stress experimental tasks (e.g., working on the ground level and working right after break); **b** High stress experimental tasks (e.g., working at top of a ladder, working in a confined space, and working in dangerous environment); **c** Wearable EEG headset fit into worker's safety hardhat; **d** Salivary cortisol samples kit

Workers' brain waves were collected across 14 different channels using a wearable EEG headset (Fig. 21.3c). The data collection rate was set at 128 data per second, with the recording resolution of 14 bits with the connectivity at a 2.4 GHz band a dynamic range of 8400 μV (peak to peak). Subjects' actual stress was determined by measuring their cortisol level. Cortisol is known as stress hormone and is highly associated with subjects' stress. In this study subjects' cortisol level was measured using the saliva sample (Fig. 21.3d). Subjects' cortisol level was used as a baseline to label their stress level as low or high while working in different conditions.

21.4 Results and Findings

The authors applied two proposed deep learning neural network on the data collected at actual construction sites. The result of this study shows that the proposed Fully Connected Deep Neural Network led to an overall prediction accuracy of 86.62%. On the other hand, the Convolutional Deep Neural Network model led to an overall prediction accuracy of 64.20%.

Figure 21.4 shows the stress recognition accuracy of the model under different network structures (different number of layers and neuron in the model). According to Fig. 21.4a, a network with two hidden layers is preferable and will lead to the highest prediction accuracy and lowest computation cost as well. The result of optimizing the number of neurons in each layer show that selection of 83 neurons in the first layer and 23 neurons in the second layer will lead to the optimum network structure (Fig. 21.4b).

The present finding is promising, considering that highest EEG-based stress recognition prediction accuracy using supervised learning algorithms is around 80.00% by applying Gaussian Kernel Support Vector Machine (SVM) [19]. Also, the proposed deep learning-based stress recognition does not have the limitation of supervised learning algorithms (e.g., SVM and logistic regression), which are fundamentally a binary classifier and have not been standardized for dealing with multi-class problems, to identify multiclass classification (identifying different stress levels).

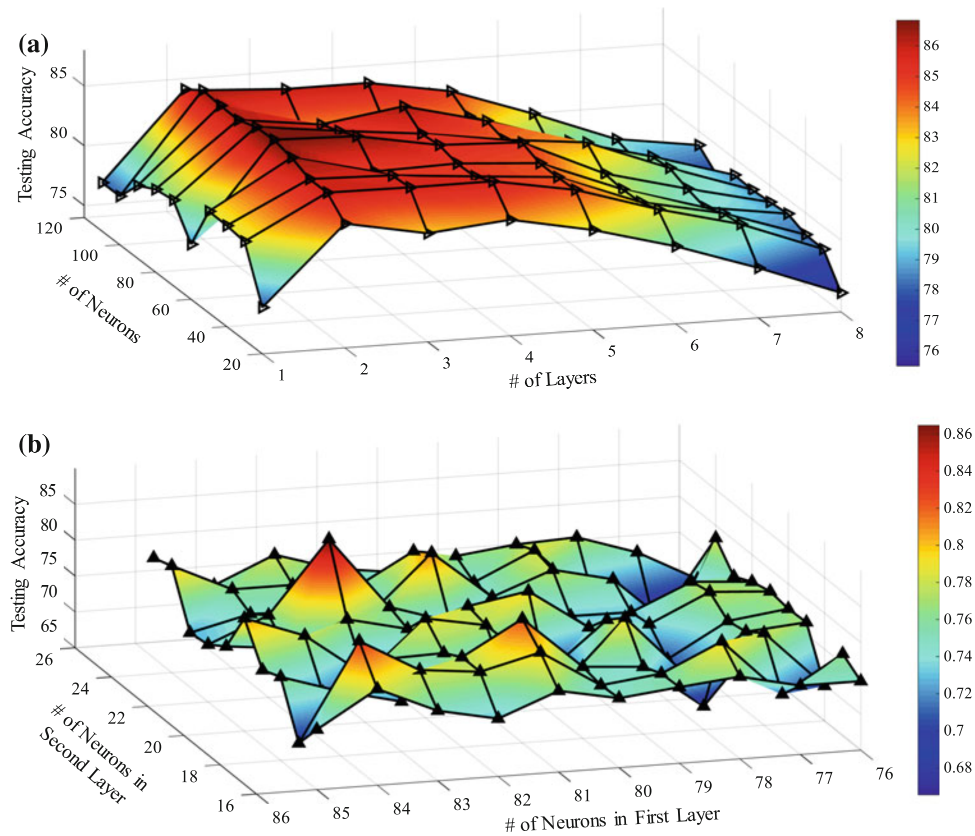

Fig. 21.4 Optimizing the architecture of Fully Connected Deep Neural Network: **a** optimizing the number of layers in the network; **b** optimizing the number of neurons in each layer

Table 21.1 Confusion matrices of training and testing steps

Training	Low stress	High stress	Recall
Low stress	2670	320	0.893
High stress	270	2740	0.91
Precision	0.90	0.89	Accuracy: 0.90
Testing	*Low stress*	*High stress*	*Recall*
Low stress	580	70	0.89
High stress	100	540	0.84
Precision	0.85	0.88	Accuracy: 0.87

To further investigate the classification performance, the confusion matrices for training and testing steps of the proposed network are shown in Table 21.1. In this table, each row represents actual labels (stress level) while each column corresponds to predicted labels. In addition to classifier accuracy, Table 21.1 shows two critical parameters to further examine the performance of the classifier; accuracy and recall. Precision is defined as the ratio of the number of correct prediction to the total number of instances classified as positive (high stress) or negative (low stress). The recall represents the ratio of the number of correct predictions (correct high or low stress) to the total number of instances (total high stress or low stress). Both “high stress” and “low stress” labels achieved relatively high recall and precision, which shows the high performance of the performance in detecting both low stress and high stress conditions.

21.5 Conclusion

This study was undertaken to develop an EEG-based stress recognition framework by applying deep learning algorithms to recognize construction workers' stress while performing different tasks at actual construction sites. This study showed the capability of a Fully Connected Deep Neural Network to recognize workers stress with high accuracy. According to the results, the optimum network configuration to recognize construction workers' stress requires two hidden layers, 83 neurons in the first hidden layer and 23 neurons in the second hidden layer. Also, the proposed DNN based stress recognition eased the need for feature extraction and feature engineering, one the most time-consuming steps in the Supervised Learning algorithms. Besides, multi DNN based stress recognition is expected to be the ultimate classifier to recognize workers' stress with high accuracy, particularly while dealing with different levels of stress, where most of the supervised learning algorithms are limited to a binary classification setting. This study will serve as a basis for future studies to accurately identify different workers' stress levels using their brain waves in the field.

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References

1. Campbell, F.: Occupational stress in the construction industry, Berkshire. Chartered Institute of Building, UK (2006)
2. Leung, M.Y., Liang, Q., Olomolaiye, P.: Impact of job stressors and stress on the safety behavior and accidents of construction workers. J. Manag. Eng. **32**, 04015019 (2015). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000373
3. Mucci, N., Giorgi, G., Cupelli, V., Gioffrè, P.A., Rosati, M.V., Tomei, F., Tomei, G., Breso-Esteve, E., Arcangeli, G.: Work-related stress assessment in a population of Italian workers. The Stress Questionnaire. Sci. Total Environ. **502**, 673–679 (2015)
4. Al-shargie, F., Tang, T.B., Badruddin, N., Kiguchi, M.: Mental stress quantification using EEG signals. In: International Conference for Innovation in Biomedical Engineering and Life Sciences. Springer, pp. 15–19 (2015). https://doi.org/10.1007/978-981-10-0266-3_4
5. Goodman, R.N., Rietschel, J.C., Lo, L.-C., Costanzo, M.E., Hatfield, B.D.: Stress, emotion regulation and cognitive performance: The predictive contributions of trait and state relative frontal EEG alpha asymmetry. Int. J. Psychophysiol. **87**, 115–123 (2013)
6. Al-Shargie, F., Tang, T.B., Kiguchi, M.: Assessment of mental stress effects on prefrontal cortical activities using canonical correlation analysis: an fNIRS-EEG study. Biomed. Opt. Express **8**, 2583–2598 (2017). https://doi.org/10.1364/BOE.8.002583
7. Hou, X., Liu, Y., Sourina, O., Tan, Y.R.E., Wang, L., Mueller-Wittig, W.: EEG based stress monitoring. In: Systems, Man, and Cybernetics. IEEE, Kowloon, China, pp. 3110–3115 (2015). https://doi.org/10.1109/SMC.2015.540
8. Jebelli, H., Ahn, C.R., Stentz, T.L.: Comprehensive fall-risk assessment of construction workers using inertial measurement units: validation of the gait-stability metric to assess the fall risk of iron workers. J. Comput. Civ. Eng. **30**, 04015034 (2015). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000511
9. Jebelli, H., Ahn, C.R., Stentz, T.L.: Fall risk analysis of construction workers using inertial measurement units: validating the usefulness of the postural stability metrics in construction. Saf. Sci. **84**, 161–170 (2016). https://doi.org/10.1061/9780784481264.036
10. Nouredanesh, M., Kukreja, S.L., Tung, J.: Detection of compensatory balance responses using wearable electromyography sensors for fall-risk assessment. In: Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of The, IEEE, pp. 1680–1683 (2016)
11. Jebelli, H., Ahn, C.R., Stentz, T.L.: The validation of gait-stability metrics to assess construction workers' fall risk. Comput. Civ. Build. Eng. **2014**, 997–1004 (2014). https://doi.org/10.1061/9780784413616.124
12. Jebelli, H., Hwang, S., Lee, S.: Feasibility of field measurement of construction workers' valence using a wearable EEG device. In: Computing in Civil Engineering 2017, ASCE, Reston, VA, pp. 99–106 (2017). https://doi.org/10.1061/9780784480830.013
13. Baghdadi, A., Megahed, F.M., Esfahani, E.T., Cavuoto, L.A.: A machine learning approach to detect changes in gait parameters following a fatiguing occupational task. Ergonomics. 1–14 (2018)
14. Jebelli, H., Hwang, S., Lee, S.: EEG-based workers' stress recognition at construction sites. Autom. Constr. **93**, 315–324 (2018). https://doi.org/10.1016/j.autcon.2018.05.027
15. Hwang, S., Seo, J., Jebelli, H., Lee, S.: Feasibility analysis of heart rate monitoring of construction workers using a photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker. Autom. Constr. **71**, 372–381 (2016). https://doi.org/10.1016/j.autcon.2016.08.029
16. Hwang, S., Jebelli, H., Choi, B., Choi, M., Lee, S.: Measuring workers' emotional state during construction tasks using wearable EEG. J. Const. Eng. Manag. **144**, 04018050 (2018). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001506
17. Kim, H., Ahn, C.R., Stentz, T.L., Jebelli, H.: Assessing the effects of slippery steel beam coatings to ironworkers' gait stability. Appl. Ergon. **68**, 72–79 (2018). https://doi.org/10.1016/j.apergo.2017.11.003
18. Yang, K., Jebelli, H., Ahn, C., Vuran, M.: Threshold-based approach to detect near-miss falls of iron workers using inertial measurement units. In: Computing in Civil Engineering 2015, ASCE, pp. 148–155 (2015). https://doi.org/10.1061/9780784479247.019
19. Jebelli, H., Yang, K., Khalili, M.M., Ahn, C.R., Stentz, T.: Assessing the effects of tool-loading formation on construction workers' postural stability. In: Construction Research Congress 2018, pp. 292–302 (2018). https://doi.org/10.1061/9780784481288.029
20. Jebelli, H., Choi, B., Kim, H., Lee, S.: Feasibility study of a wristband-type wearable sensor to understand construction workers' physical and mental status. In: Construction Research Congress 2018, ASCE, Reston, VA, pp. 367–377 (2018). https://doi.org/10.1061/9780784481264.036

21. Jebelli, H., Khalili, M.M., Hwang, S., Lee, S.: A supervised learning-based construction workers' stress recognition using a wearable electroencephalography (EEG) device. In: Construction Research Congress 2018, (2018). https://doi.org/10.1061/9780784481288.005
22. Levine, A., Zagoory-Sharon, O., Feldman, R., Lewis, J.G., Weller, A.: Measuring cortisol in human psychobiological studies. Physiol. Behav. **90**, 43–53 (2007). https://doi.org/10.1016/j.physbeh.2006.08.025
23. Jebelli, H., Hwang, S., Lee, S.: EEG signal-processing framework to obtain high-quality brain waves from an off-the-shelf wearable EEG device. J. Comp. Civ. Eng. **32**, 04017070 (2017). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000719
24. Urigüen, J.A., Garcia-Zapirain, B.: EEG artifact removal-state-of-the-art and guidelines. J. Neural Eng. **12**, 031001 (2015). https://doi.org/10.1088/1741-2560/12/3/031001
25. Jung, T.P., Makeig, S., Stensmo, M., Sejnowski, T.J.: Estimating alertness from the EEG power spectrum. IEEE Trans. Biomed. Eng. **44**, 60–69 (1997)
26. Kar, S., Bhagat, M., Routray, A.: EEG signal analysis for the assessment and quantification of driver's fatigue. Transp. Res. Part F: Traffic Psychol. Behav. **13**, 297–306 (2010)
27. Shao, S.Y., Shen, K.Q., Ong, C.J., Wilder-Smith, E.P., Li, X.P.: Automatic EEG artifact removal: a weighted support vector machine approach with error correction. IEEE Trans. Biomed. Eng. **56**, 336–344 (2009)
28. Delorme, A., Makeig, S.: EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods **134**, 9–21 (2004). https://doi.org/10.1016/j.jneumeth.2003.10.009
29. Vigário, R.N.: Extraction of ocular artefacts from EEG using independent component analysis. Electroencephalogr. Clin. Neurophysiol. **103**, 395–404 (1997). https://doi.org/10.1016/S0013-4694(97)00042-8
30. Zhukov, L., Weinstein, D., Johnson, C.: Independent component analysis for EEG source localization. IEEE Eng. Med. Biol. Mag. **19**, 87–96 (2000). https://doi.org/10.1109/51.844386
31. Comon, P.: Independent component analysis, a new concept? Sig. Process. **36**, 287–314 (1994)
32. Hecht-Nielsen, R. : Theory of the backpropagation neural network. In: Neural Networks for Perception. Elsevier, pp. 65–93 (1992)

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22 Feasibility of Wearable Electromyography (EMG) to Assess Construction Workers' Muscle Fatigue

Houtan Jebelli and SangHyun Lee

Abstract

Due to the labor-intensive nature of construction tasks, a large number of construction workers frequently suffer from excessive muscle fatigue. Workers' muscle fatigue can adversely affect their productivity, safety, and well-being. Several attempts have been made to assess workers' fatigue using subjective methods (e.g., fatigue questionnaire). Despite, the success of subjective methods in assessing workers' fatigue in a long period, these methods have limited utility on construction sites. For instance, these methods interrupt workers' ongoing tasks. These methods are also subject to high biases. To address these issues, this study aims to examine the feasibility of a wearable Electromyography (EMG) sensor to measure the electrical impulses produced by workers' muscles as a means to continuously evaluate workers muscle fatigue without interfering with their ongoing tasks. EMG signals were acquired from eight subjects while lifting a concrete block using their upper limbs (i.e., elbow and shoulder muscles). As the first step, filtering methods (e.g., bandpass filter, rolling filter, and Hampel filter) were applied to reduce EMG signal artifacts. After removing signal artifacts, to examine the potential of EMG in measuring workers' muscle fatigue, various EMG signal metrics were calculated in time domain (e.g., Signal Mean Absolute Value (MAV) and Root Mean Square (RMS)) and frequency domain (e.g., Median Frequency (MDF) and Mean Frequency (MEF)). Subjects' perceived muscle exertion (Borg CR-10 scale) was used as a baseline to compare the muscle exertion identified by EMG signals. Results show a significant difference in EMG parameters while subjects were exerting different fatigue levels. Results confirm the feasibility of the wearable EMG to evaluate workers' muscle fatigue as means for assessing their physical stress on construction sites.

Keywords

Wearable electromyography (EMG) • Local muscle fatigue • Physical fatigue • Wearable biosensors • Workers' productivity • Safety • Health • Signal processing

22.1 Introduction

Construction is one of the most labor-intensive occupations in which workers are repetitively performing physically demanding tasks [1]. As a result, construction workers often suffer from a significant level of muscle fatigue that adversely affects their productivity, safety, and health [2]. Workers' fatigue has been introduced as one of the major factors that increase workers' error rate and lead to unsafe work actions [3]. Also, Workers' fatigue adversely affects their alertness, reaction time, mental acuity and disposition [4]. For these reasons, it is essential to mitigate the factors and tasks associated with workers' muscle exertion. The first step toward mitigating fatigue in the workplace is to evaluate muscle exertion. Evaluating the level of workers' muscle fatigue in planned tasks before engaging in these tasks can greatly contribute to

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identifying the tasks that may lead to muscle exertion. Then, adjusting the scheduled tasks and actions before severe fatigue takes place will enhance workers' safety, productivity, and well-being.

Previous research efforts have attempted to assess workers' muscle fatigue using subjective assessment (e.g., fatigue questionnaires) [5, 6]. However, interrupting workers' ongoing work to complete questionnaires interferes with time-sensitive tasks. Also, such methods are subjective and therefore include high biases. In addition to subjective assessment of physical fatigue, theoretical models of physiological or mechanical mechanisms (e.g., mathematical models) have been developed to assess workers' muscle fatigue [7, 8]. Despite their potential to evaluate workers' muscle fatigue, these mathematical models are limited in the context of construction tasks that have time-varying force exertions and irregular pauses and short breaks [8]. Therefore, there is a definite need for a measurable and noninvasive method that can continuously measure construction workers' muscle fatigue.

In recent decades, one well-known method for measuring human beings' muscle fatigue is the use of electromyography (EMG), which is the measurement of the electrical impulses produced by the muscle during its contraction [9]. The EMG signal has been used widely in the clinical domain for the diagnosis of muscle fatigue [10–12] and nerve disorders [13, 14]. However, the EMG signal acquired in the clinical domain is based on invasive methods, either by inserting a needle directly into the muscle through the skin or by measuring surface EMG using wired electrodes placed on the skin. Despite the high quality of the EMG signals recorded using these methods, the use of these methods to measure muscle activity is impractical at construction sites due to their invasive experimental settings. However, with recent advancement in sensing technologies, wearable and portable sensors are available and contributed to enhancing job site conditions [15–29]. In this regard, a wearable EMG can open a new door toward a noninvasive and continuous measurement of workers' muscle activity.

Despite the potential of a wearable EMG to collect workers' muscle activity while performing different tasks, the feasibility of a wearable EMG to measure workers' muscle fatigue has not been tested. To address this issue, this study tests the feasibility of a wearable Electromyography (EMG) sensor to measure the electrical impulses produced by workers' muscles as a means of continuously evaluating their muscle exertion and recovery without interfering with their ongoing tasks. To this end, the authors conducted an experiment to collect EMG signals of eight subjects' upper limb muscles (e.g., bicep and shoulder muscle) while they were experiencing different fatigue levels. The authors applied various filtering methods (e.g., a bandpass filter, a rolling filter, and a Hampel filter) to reduce EMG signal artifacts. Then the feasibility of a wearable EMG in distinguishing different levels of muscle fatigue was examined by comparing various metrics (e.g., signal Mean Absolute Value (MAV), Root Mean Square (RMS), Mean Frequency (MNF), and Median Frequency (MDF)) that were calculated based on the EMG signal. The Borg Rate of Perceived Exertion (RPE) scale, which is a well-known method to evaluate perceived muscle exertion, was used as a baseline to measure subjects' muscle fatigue level. Lastly, the feasibility of a wearable EMG sensor in measuring workers' muscle fatigue was examined by comparing the EMG-based metrics for different levels of muscle exertion.

22.2 Surface EMG to Measure Workers' Muscle Fatigue

Surface Electromyography (EMG) is a noninvasive method that provides useful information about the early manifestation of muscle fatigue by measuring the electrical activity of the muscle [9]. Even though raw EMG signals offers valuable information about the muscle activity, these signals need to be processed to measure muscle fatigue level. EMG signals are informative only if they can be quantified. Several studies have illustrated that there exists a significant relationship between EMG parameters (e.g., mean signal amplitude, root mean square, signal variance, mean power frequency, and median power frequency) and muscle fatigue [10–12, 30].

In this section, the authors explain two essential steps to examine the feasibility of measuring construction workers' muscle fatigue using a wearable EMG sensor. Before analyzing the signal, one essential step is to reduce signal noises and signal artifacts. After reducing signal artifacts, to examine the feasibility of a wearable EMG to distinguish different muscle fatigue levels, the authors' extracted different metrics based on the EMG signals.

22.2.1 Artifacts Removal

EMG signal quality can be adversely affected by different sources and forms of signal artifacts. The recorded EMG signal contains a component that shows the electrical response of the muscle activity (desired signal) as well as various noise components that come from sources other than muscle activity (undesired signals) [9]. Ambient noise, motion artifacts, electrical noise from power lines, and inherent instability of the EMG signal are main noise sources [31, 32]. The authors

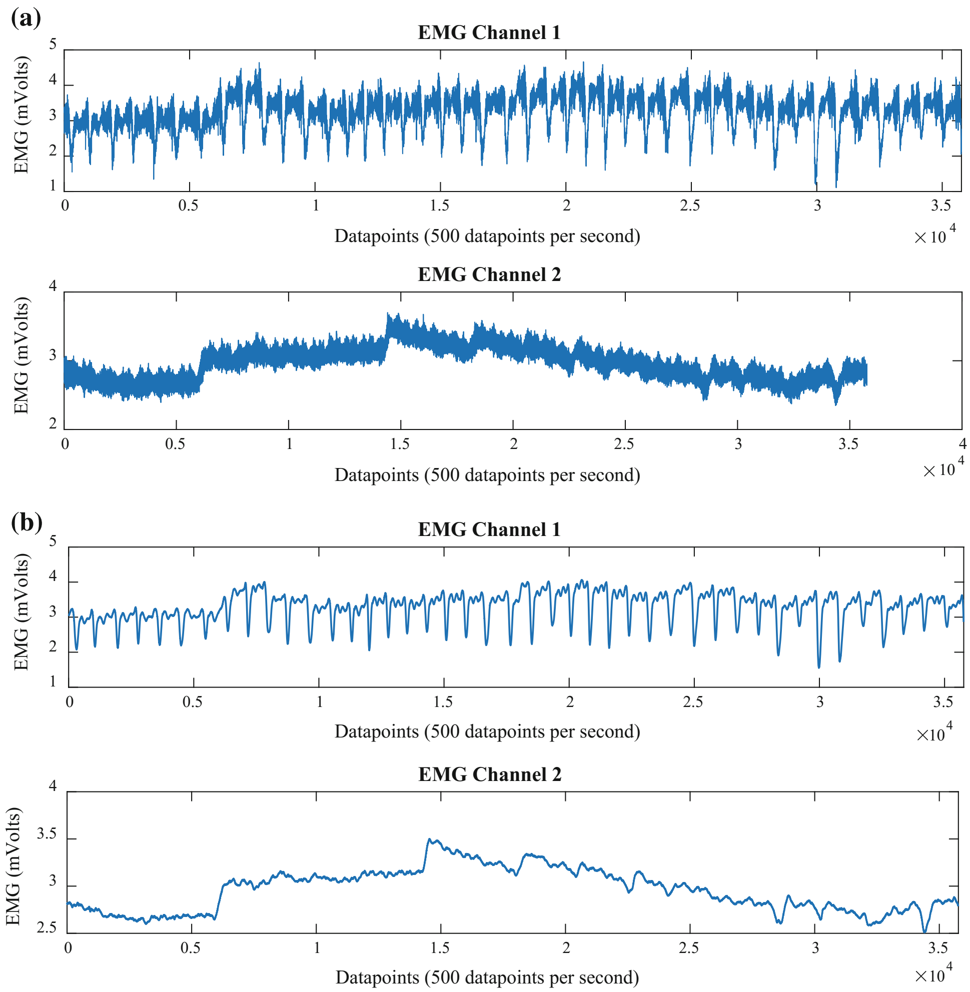

Fig. 22.1 EMG signal artifacts removal: **a** Raw EMG signals recorded from a worker's bicep muscle (Channel 1) and shoulder muscle (Channel 2); **b** Filtered EMG signals

applied different filtering methods (e.g., a bandpass filter, a rolling filter, a Hampel filter and a notch filter) to remove noises from the EMG signals. To remove ambient noise that comes from external electromagnetic sources (e.g., device wire noise), the authors applied a notch filter with a cutoff frequency of 60 Hz, which was recommended by previous researchers as an appropriate cutoff frequency to remove this type of noise [33]. To remove signal outliers a Hampel filter was applied, Hampel filter has been introduced as a useful method to remove EMG signal outliers [34]. A bandpass filter with the lower cutoff frequency of (0.5 Hz) and higher cutoff frequency of 250 Hz was applied to reduce other external signal artifacts (e.g., motion artifacts, ambient noise, and inherent instability of the EMG signals) [35]. To smooth the signal and to avoid aliasing in the data, a rolling filter was applied [31]. Figure 22.1 shows the raw EMG signals and the filtered EMG signals.

22.2.2 EMG-Based Metrics

Signal Mean Absolute Value (MAV), Root Mean Square (RMS), Mean Frequency (MEF), and Median Frequency (MDF) were calculated as the metrics to examine the potential of EMG in measuring workers' muscle fatigue. All of these metrics have been used widely in the clinical domain to assess muscle fatigue. EMG amplitude related parameters in the time domain (e.g., MAV and RMS) have been introduced as the informative metrics to evaluate muscle fatigue and estimate the endurance time [36, 37]. In addition, to the parameters that are calculated in the time domain, previous researchers found that changes in EMG signal patterns in frequency domain also are significantly associated with a decline in muscle force from the fresh state and therefore, it has a high potential to be used to measure muscle fatigue [12, 38]. Table 22.1 shows the extracted parameters based on EMG signal in time and frequency domains. In this research, the authors extracted different EMG signal

Table 22.1 Extracted EMG signal metrics in time and frequency domain

Domain	Parameters	Equation	Explanation
Time domain	Mean Absolute Value (MAV)	$MAV = \frac{\sum_{i=1}^{N} \lvert EMG_i \rvert}{N}$	Average absolute value of EMG amplitude
	Root Mean Square Level (RMS)	$RMS = \sqrt{\frac{\sum_{i=1}^{N} EMG^2}{N}}$	Norm 2 of the EMG amplitude divided by the square root of the number of samples
Frequency domain	Average Frequency (MEF)	$power(EMG, f \in [0Hz, 250Hz])$	Power of the EMG the signal in the frequency domain in the interval $[[0Hz, 250Hz]]$
	Median Frequency (MDF)	$power(EMG, f \in [0Hz, MDF]) = power(EMG, f \in [MDF, 250Hz])$	Half of the signal power is distributed in the frequencies less than MDF

parameters from a block of 500 consecutive data point (1 s) since A single EMG data point is not informative to Due to the high temporal resolution of EMG recording (500 data point in a second).

22.3 Experimental Setting

To examine the feasibility of the EMG-based parameters in measuring workers' muscle fatigue, the authors conducted an experiment and measured the electrical activity of eight healthy subjects while performing tasks with different fatigue level. Subjects were asked to use their upper limbs (i.e., elbow and shoulder muscles) and perform two tasks. In Task 1, subjects were asked to use their shoulder muscle (shoulder flexions from 0° to 120°) to lift a concrete brick that weighed 30% of their maximum shoulder muscle strength (Fig. 22.2a). In Task 2, subjects were asked to lift a concert brick that weighted 30% of their maximum bicep muscle strength using their bicep muscle (Fig. 22.2b). Subjects' maximum muscle strength of elbow and shoulder muscle was measured using a hand-held manual muscle tester (e.g., JTECH Commander Muscle Tester). Also, subjects were asked to maintain a constant lifting speed to prevent accelerations in lifting and to minimize variations in

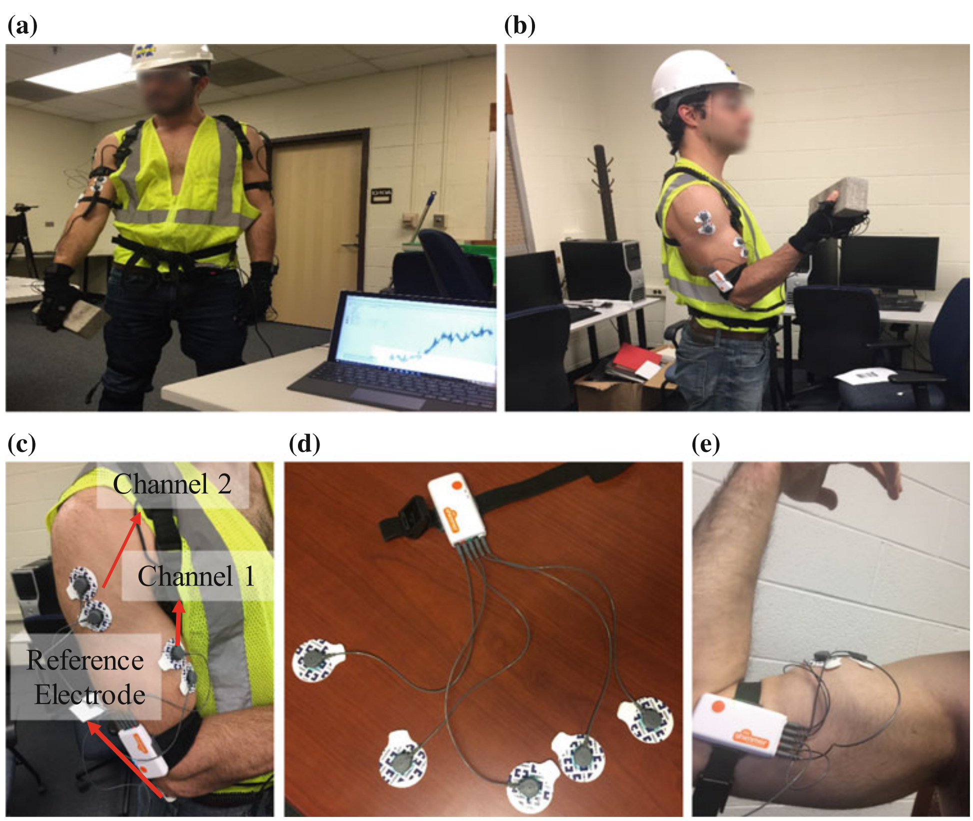

Fig. 22.2 Experimental setup: **a** Task 1: lifting concert brick using shoulder muscle; **b** Task 2: lifting concrete block using bicep muscle; **c** Placement of EMG channels; **d** An off-the-shelf wearable EMG sensor that was used in this study; **e** Placement of EMG electrodes on muscle peak

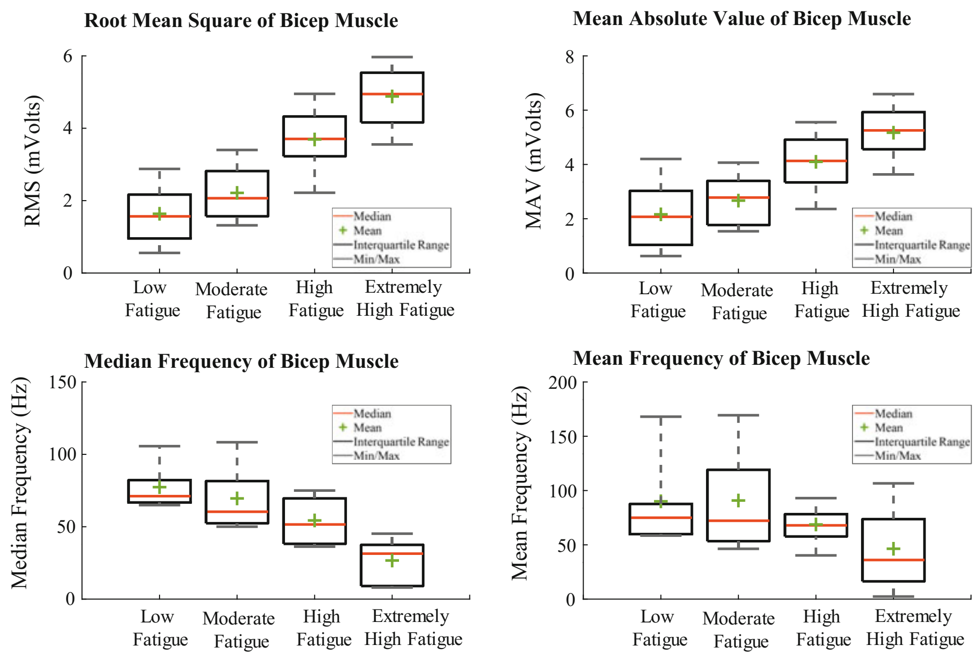

Fig. 22.3 The values of MAV, RMS, MEF, and MDF for bicep muscle

forces during different tasks. EMG signals were acquired from subjects' bicep and shoulder muscles across two channels using a wearable EMG device (Fig. 22.2c, d). EMG electrodes were placed parallel with the muscle fiber between the motor point and the tendinous insertion, near the center of the muscle. A reference electrode was placed far away from the bicep and shoulder muscles at an electrically neutral point of the body (Fig. 22.2e). The Borg Rate of Perceived Exertion scale [39], which assesses perceived exertion of the subjects was used as a baseline to assess subjects' perceived exertion [39]. Subjects were asked to rate their upper body muscles (shoulder muscle in Task 1 and bicep muscle in Task 2) fatigue level every 15 s. According to subjects' perceived exertion, the recorded EMG signals were divided into: Low Fatigue Level

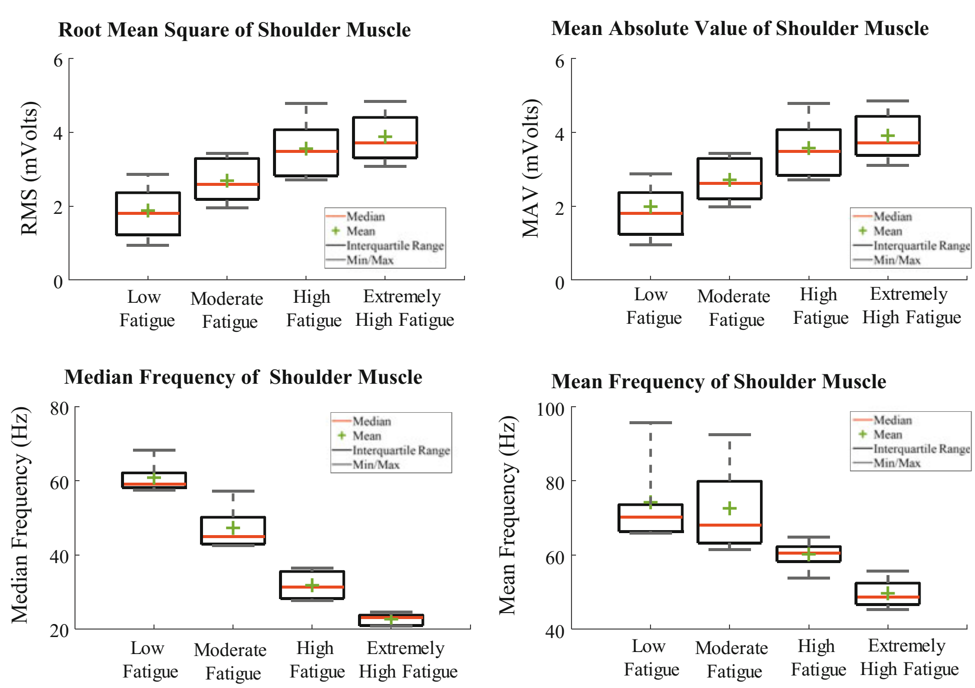

Fig. 22.4 The values of MAV, RMS, MEF, and MDF for shoulder muscle

(RPE scale between 0 and 2), Moderate Fatigue Level (RPE scale between 3 and 4), High Fatigue Level (RPE scale between 5 and 7), and Extremely High Fatigue Level (RPE scale between 8 and 10) [39].

22.4 Results and Findings

Figures 22.3 and 22.4 show the calculated EMG-based metrics values for bicep and shoulder muscles while subjects' were performed the experiment tasks under different fatigue levels. Results indicated a clear difference in MAB, RMS, MEF and MDF values while subjects were perceiving different fatigue levels for both bicep and shoulder muscles. Results show higher MAB, RMS values while subjects experienced higher muscle fatigue level (higher Borg scale rate) compared to the situation with less muscle fatigue (lower Borg scale rate). Higher MAB and RMS values show higher muscle exertion [40]. This confirms the feasibility of the extracted metrics in the time domain to measure workers' upper limb muscle fatigue.

In addition, there was a clear difference in the metrics that were calculated in the frequency domain (MEF and MDF) among different fatigue levels. The results of this study are in accordance with the previous studies in the clinical domains that stated a lower MEF and MDF values shows greater muscle fatigue level [41]. Furthermore, the values of MEF and MDF are consistent, and both illustrated that subjects' experience higher muscle fatigue while they keep lifting the concert bricks continuously. In comparison of time and frequency domain metrics, the metrics that were calculated in the frequency domain led to a higher performance in distinguishing different levels of fatigue; this can be related to less sensitivity of these metrics to the signal noise as well as data aliasing [42].

22.5 Conclusion

The present study was designed to determine the feasibility of a wearable EMG sensor to measure construction workers' upper limb muscle fatigue. The results of this study show the feasibility of the wearable EMG to evaluate workers' muscle fatigue, which can result in measuring physical stress at construction sites. The results showed that higher muscle fatigue level leads to higher MAB and RMS values and Lower MEF and MDF values. These finding may be used to improve construction workers' productivity, safety, and well-being by developing an automatic and mountainous framework to measure workers' muscle fatigue based on their EMG signal. It is recommended that further research be undertaken to validate the use of current metrics in this study in measuring construction workers' fatigue through additional experiments with a larger number of subjects on different muscle groups.

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References

1. Ng, S.T., Tang, Z.: Labour-intensive construction sub-contractors: their critical success factors. Int. J. Project Manage. **28**, 732–740 (2010)
2. Kajimoto, O.: Development of a method of evaluation of fatigue and its economic impacts. In: Fatigue Science for Human Health. Springer, pp. 33–46 (2008)
3. Slack, P.S., Coulson, C.J., Ma, X., Pracy, P., Parmar, S., Webster, K.: The effect of operating time on surgeon's hand tremor. Eur. Arch. Otorhinolaryngol. **266**, 137 (2009)
4. Bowen, P., Edwards, P., Lingard, H., Cattell, K.: Workplace stress, stress effects, and coping mechanisms in the construction industry. J. Constr. Eng. Manag. **140**, 04013059 (2013)
5. Conrad, D., Kellar-Guenther, Y.: Compassion fatigue, burnout, and compassion satisfaction among Colorado child protection workers. Child Abuse Negl. **30**, 1071–1080 (2006)
6. Sadeghniiat-Haghighi, K., Yazdi, Z.: Fatigue management in the workplace. Ind. Psychiatry J. **24**, 12 (2015)
7. Liu, J.Z., Brown, R.W., Yue, G.H.: A dynamical model of muscle activation, fatigue, and recovery. Biophys. J. **82**, 2344–2359 (2002)
8. Ma, L., Chablat, D., Bennis, F., Zhang, W.: A new simple dynamic muscle fatigue model and its validation. Int. J. Ind. Ergon. **39**, 211–220 (2009)
9. Reaz, M.B.I., Hussain, M., Mohd-Yasin, F.: Techniques of EMG signal analysis: detection, processing, classification and applications. Bio. Proced. Online **8**, 11 (2006)
10. Cifrek, M., Medved, V., Tonković, S., Ostojić, S.: Surface EMG based muscle fatigue evaluation in biomechanics. Clin. Biomech. **24**, 327–340 (2009)
11. Katsis, C., Ntouvas, N., Bafas, C., Fotiadis, D.: Assessment of muscle fatigue during driving using surface EMG. In: Proceedings of the IASTED International Conference on Biomedical Engineering (2004)

12. McDonald, A.C., Mulla, D.M., Keir, P.J.: Using EMG amplitude and frequency to calculate a multi-muscle fatigue score and evaluate global shoulder fatigue. Underst. Response Shoulder Complex Demands Repetitive Work. 89 (2017)
13. Okazaki, S., Syoichizono, M., Tamura, H., Nakashima, T., Kato, E., Tono, T.: Development of diagnosis evaluation system of facial nerve paralysis using sEMG (2017)
14. Visser, L.H., Smidt, M.H., Lee, M.L.: High-resolution sonography versus EMG in the diagnosis of carpal tunnel syndrome. J. Neurol. Neurosurg. Psychiatry **79**, 63–67 (2008)
15. Jebelli, H., Ahn, C.R., Stentz, T.L.: Comprehensive fall-risk assessment of construction workers using inertial measurement units: validation of the gait-stability metric to assess the fall risk of iron workers. J. Comput. Civ. Eng. **30**, 04015034 (2015). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000511
16. Jebelli, H., Ahn, C.R., Stentz, T.L.: Fall risk analysis of construction workers using inertial measurement units: validating the usefulness of the postural stability metrics in construction. Saf. Sci. **84**, 161–170 (2016). https://doi.org/10.1061/9780784481264.036
17. Baghdadi, A., Megahed, F.M., Esfahani, E.T., Cavuoto, L.A.,: A machine learning approach to detect changes in gait parameters following a fatiguing occupational task. Ergonomics 1–14 (2018)
18. Jebelli, H., Ahn, C.R., Stentz, T.L.: The validation of gait-stability metrics to assess construction workers' fall risk. Comput. Civ. Build. Eng. **2014**, 997–1004 (2014). https://doi.org/10.1061/9780784413616.124
19. Jebelli, H., Hwang, S., Lee, S.: Feasibility of field measurement of construction workers' valence using a wearable EEG device. In: Computing in Civil Engineering 2017, ASCE, Reston, VA, pp. 99–106 (2017). https://doi.org/10.1061/9780784480830.013
20. Nouredanesh, M., Tung, J.: Machine learning based detection of compensatory balance responses to lateral perturbation using wearable sensors. In: Biomedical Circuits and Systems Conference (BioCAS), 2015 IEEE. IEEE, pp. 1–4 (2015)
21. Jebelli, H., Hwang, S., Lee, S.: EEG-based workers' stress recognition at construction sites. Autom. Constr. **93**, 315–324 (2018). https://doi.org/10.1016/j.autcon.2018.05.027
22. Hwang, S., Seo, J., Jebelli, H., Lee, S.: Feasibility analysis of heart rate monitoring of construction workers using a photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker. Autom. Constr. (2016). https://doi.org/10.1016/j.autcon.2016.08.029
23. Hwang, S., Jebelli, H., Choi, B., Choi, M., Lee, S.: Measuring workers' emotional state during construction tasks using wearable EEG. J. Constr. Eng. Manag. **144**, 04018050 (2018). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001506
24. Kim, H., Ahn, C.R., Stentz, T.L., Jebelli, H.: Assessing the effects of slippery steel beam coatings to ironworkers' gait stability. Appl. Ergon. **68**, 72–79 (2018). https://doi.org/10.1016/j.apergo.2017.11.003
25. Yang, K., Jebelli, H., Ahn, C., Vuran, M.: Threshold-based approach to detect near-miss falls of iron workers using inertial measurement units. In: Computing in Civil Engineering 2015, ASCE, pp. 148–155 (2015). https://doi.org/10.1061/9780784479247.019
26. Jebelli, H., Yang, K., Khalili, M.M., Ahn, C.R., Stentz, T.: Assessing the effects of tool-loading formation on construction workers' postural stability. In: Construction Research Congress 2018, pp. 292–302 (2018). https://doi.org/10.1061/9780784481288.029
27. Jebelli, H., Choi, B., Kim, H., Lee, S.: Feasibility study of a wristband-type wearable sensor to understand construction workers' physical and mental status. In: Construction Research Congress 2018. ASCE, Reston, VA, pp. 367–377 (2018). https://doi.org/10.1061/9780784481264.036
28. Jebelli, H., Khalili, M.M., Hwang, S., Lee, S.: A supervised learning-based construction workers' stress recognition using a wearable electroencephalography (EEG) device. In: Construction Research Congress 2018 (2018). https://doi.org/10.1061/9780784481288.005
29. Jebelli, H., Hwang, S., Lee, S.: EEG signal-processing framework to obtain high-quality brain waves from an Off-the-Shelf wearable EEG device. J. Comput. Civ. Eng. **32**, 04017070 (2017). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000719
30. De Luca, C.J.: Use of the surface EMG signal for performance evaluation of back muscles. Muscle Nerve **16**, 210–216 (1993)
31. De Luca, C.J., Gilmore, L.D., Kuznetsov, M., Roy, S.H.: Filtering the surface EMG signal: movement artifact and baseline noise contamination. J. Biomech. **43**, 1573–1579 (2010)
32. Nouredanesh, M., Kukreja, S.L., Tung, J.: Detection of compensatory balance responses using wearable electromyography sensors for fall-risk assessment. In: 2016 IEEE 38th Annual International Conference of The Engineering in Medicine and Biology Society (EMBC). IEEE, pp. 1680–1683 (2016)
33. Hogan, N.: A review of the methods of processing EMG for use as a proportional control signal. Biomed. Eng. **11**, 81–86 (1976)
34. Marateb, H.R., Rojas-Martínez, M., Mansourian, M., Merletti, R., Villanueva, M.A.M.: Outlier detection in high-density surface electromyographic signals. Med. Biol. Eng. Compu. **50**, 79–89 (2012)
35. Merletti, R., Di Torino, P.: Standards for reporting EMG data. J. Electromyogr. Kinesiol. **9**, 3–4 (1999)
36. McCrary, J.M., Ackermann, B.J., Halaki, M.: EMG amplitude, fatigue threshold, and time to task failure: a meta-analysis. J. Sci. Med. Sport (2017)
37. Tkach, D., Huang, H., Kuiken, T.A.: Study of stability of time-domain features for electromyographic pattern recognition. J. Neuroeng. Rehabil. **7**, 21 (2010)
38. Mannion, A.F., Dolan, P., Mannion, A.: Relationship between myoelectric and mechanical manifestations of fatigue in the quadriceps femoris muscle group. Eur. J. Appl. Physiol. **74**, 411–419 (1996)
39. Borg, G.A.: Psychophysical bases of perceived exertion. Med. Sci. Sports Exerc. **14**, 377–381 (1982)
40. Dideriksen, J.L., Farina, D., Enoka, R.M.: Influence of fatigue on the simulated relation between the amplitude of the surface electromyogram and muscle force. Philos. Trans. Royal Soc. London A: Math. Phys. Eng. Sci. **368**, 2765–2781 (2010)
41. Allison, G., Fujiwara, T.: The relationship between EMG median frequency and low frequency band amplitude changes at different levels of muscle capacity. Clin. Biomech. **17**, 464–469 (2002)
42. Watanabe, K., Akima, H.: Neuromuscular activation of vastus intermedius muscle during fatiguing exercise. J. Electromyogr. Kinesiol. **20**, 661–666 (2010)

23 Tacit Knowledge: How Can We Capture It?

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Abstract

The importance of knowledge transfer or mentoring as a way to pass tacit knowledge (experience) across generations is discussed widely. Within project management this tends to rely on proximity and mutual exchange. The sender/receiver approaches used to transfer learning from one project to another is inhibited by the context of the projects, and the lack of time, which may obscure its relevance or purpose. There is concern that the knowledge captured in the minds of senior project managers is not being passed on to the next generation. Conversely it may be that much of the knowledge senior project managers have is obsolete or has been superseded by new methods and systems. This study used a grounded theory approach when interviewing 25 construction project managers from Australia on the management of project risk. Experience accumulated over time was considered by almost all interviewees to be the most important way of accumulating knowledge. Methods such as lessons learnt and close off reports are poorly used; most tacit knowledge is transferred through mentoring with very limited use of technology in this process. Changing construction technology did not concern the PMs as they perceived their job as managing processes and their role being flexible enough to adapt to change. From an industry perspective this lack of concern with the sharing of tacit knowledge and the lack of effective systems to capture it is going to be detrimental for its future. Project managers tended to still rely on traditional and the often poorly utilized methods such as lessons learnt and mentoring to capture this knowledge. Using this information, the study examines the key issues around knowledge management in project organizations and possible avenues for capturing tacit knowledge. Tacit knowledge will potentially be lost unless better systems are developed. This paper questions how Building Information Modelling, IT systems and the more visually based techniques such as pod casting, 3D photography, time-lapse cameras, web-based methods can to be used to accumulate and enable more effective knowledge transfer. The conclusion derived is that experience accumulated to generate tacit knowledge is essential for the successful management of future projects.

Keywords

Knowledge management • Project management • Tacit knowledge • Experience • Grounded theory

23.1 Introduction

Knowledge and organizational learning are important factors in optimizing risk management and decision-making within a project. The terms knowledge management (KM) and organizational learning have various interpretations. Knowledge and the learning attributed to knowledge, is highly subjective and dependent upon the perception of the individual, as demonstrated by a change in behavior [1]. KM in a project context is '*the management activities required to source the knowledge stock, create the enabling environment, and manage the knowledge practices to result in an aligned set of*

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project-based knowledges' ([2], p. 665). The project management body of knowledge ([3], p. 709) defines knowledge as '*a mixture of experience, values and beliefs, contextual information, intuition, and insight that people use to make sense of new experiences and information*'. Other authors apply different attributes to knowledge including '*the leveraging of collective wisdom to increase responsiveness and innovation*' from Frappaolo ([4], p. 8). The aim for KM is to create an asset based on information and expertise and to turn this asset into a competitive advantage [5]. The stock of knowledge is important [2] and its reuse is significant for stimulating creative and innovative outcomes [6, 7].

Knowledge is the most important resource needed by project managers (PMs) [8]. The rising complexity of projects has increased the need to manage knowledge better. The increasing complexity of projects is attributed to a number of factors. These include the growth in the size of projects, rising competitive and dynamic environments and the transit nature of programs and projects [9–11]. The management of complexity in projects includes: setting up contracting and procurement processes, developing temporary organizational structures, managing new legislative controls, keeping abreast of changing technology, managing a multicultural workforce, cultivating talent, providing leadership, and generating flexible resilient workforces [12].

This paper builds on the experiences of 25 PMs in the construction industry who demonstrated from their conversations the importance of experience (tacit knowledge (TK)) in shaping their ability to manage projects. A literature review was conducted to compare their experiences as captured through this research with literature. This paper provides an explanation for what TK is, offers evidence of its importance, reveals how it is transferred and whether there are more effective ways that project organizations can use to transfer knowledge. The following section provides an outline of the importance of KM, what it is and how explicit KM differs from TK. The subsequent sections of the paper explain the research method used, a discussion as to the findings of this research and finally the concluding remarks.

23.2 The Process of Knowledge Transfer

23.2.1 Explicit Knowledge and Tacit Knowledge

Knowledge can be categorized as a mix of explicit knowledge and tacit knowledge. Both are critical for further knowledge creation. Explicit knowledge is universal in its character, and accessible through conscious learning [13]. It tends to be the knowledge that PMs learn through their application of systems and processes usually via their learning through academic courses, corporate systems and processes, their Project Management Offices and via the PM Associations qualifications [14]. Explicit knowledge is particularly important when managing multiple projects and the time/cost/quality constraints of the organization. This knowledge needs to be made explicit, so that it can be examined, verified, shared and there is consistency between the multiple projects. [2, 15]. This type of knowledge is important for enabling PMs to establish the formal boundaries, processes and systems of good practice. Explicit knowledge is much easier to transfer as it can be taught. Todorovic [16] found that the best way to improve KM in projects was by applying a systematic approach to analyzing the projects factors and providing good documentation and information for future projects. This finding however, focuses on only explicit knowledge systems and does not allow for added benefits that could be obtained by including methods for TK to be accumulated by the PM and their team [17].

This paper looks at TK and some of the issues and suggestions as to how this type of knowledge can be transferred. Nonaka and Krogh ([13], p. 635) suggest that '*the concept of "tacit knowledge" is a corner-stone in organizational knowledge creation theory and covers knowledge that is unarticulated and tied to the senses, movement skills, physical experiences, intuition, or implicit rules of thumb*'. TK is accumulated via experience and is related to a specific context. TK is deeply rooted in individual's actions and experiences, their ideals, values, and emotions. '*The subjective and intuitive nature of tacit knowledge makes it difficult to process or transmit the acquired knowledge in any systematic or logical manner*' according to DeSouza ([18], p. 86). TK is what people possess, which cannot be made explicit using standard written based methods, yet it influences how people think, act and make decisions [17, 19, 20]. TK is what distinguishes a successfully run project from one poorly run [19, 21–24].

Experience is what provides TK and it is this form of knowledge that is important to the PMs and their organizations. Experience allows for professionals to find patterns in situations and to differentiate what information is relevant to a decision. The cognitive abilities of the unconscious mind are integrated with the conscious mind and are particularly relevant in complex and novel situations [25]. PMs use this experience to make decisions based on unconscious reasoning or intuition. As indicated by Elbanna [26] intuition enhances the outcomes of project management decision-making.

Experience is the knowledge or mastery of an event or subject gained through involvement in or exposure to it, plus experience enhances the knowledge transfer [27].

23.2.2 Knowledge Transfer

There are many factors that assist the successful transfer process, whether explicit or tacit. Bakker et al. [28] demonstrated with his case studies that successful knowledge transfer between the project and the parent organization relied upon multiple factors including the absorptive ability of the project owner; their proximity and communication ability. Interestingly, the authors imply that the responsibility for knowledge transfer lies with the parent organization, not with the PM. This is supported by Lindner and Wald [29] who found that the cultural factors are the most significant factor in KM success. As temporary organizations, the project management team's positive values, their attitudes and expectations, the willingness to share knowledge and to trust in knowledge from other persons become significant factors. Akhavan and Zahedi [22] attributed successful knowledge transfer to: aligning strategies to encouraged knowledge sharing among employees, providing a suitable knowledge structure, educational initiatives and access to advanced gather and share tools, plus a positive organizational culture with appropriate rewards and incentives.

TK is associated with informal learning. Informal learning includes: learning recorded and passed on to the uninitiated by mechanisms such as non-credited learning, work-based learning, volunteerism and service learning, mentoring and coaching, community of practice and on the job training [17]. Typically, project organizations use mentoring or lessons learnt as part of the process of capturing experience in projects. This sender/receiver approach to the transfer of learning from one project to another appears to be restricted by the context of the project, with associated time restrictions, and project team membership. For knowledge transfer to be successful it needs to be aligned to the needs of the recipient. Bresnen et al. [30] concluded that to be effective in the transfer of TK organizations needed to allow for the nature of projects, and the replication of common properties to enable experience building but also allow flexibility to adjust for the unique and unpredictable nature of new projects.

It is difficult to measure the efficacy of TK but productivity improvements are one possible measure [29, 31, 32]. The construction industry has made some changes to improve its productivity by shifting from onsite construction to onsite assembly, changing from traditional paper based documentation to the use of computer-aided systems, and adopting more sophisticated project management practices [33]. Naoum [31] suggests that advances in technology that lead to increasing site productivity are associated mainly with pre-construction activities, and the experience of PMs. However, even with advancements in the construction industry, the core technologies and systems appear to have changed little over the past twenty years with many technologies and systems that emerged post-World War II remaining dominant [34].

23.2.3 The Construction Industry in Australia

In 2015, the Commonwealth Government report on the Construction Industry [35] indicated that construction is the third largest industry in Australia employing over a million workers. Australia's national construction code (NCC) integrates all on-site construction requirements into a single code. The Building Code of Australia (BCA) is produced and maintained by the Australian Building Codes Board on behalf of the Australian Government and State and Territory Governments [36]. Each State in Australia has a different composition of its construction industry with some States heavily into mining, while others focus on heavy civil or built construction. South Australia has a higher proportion of mining and building construction and less civil construction [37].

The Australian Industry Group 2015 Report [35] indicated that the construction industry generally tends to attract a young workforce with 43.3% being under 34 years, but with a rising number of older (over 55 years) participants growing. Added to this is an apparent loss of skills and the potential for a skills shortage particularly among the trade skills [38]. The traditional career paths of moving up the ranks of an organisation from the trades, is being replaced by the higher stream employees coming in as graduates with limited or no practical experience. According to AIQS report Report [39], commencements with a Bachelor and Master's degrees in building construction management have increased strongly from 682 in 2005 to 965 in 2015. Employment outcomes for graduates in building construction management remains strong with fulltime employment for those completing bachelor's degrees in this field at 95.6% in 2016, compared with 71.0% for all bachelor degree graduates.

There is growing apprehension that the lack of effective KM between different groups of workers and the potential for a loss of relevant knowledge associated with an ageing workforce [40–42]. Vocational and university graduates bring with them new skills and explicit knowledge. Integrated into most of these tertiary programs are structured BIM courses enabling graduates to apply this in their work, to interact with, interpret, and potentially update information available on the BIM database. Research has shown (BIM) is becoming an increasingly important factor in both the efficiency and international competitiveness of the Australian construction industry [43, 44]. Most graduates lack the work experience that older workers have but conversely they bring with them new skills/knowledge that the older workers lack. The lack of these skills in the older workforce potentially increases a need for up-skilling and re-skilling of existing construction workers. Thus the transfer of knowledge needs to be between different groups in the workforce.

23.2.4 How Tacit Knowledge Can Be Transferred

Explicit knowledge can be acquired, written down, codified, and stored. It can, therefore, be easily transferred between projects, teams and within the profession or organization. TK transfer is more problematic. As Terzieva [17], p. 1088 explains '*tacit knowledge is usually subconscious, internalized, and the individual may or may not be aware of what he or she knows or how he or she accomplishes particular results*'. This usually necessitates that the PMs have extensive personal contact and regular interaction via the process of learning through reflection on experience (their own and others), through work placement and exposure and by the advice and guidance provided by a mentor. Most contemporary research focuses on understanding learning through collaboration, the value of a reflective practitioner and the growing use of big data [7] and not on how it is transferred.

The recommendations of appropriate tools and techniques for risk management from the PMI [3], and the ISO 31010:2009 include qualitative techniques such as lessons learnt, mentoring, brainstorming and nominal group techniques to capture this knowledge. All rely on the experience of the PMs, the project team and other experts. Lessons learnt relies on other PMs perception and their evaluation of whether to include them in their summative reports. Li et al. [14] suggested these methods provide useful tools for allowing the documentation of experience, but the use of them requires extensive expertise as they structure and formalize the experience making it less useful for inquiring PMs because it is static and deterministic.

More recently with the use of technology, there is potential to improve and expand the transfer of TK to those not in personal contacts with the dispenser of that knowledge. This can be achieved through the use of verbal, visual and internet-based communications. Contemporary technology has enabled new mechanisms for the transmitting of TK with time-lapse photography, 3D photography, case studies, games, interviews, and more mobile applications such as 'face timing' and podcasting. This means mentors can be on the other side of the world, communications need not to be synchronized, historical knowledge can be capture permanently and comparative projects can be sourced easily; however unique they may be. Learning can also be through simulations, interactive case studies, computer-based methods and other modern forms of education. Terzieva [17] provides a list of ways to transfer TK: via networks (social or sharing platforms/forums), interactive PM training, coaching and mentoring, videotaping, storytelling, after action reviews, post mortem sessions, exit interviews, and emeritus or alumni programs. Podcasts are increasingly being used for reflective learning with success. Much of the tacit learning is based on reflection, which enables participants to reflect on their approach and the practice of others [45].

Information Systems (IS) are also commonly used to capture knowledge though they are considered to be much better at transferring explicit knowledge than for transferring the less easily documented TK [20]. The standard way for corporations to access accumulated knowledge is via extensive software systems that store the knowledge as tables or other documents. Project Management Information Systems (PMIS) are software applications that help managers track projects from their inception to their closeout. PMIS act as KM systems to provide PM and their organizations with pertinent information, a systematic methodology and an effective communication platform [46]. The applicability and coverage of PMIS is likely to increase with the complexity of projects and when the users are physically separated [47]. The quality of the PMIS information was directly related to the quality of decision making and the satisfaction of multi-PMs with that system [23]. There also appears to be a clear positive relationship between the effectiveness of these systems and positive project outcomes [47]. Traditional analytical modelling approaches only present a static and mono-perspective image of a highly dynamic industry and do not allow for a more collaborative approach; which is required in the construction industry [48].

An additional way that research papers discuss the transfer of knowledge is via Building Information Modeling (BIM). BIM has all the potential to be a unique KM system [49]. BIM is an all-embracing term to describe a variety of activities in object-oriented Computer Aided Design, which supports the representation of building elements in terms of their 3D geometric and non-geometric functional attributes. BIM facilitates inter-organizational cooperation in the construction industry [48] leading to improved productivity by enhancing design, construction and asset management practices. BIM applies a format, which allows for complexity, enables revisions and provides a visual perspective to the design, construction and maintenance of projects [50–52]. BIM has been an important KM application for improving risk management in construction projects [53]. The potential for improvements capturing learning in risk management with better KM systems such as BIM was strong, particularly with the development of 4D versions [52, 54].

23.3 Research Method

This study applied the grounded theory (GT) method. GT approach is the discovery of emerging patterns in information gathered by discussing specific experiences directly with the research participants allowing them to understand, interpret and then express their opinions [55]. The semi-structured interviews were particularly appropriate for this enquiry, as they drew on the knowledge and experience of a diverse range of topics. Analysis of the interview conversations enables the development of themes that reflect the richness and truths far more than the other structured methods such as by survey, questionnaire or quiz. Qualitative research methods with their emphasis on experiences are appropriate for locating the meanings around the events, concepts and the social context within which a PM operates [55]. Research questions were open requiring respondents to describe and explain their own experiences.

Interviews were conducted with 25 PMs. A series of open-ended questions were asked of the PMs including what tools and techniques they used to manage risks, their level of confidence and ability manage the all types of risks, what they considered important to their ability to manage risk, their planning or risks and how important they considered their experience to be. Using Nvivo 10 software to provide an intensive analysis of this qualitative information, data was sorted so the latent social patterns were conceptualized and structured to develop a theme related to the use of experience. Building on this research and the knowledge, that experience was fundamental to their ability to identify and manage risks, the author undertook a review of literature on how this TK was captured and transferred. The choice to interview 25 PM was based on the concept of purposive sampling; whereby data saturation and the cessation of interviewing was determined when no additional information was gained by undertaking further interviews [56].

The selection criteria for the interviewees were based on the following criterion: involved in or recently retired from project management positions/roles; at least 4 years PMS experience, and had managed one or more projects valued over $500,000. Participants were from South Australia. Half had worked on interstate or national projects. Participants were also chosen for their variety of employment experience (30% of the participants had over 30 years, 32% has between 20 and 29 years, 20% 10 years to 19 years and the remaining 20% less than this) and varied areas of industry. Participants represented: 11% residential building construction, 34% non-residential building (commercial/industrial), 29% heavy and civil engineering construction and 26% construction services (including services in land development and site preparation, building structure, building installation, building completion, and other construction areas). The organizations in which they were employed varied in respect to employee numbers.

23.4 Research Findings and Discussion

The semi-structured interviews have been analyzed into themes that showed common aspects. The common aspects are summarized in the list below.

1. Capturing of tacit knowledge not the focus of organizations

The interviews reinforce Terzieva's [17] finding that explicit KM methods are more commonly applied. TK methods such as videotaping, storytelling, exit interviews and emeritus or alumni programs were less visible and less frequently used. His conclusion was that this was due to the more sensitive nature of TK and the effort required to capturing it.

2. Experience accumulated over time was considered by almost all interviewees to be the most important way of accumulating knowledge

This is consistent with the finding that management of risks in a project depends on in-house knowledge and experience [57]. The '*processes of knowledge capture, transfer and learning in project settings rely very heavily upon social patterns, practices and processes in ways which emphasize the value and importance of adopting a community-based approach to managing knowledge*' [13, p. 157]. The PMs relied on experience because they are in an industry which uses temporary structures, has changing teams, is faced with constraints of time and cost, and is constantly exposed to new construction techniques and processes. PMs used their accumulated experience and that of their team to better identify and manage risks in subsequent projects. However, TK is seen by some as a source of their power so there was some reluctance to transfer all knowledge to other members.

3. Lessons learnt and close out reports poorly used

There was a clear understanding by the interviewees of the purpose of lessons learnt with all but one participant indicated they collected some form if this or close out reports but not all applied them to their future projects. Some PMs used previous project lessons learnt as a checklist for future projects or referred to them prior to commencing their next project. Several interviewees, however, openly stated that they did not consult other PMs lessons learnt, as their projects were too unique to learn from. Time constraints also limited their capacity to gather quality information and their ability to apply lessons learnt. This is similar to the results found by Tserng, [58] who concluded that the nature of the construction industry makes projects unique, often with transient ad hoc project teams, on-site production, and a corresponding high turnover of staff especially those with low skills. Making it problematic for the construction industry to coordinate, store, and reuse relevant knowledge from past projects for future projects.

4. Tacit knowledge is transferred through mentoring

Main mechanism to accumulate knowledge according to interviewees is via mentoring and accumulating experience over time. The importance of TK transfer inter-generationally was discussed widely. Common methods such as work placement and mentoring rely on the proximity and mutual exchange within the PM context [5]. This is consistent with the findings of this study.

5. Limited use of technology to transfer knowledge

Interviewees commonly utilized the internet or accessed experts to provide information where they perceived a gap in their knowledge. Technology is progressively altering the visibility of and changing way knowledge is transferred. The interviewees relied on PMIS and some used IT systems to source lessons learnt. Most interviewees criticized their organization's processes and systems for managing lessons learnt and the lack of practical access to lessons learnt from others. PMs also indicated their organizations did not use BIM due to the cost and complexity of implementing it but also due to the lack of training and knowledge. This was consistent with the summation that the potential for investment in innovation is restricted to the relatively few large companies who deal with sophisticated clients who procure buildings on a frequent basis,. Smaller construction projects clients/companies were too focused on attaining the lowest price to make effective innovation possible [59]. The adoption of BIM appeared to be resisted by many in the industry, due to the poor perception of BIM and the belief by many that it is an unrewarding burden for construction managers [60]. Smaller firms tend to equate BIM with purely 3D modelling and unjustifiable costs, while large organizations seem to understand the benefits of its ability to improve managing design and construction, managing costs, schedules and as a mechanism to exchange of information; though whether they equated this with KM was hard to determine. The biggest gains, from the introduction of enhanced BIM technologies, appeared to accrue to larger companies [51, 61].

6. Changing construction technology did not concern the PMs as they perceived their job as managing the processes and their role was flexible enough to adapt to change

The shortening of the knowledge value lifespan is evident in the construction industry, which is moving to adopt new technology, materials and manage in an increasingly complex world. This view is consistent with the project manager's perception, that construction projects are increasing using innovative methods and experiencing increasing rates of change. However, the issue of whether the use of lessons learnt is increasingly less relevant to future projects due to the adopted new construction techniques or new work practices was not accepted by the interviewees. The concept of ‘knowledge risk’, which implies that the value or useful relevance of knowledge is becoming shorter, did not appear to be of concern for the interviewed PMs [62]. This is consistent with previous studies [1, 59]. They managed any unknown by bringing in new team members or sourcing expertise. It was their ability to do this effectively and to draw on their experience that enables them to ask the right questions. From an industry perspective it appears that this lack of concern with the passing or sharing of knowledge plus the lack of effective systems to capture and pass on TK is going to be detrimental for its future.

23.5 Conclusions

This research paper focused on explaining what TK is, its importance, and how it is being utilized in the Australian construction industry. This paper outlines how TK is transferred and whether there are more effective ways that project organizations can seek to transfer knowledge. Through empirical research and a GT strategy employed, it was concluded that experience was of utmost importance for construction project managers. However, past knowledge was not always documented effectively in systems or processes of their organizations. There was some evidence that knowledge storage was slowly happening in some organizations with BIM and with some visual records being adopted. The interviewees provided no evidence of any effective commercial or bespoke IT/digital systems used by PMs for capturing experience. In cases where knowledge was captured, this relied on systems that captured lessons learnt as part of a closeout report or similar. This reliance on traditional methods for transferring TK did not seem to be effective as the new project management team members had to be mentored or had to learn though observation. KM systems appear to be poor or none existent. This raised major questions as to how the construction industry is going to manage its changing profile of its workers in terms of age and education. There is clear evidence that those at management level in the construction industry are increasingly gaining employment through university qualifications, not the traditional career progression pathway. A divide between educated employees with no TK and ageing employees with TK and a lack of technical nous is emerging. The need to adopt effective TK KM processes is needed for industry growth. The suggestion is that organizations in this industry need to develop a more sophisticated approach to capturing TK to utilizing. Organizations need to utilize more technically flexible methods such as video recording, time-lapse photography, 3D etc. Further research remains to be done on how these sophisticated methods can actually improve TK communication.

References

1. McClory, S., Read, M., Labib, A.: Conceptualising the lessons-learned process in project management: Towards a triple-loop learning framework. Int. J. Project Manage. **35**(7), 1322–1335 (2017)
2. Reich, B.H., Gemino, A., Sauer, C.: Knowledge management and project-based knowledge in it projects: a model and preliminary empirical results. Int. J. Project Manage. **30**(6), 663–674 (2012)
3. Project Management Institute (PMI).: The PMI guide to business analysis. Project Management Institute, Inc, Newtown Square, Pennsylvania (2017)
4. Frappaolo, C.: Knowledge management. Capstone Publishing, online (2006)
5. Aerts, G., Dooms, M., Haezendonck, E.: Knowledge transfers and project-based learning in large scale infrastructure development projects: an exploratory and comparative ex-post analysis. Int. J. Project Manage. **35**(3), 224–240 (2017)
6. Khedhaouria, A., Jamal, A.: Sourcing knowledge for innovation: knowledge reuse and creation in project teams. J. Knowl. Manag. **19**(5), 932–948 (2015)
7. Walker, H.T.: Reflecting on 10 years of focus on innovation, organisational learning and knowledge management literature in a construction project management context. Constr. Innovation **16**(2), 114–126 (2016)
8. Gasik, S.: A model of project knowledge management. Project Manage. J. **42**(3), 23–44 (2011)
9. Antunes, R., Gonzalez, V.: A production model for construction: a theoretical framework. Buildings **5**(1), 209–228 (2015)
10. Curlee, W., Gordon, R.L. ©, Complexity theory and project management, Wiley, Hoboken, N.J. (2011)
11. Qazi, A., Quigley, J., Dickson, A., Kirytopoulos, K.: Project Complexity and Risk Management (ProCRiM): towards modelling project complexity driven risk paths in construction projects. Int. J. Project Manage. **34**, 1183–1198 (2016)
12. Bakhshi, J., Ireland, V., Gorod, A.: Clarifying the project complexity construct: Past, present and future. Int. J. Project Manage. **34**(7), 1199–1213 (2016)
13. Nonaka, I., Von, K.G.: Tacit knowledge and knowledge conversion: controversy and advancement in organizational knowledge creation theory. Organ. Sci. **20**(3), 635–652 (2009)
14. Li, L., Liu, M., Shen, W., Cheng, G.: An expert knowledge-based dynamic maintenance task assignment model using discrete stress–strength interference theory’ Knowledge. Based Syst. 131, 135–148 (2017) (1 September 2017)

15. Kanapeckiene, L., Kaklauskas, A., Zavadskas, E., Seniut, M.: Integrated knowledge management model and system for construction projects. Eng. Appl. Artif. Intell. **23**(7), 1200–1215 (2010)
16. Todorović, M.L., Petrović, D.Č., Mihić, M.M., Obradović, V.L., Bushuyev, S.D.: Project success analysis framework: a knowledge-based approach in project management. Int. J. Project Manage. **33**(4), 772–783 (2015)
17. Terzieva, M.: Project knowledge management: how organizations learn from experience. Procedia Technol. **16**, 1086–1095 (2014)
18. DeSouza, K.: Facilitating tacit knowledge exchange. Commun. ACM **46**(6), 85–88 (2003)
19. Hislop, D.: Knowledge management in organizations: a critical introduction, 3rd edn. Oxford University Press, Oxford (2013)
20. Omotayo, F.O.: Knowledge management as an important tool in organisational management: a review of literature. Libr. Philos. Pract. (e-journal). 1238 (2015)
21. Abu, A.H., Yusof, M.N., Tufail, M.A., Virgiyanti, W.: Effect of knowledge management on growth performance in construction industry. Manag. Decis. **54**(3), 735–749 (2016)
22. Akhavan, P., Zahedi, M.: Critical Success Factors in Knowledge Management Among Project-Based Organizations: A Multi-Case Analysis. ICFAI J. Knowl. Manag. **12**(1), 20–20 (2014)
23. Caniëls, M.C., Bakens, R.J.: The effects of project management information systems on decision making in a multi project environment. Int. J. Project Manage. **30**, 162–175 (2011)
24. Okere, G.: Barriers and enablers of effective knowledge management: a case in the construction sector. Electr. J. Knowl. Manag **15**(2), 85–97 (2017)
25. IBISWorld 'Construction in Australia Industry Report E', IBISWorld Network, Melbourne, 4 (2016)
26. Elbanna, S.: Intuition in project management and missing links: analyzing the predicating effects of environment and the mediating role of reflexivity. Int. J. Project Manage. **33**(6), 1236–1248 (2015)
27. Liu, R., Hart, S.: Does experience matter?-A study of knowledge processes and uncertainty reduction in solution innovation. Ind. Mark. Mgt **40**(5), 691–698 (2011)
28. Bakker, R.M., Cambré, B., Korlaar, L., Raab, J.: Managing the project learning paradox: a set-theoretic approach toward project knowledge transfer. Int. J. Project Manage. **29**(5), 494–503 (2011)
29. Lindner, F., Wald, A.: Success factors of knowledge management in temporary organizations. Int. J. Project Manage. **29**(7), 877–888 (2011)
30. Bresnen, M., Edelman, L., Newell, S., Scarbrough, H., Swan, J.: Social practices and the management of knowledge in project environments. Int. J. Project Manage. **21**(3), 157–166 (2003)
31. Naoum, S.G.: Factors influencing labor productivity on construction sites. Int. J. Prod. Performance Manag. **65**(3), 401–421 (2016)
32. Torabi, F., El-Den, J.: The impact of knowledge management on organizational productivity: a case study on Koosar Bank of Iran. Procedia Comput. Sci. **124**, 300–310 (2017)
33. McKinsey Global Institute.: Reinventing construction: a route to higher productivity. 2017 Accessed 19 Apr 2018
34. Isenman, L.: Understanding unconscious intelligence and intuition: "Blink" and beyond. Perspect. Biol. Med. **56**(1), 148–166 (2013)
35. Australian Industry Group, Australia's construction industry: profile and outlook. July, Australian Government Department of Employment, Melbourne, Victoria (2015)
36. ABCB Homepage, http://www.abcb.gov.au/, last accessed 2018/04/10
37. Chancellor, W.: Drivers of productivity: a case study of the Australian construction industry. Constr. Econ. Build. **15**(3), 85–97 (2015)
38. Sivam, A., Trasente, T., Karuppannan, S., Chileshe, N.: The impact of ageing workforce on the construction industry in Australia, In: Emuze, F. and Smallwood, J. (eds), Valuing People in Construction, Abingdon, Oxon New York, NY Routledge, an imprint of the Taylor & Francis Group, Chapter 5, 78–97 (2018)
39. The Australian Institute of Quantity Surveyors.: When Costs Count—Engage a Certified Quantity Surveyor', AIQS (2017)
40. Crawford, L., French, E., Lloyd-Walker, B.: From outpost to outback: project career paths in Australia. Int. J. Project Manage. **31**(8), 1175–1187 (2013)
41. Harvey, J.: Managing organizational memory with intergenerational knowledge transfer. J. Knowl. Manag. **16**(3), 400–417 (2012)
42. Pollack, J.: Transferring knowledge about knowledge management: implementation of a complex organisational change programme. Int. J. Project Manage. **30**(8), 877–886 (2012)
43. Newton, K., Chileshe, N.: Awareness, usage and benefits of Building Information Modelling (BIM) Adoption—The case of the South Australian construction organisations. In: S. Smith (ed), Association of Researchers in Construction Management, vol. 1. United Kingdom, pp. 3–12, (2012)
44. Construction Engineering Australia, Advisory board driving BIM benefits in construction projects [online]. Vol. 3, No. 5, Oct/Nov: 4. Availability: https://search.informit.com
45. Rotimi, O.B., Ramanayaka, D.D.: Reflective practice and technical rationality in construction project planning. Civ. Eng. Environ. Syst. **32**(4), 1–15 (2015)
46. Ahlemann, F.: Towards a conceptual reference model for project management information systems. Int. J. Project Manage. **27**(1), 19–30 (2009)
47. Braglia, M., Frosolini, M.: An integrated approach to implement project management information systems within the extended enterprise. Int. J. Project Manage. **32**(1), 18–29 (2014)
48. Boton, C., Forgues, D.: The need for a new systemic approach to study collaboration in the construction industry. Procedia Eng. **196**, 1043–1050 (2017)
49. Deshpande, A., Azhar, S., Amireddy, S.: A framework for a BIM-based knowledge management system. Procedia Eng. **85**, 113–122 (2014)
50. Bradley, A., Li, H., Lark, R., Dunn, S.: BIM for infrastructure: An overall review and constructor perspective. Autom. Constr. **71**, 139–152 (2016)
51. Gerrard, A., Zuo, J., Zillante, G., Skitmore, M., Building information modeling in the australian architecture engineering and construction industry. In: Handbook of Research on Building Information Modeling and Construction Informatics, Chapter 23, pp. 521–545 (2010)

52. Musa, A.M., Abanda, F.H., Oti, A.H., Tah, J.H.M.: Boton Proceedings of the CIB World Building Congress 2016: Volume V. Advancing products and services. In: Achour N. (ed.) Published by Tampere University of Technology The Potential of 4D Modelling Software Systems for Risk Management in Construction Projects,. pp. 988–999 (2016)
53. Ding, L., Zhong, B., Wu, S., Luo, H.: Construction risk knowledge management in BIM using ontology and semantic web technology. Saf. Sci. **87**, 202–213 (2016)
54. Tomek, A., Matějka, P.: The impact of BIM on risk management as an argument for its implementation in a construction company. Procedia Eng. **85**, 501–509 (2014)
55. Charmaz, K.: The power of constructivist grounded theory for critical inquiry. Qual. Inq. **23**(1), 34–45 (2017)
56. Hennink, M.M., Kaiser, B.N., Marconi, V.C.: Code saturation versus meaning saturation. Qual. Health Res. **27**(4), 591–608 (2017)
57. Jafari, M., Rezaeenour, J., Mahdavi, M.M., Hooshmandi, A.: Development and evaluation of a knowledge risk management model for project-based organizations. Manag. Decis. **49**(3), 309–329 (2011)
58. Tserng, H.P., Yin, S.Y., Dzeng, R., Wou, B., Tsai, M., Chen, W.: A study of ontology-based risk management framework of construction projects through project life cycle. Autom. Constr. **18**(7), 994–1008 (2009)
59. Loosemore, M., Richard, J.: Valuing innovation in construction and infrastructure. Eng., Constr. Architect. Manag. **22**(1), 38–53 (2015)
60. Howard, R., Restrepo, L., Chang, C.: Addressing individual perceptions: an application of the unified theory of acceptance and use of technology to building information modelling. Int. J. Project Manage. **35**(2), 107–120 (2017)
61. Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., et al.: Building Information Modelling (BIM) uptake: clear benefits, understanding its implementation, risks and challenges. Renew. Sustain. Energy Rev. **75**, 1046–1053 (2017)
62. Ishikawa, A., Naka, I.: Knowledge management and risk strategies. World Scientific Publishing Co Pte Ltd, ProQuest Ebook Central (2007)

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24 Inside the Collective Mind: Features Extraction to Support Automated Design Space Explorations

Lucian-Constantin Ungureanu and Timo Hartmann

Abstract

The paper investigates the possibility to extract meaningful information out of natural language design conversation. This meaningful information, referred in this paper as features, represents possible design changes and solutions discussed during collaborative design sessions. Without relying on user input and without disrupting the natural course of the conversations, we envision an automatic implementation of these changes and solutions into a parametric model. The aim of such a system is to allow for an automatic design space exploration without interrupting the design sessions. In this direction, the paper employs mixed research methods which make use of quantitative and qualitative analysis. The results obtained indicate the possibility of extracting structured information to perform changes in various parametric models automatically. The paper also provides discussions around specific limitations, such as unclear precedents due to multimodality input.

Keywords

Natural language • Collaborative design • Design automation • Design meetings

24.1 Introduction

Collaborative design meetings involve all parties interested in developing the design of a product. During this process, the participants create a collective pool of knowledge, meant to progress the design. This knowledge is created by making use of natural language to communicate and discuss ideas, solutions and scenarios. This whole picture, is expected to be supported by state-of-the art computational tools.

Current interfaces focus on formalized queries, such as "*do that …*", "*change that …*", "*search for …*", mainly used for information access or simple tasks [7]. Even though users use spoken language to query a system such as Siri, Google Assistant or Cortana, the query still gets an unnatural formalized form. Human to human conversations, more precisely multi-party conversations, represent the informal dimension of the natural language communication. Without any script to follow, the participants develop a dialogue. In most of the settings, this dialogue is centred around a specific idea. More specifically, during collaborative design sessions, design goals drive the dialogue. Each participant contributes to the development of the dialogue building the conversation on top of previous ideas, as well as bringing new ideas based on personal experience and expertise to the table [1].

Aiming at understanding the way design conversations develop, previous researchers focused on different aspects such as participants interaction [14], social dimension [10], reported speech [15], the role of communication and different artefacts [17], semantic design information capturing based on function, behaviour and structure [8], or design negotiation [12, 10]. The studies listed above represent the building blocks towards the understanding of the social dimension of the design and

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engineering conversations, as well as the way the design is developed. In the end the outcome, meant to progress the design, need to be implemented as a virtual representation of it, usually through the use of computers and computational environments. Moreover, previous research reported the need of increased use of the computer support during multi-party design and engineering collaboration sessions [17]. In contrast, the limited use of the computational support restricted the role of the collaborative sessions to coordination, in lieu of design development [17].

Over the time, the purpose of computers and computational environments to support the civil engineering industry evolved, from the basic support of representing the design in a digital form [21] to more intelligent systems [6, 16, 19, 23]. Even though these systems are advancing and offering engineers more and more capabilities, a major limitation is represented by the fact that most applications still require user attention and effort to provide input. This disrupts and hinders the creativity, through shifting the focus from design to machine manoeuvrability [1]. Moreover, most of the times, the number of explored design solutions is reduced to allow for a timely implementation and to align these with the tools' capabilities, which shifts the engineering focus away from the design exploration to software related issues. While Bernal et al. [1] propose to consider a "*less ambitious role for a computer in design tasks*", current progress in the field of machine learning and artificial intelligence push us to be ambitious.

The system we envision plays the role of a smart machine agent which continuously listens to multi-party conversations and extract meaningful information which leads to design changes, adjustments, and exploration. Then, it implements these into parametric models meant to adjust the design embodiments or to trigger various simulations. To move towards this vision, a first step is to investigate whether such constructs exist which will trigger changes in the design and the simulation models, how these are formed and the usefulness of the information communicated during design dialogues to steer the parametric models. We present the current state of the art of spoken language understanding, then we introduce the research method. The paper continues with the analysis of a set of design conversations, discussion of the results, ending with a conclusion section which provide a critical discussion the findings and develops directions of future research directions based on the limitations of the current study.

24.2 Human-Computer Interaction Through Natural Language

Human beings exchange information in a natural way through language as an intentional act [20]. We can make a separation of the act of producing the natural language communications in written and spoken. While the act of writing takes a more formal form, the act of speaking, especially when it involves more than two participants, is considered to be informal. One focus of the current human-computer interfaces is how to allow computers to understand the conversations between humans. Spoken language understanding is a relatively new research area [24]. A main requirement to conduct research in this direction is the collection of data, which mainly takes the form of audio recordings and in the literature is named corpora. Tur and De Mori [24] provides a good summary of various corpora collected by various researchers with various goals in mind. This summary includes mentions such as Augmented Multi-party Interaction (AMI) [11] and ISL meeting corpus [2].

An overview of various methods [24] covers concerns related to "*dialog act tagging*", "*dialog act segmentation*", "*discourse and topic segmentation*", "*summarization*", "*action items and decision detection*", "*agreement/disagreement detection*", "*subjectivity and opinion detection*", "*modeling dominance*", "*speaker role detection*", "*hot spot detection*", "*addressee detection*", and "*argument diagramming*". Moreover, most of these methods need to be coupled with natural language processing techniques which focus learning, understanding and production of human language by machines [7]. Nevertheless, both techniques make intensive use of various knowledge representation techniques. Usefulness of the corpora to support specific tasks is a pre-requirement of employing such modern techniques.

$$tf = n/total \tag{24.1}$$

One aim of the pre-processing analysis is to identify the purpose of a document. A useful measure for this is term frequency(*tf*), which provides information about how often specific terms occur in a corpus. Equation 24.1 presents the basic way to compute tf, where n is the total number of occurrences of a term and *total* represents the total number of words in the corpus. One limitation of this approach is that common words will have a higher frequency [3]. Instead of getting the most frequent words, we can get the most relevant ones for each document using term frequency inverse document frequency (tf-idf). The basic reasoning behind tf-idf is that it takes into account the inverse frequency of a word on a document in relation to all the other documents on which this word occurs [18]. Equation 24.2 [18] calculates the tf-idf value for each word w part an individual document d, where document d is part of a collection of documents D. In addition, $f_{w,d}$ represents the number of the occurrences of word w in document d and $|D|$ represent the length of the corpus [18].

$$w_d = f_{w,d} * log(|D|/f_{w,D}) \quad (24.2)$$

The same equations can be applied, not only for identifying the term frequency, but also identifying the frequencies of sequences of words, termed in the literature as n-grams. N-grams can have sizes from 1 to n. One word n-gram often termed as unigram analyses the occurrence of a specific word in a text. Increasing the size from 2 to n represent a modality to extract utterances with high frequency. During this analysis, the text body is cleaned using different text mining techniques. For ranking the terms frequency we employed term frequency-inverse document frequency(tf-idf) presented in Eq. 24.2.

Moreover, besides the automated analysis of the corpus, the pre-processing phase might also include manual investigation of text. The current trend focuses on automatic identification of specific features in the multi-party conversation datasets [4, 5], mainly aiming to perform specific actions based on the items already existing in the corpus. To our knowledge, there are no computational methods to identify if specific features are missing or not. Therefore, we consider that an additional step is needed to perform a qualitative analysis of the corpus to identify if there is enough spoken information which will be used to trigger changes and action in parametric models.

24.3 Research Method

Our research presented in this paper employs a multi-method research approach combining quantitative and qualitative analyses to get insight into the information generated during collaborative design sessions. Figure 24.1 presents the proposed research method. The quantitative analysis (QtA) focuses on the identification of the frequency of an adjacent sequence of n words called n-grams. The extracted n-gram will be used to support the qualitative analysis of the design conversations.

The quantitative analysis was conducted using R software and *tidyr* package [22]. The first step of the analysis consist on removing the names of the participants from the transcript, as the main focus is the analysis of the natural conversation without any focus on the participants.

The qualitative analysis (QlA) is performed in two steps. The first step is to perform a two level segmentation of the design conversation. The first level is based on conversation blocks which focus on the design of specific parts. At the second level, each 1st-level conversation block will be further analysed and segmented into 2nd-level conversation blocks aiming to identify different attitudes during design, such as proposal, acceptance, rejection, negotiation. The third step of the qualitative analysis consists of the identification and codification of the utterance which implies specific candidate actions that could potentially be used to steer the parametric models. This step is supported by the n-grams extracted during quantitative analysis. Moreover, we developed a codification schema for utterances that could trigger specific actions into the parametric models. At the current stage of this research the codification is kept simple, using three codes: embodiment, process, and query. These codes can be explained as following: *embodiment* mark those utterances which are related to specific changes in embodiment, where *process* mark those utterances used to indicate the utterances about possible

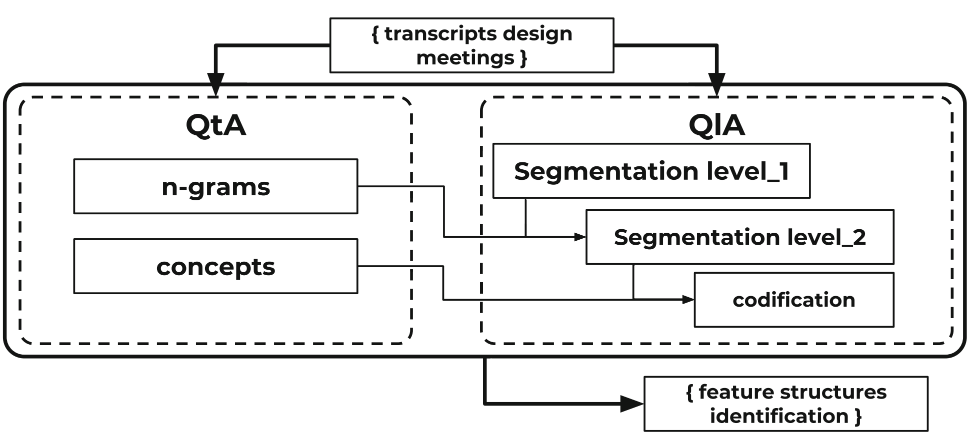

Fig. 24.1 Research method

simulations, and *query* mark those utterances related to different queries about both—embodiment and process. The qualitative analysis was conducted by manually reading and marking the transcript. A case study which implements the proposed methodology to analysing the design conversations of two real architectural design meetings is presented in the next section of the paper.

24.4 Design Conversation Analysis: Results and Discussions

The proposed stepwise methodology is use to analyse the transcripts of two architectural design meetings [9] which aim at the design of a new crematorium. McDonnell and Lloyd [13] provides a detailed description of the project and design meetings, thus we provides only a short summary. The project was in the phase after the conceptual design, already having the main feature and the main functions allocated. The stakeholders involved in the design meetings were the architects and the client. The first meeting (A1) aims to obtain the clients and building users feedback on design, concluding with some agreed actions. The second meeting (A2) is organized after 8 months and is a follow-up for the A1 meeting. The architects used the meeting (A2) to present the implementation of meeting's (A1) action points, as well as to raise additional issues and queries regarding the design. In this paper, the quantitative analysis conducted analyses the transcripts of both meetings, while the qualitative analysis conducted analyses the transcript of the first meeting (A1) only. In the following subsection, we present and discuss the results of the quantitative analysis. This is followed by the subsection on which we present and discuss the results of the qualitative analysis.

24.4.1 Quantitative Analysis

The results obtained for 2-grams are presented in Table 24.1. Within this table, meet represent the meeting of which transcript the word was extracted, *n* represents the number of occurrences for that specific word, *tf* represent a statistical measure of the term frequency, *idf* represent the statistical measure termed as inverse document frequency, and *tf_idf* represent the importance of the word for that specific document in relation to the corpus. In this study, the transcripts represent the corpus.

Additional cleaning of the corpus was conducted to remove interjections such as *errm, th, err,* etc. which are not commonly used in the formal writing, but very often during human-to-human dialogues. Analysing both transcripts, we identify words which express the attitude of the participants. A good example is the word *laugh*. This indicates in the transcripts that the participants are *laughing*. Thus, we make use of additional filtering to removing these words from the analysis. After filtering, the results obtained for unigram are partially presented in Fig. 24.2. These results show that we can identify concepts which indicates different aspects considered during the meetings and related to various design aspects.

Table 24.1 Results 2-grams—filtered

	Meet bigram		n	tf	idf	tf_idf
1	A2	Plasma screens	7	0.00883	0.69315	0.00612
2	A2	Acoustic consultant	4	0.00504	0.69315	0.00350
3	A2	Freeze dried	4	0.00504	0.69315	0.00350
4	A2	Ground level	4	0.00504	0.69315	0.00350
5	A1	Bird hide	6	0.00501	0.69315	0.00347
6	A1	West chapel	5	0.00418	0.69315	0.00290
7	A2	Artificial light	3	0.00378	0.69315	0.00262
8	A2	Heat recovery	3	0.00378	0.69315	0.00262
9	A2	Independent access	3	0.00378	0.69315	0.00262
10	A2	Memorial wall	3	0.00378	0.69315	0.00262

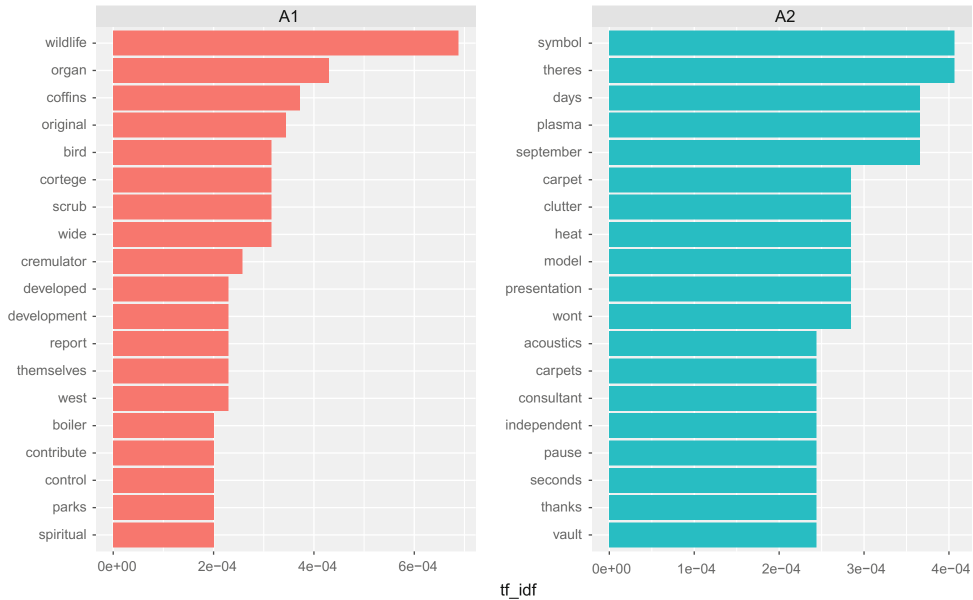

Fig. 24.2 Side by side comparison of the most frequent words used during design meetings

24.4.2 Qualitative Analysis

The results of the first segmentation step indicate that during the meeting, the design team focus on a wide variety of topics, such as increasing the size of the waiting room, circulation routes, environmental impact, materials, etc. Within this, we can classify the driving topics as the ones which initiate the discussion having as concerns (1) the design embodiments or (2) the processes. However, the two categories intersect during the design.

For example, when discussing about the size of the *waiting room* the participants make connection to the process which is supposed to take place within the boundaries of this room. Table 24.2 offers a very good illustration in this direction. Where the initiating concern is related to the rooms size, there is no direct answer, but there are concerns about the process which will take place in this room (*excerpt_4*) which leads to the quantification of the space size. Mentally implementing the process and its possible outcome, the participants provide one possible solution (*excerpt_5*).

Yet, from the computation perspective, a computer cannot implement the provided solution as more information is required to clarify where the participants are pointing to drawings for possible extensions to identify where space for additional seats will be created as pointed out in *excerpt_5*. But, without considering the provided solution, to some degree, this logic can be automated using parametric model of the room embodiment and constraints, coupled with a parametric model for the process simulation to provide various alternatives for the waiting room's growing strategies. In this case, the participants will have to analyse the provided alternatives and select for implementation the ones which they nd suitable.

From a different perspective, in the case of the items 7 and 9-circulation routes the dialogue initiation comes from the process perspective. The extend of this design topic has impact on the embodiment of several parts of the design as presented in Table 24.3. Excerpt_1 might represent the trigger for starting the parametric model of the simulation. This will allow the

Table 24.2 Example design conversation excerpts—waiting room size

Content	
excerpt_1	*[…] the first query […] about whether you wanted the size of the waiting room increased*
excerpt_2	*I'd be interested […] what sort of set/how many seats […] you could get […]*
excerpt_3	*[…] you are unlikely to get more than about 9–10, maximum 12 seats in there […] is the room big enough*
excerpt_4	*[…] if we've got as ow of people walking through […] we can't put seats through that […] we need to keep an open access […] the seating will be against the wall*
excerpt_5	*[…] extending it […] will give you seating areas here, seating areas here, as well as here and here, which effectively will double the seating capacity[…]*

Table 24.3 Example design conversation excerpts—circulation routes

Content	
excerpt_1	*The way in which the circulation works here is similar to the existing chapel […] once a service has ended […] people would leave through these doors*
excerpt_2	*We've given you double doors because of the draught issue […]*
excerpt_3	*[…] from here they ca process around the wreath court […] with the exception of certain religions […] they would actually walk through here […]*
excerpt_4	*[…] there are three possible routes, they either come through here, one[…] they go through here, two […] they can go through there, three*
excerpt_5	*[…] the only comment also I've had from the funeral directors[…] is this route here, slight concern for people over that*
excerpt_6	*[…] the second route is round the end of the pond […]*
excerpt_7	*[…] the majority of people that we get sometimes are elderly […]*
excerpt_8	*[…] we could put a bridge or something that looks like a bridge […]*
excerpt_9	*[…] it would be nice to have that […]*
excerpt_10	*[…] there is one, a very small one […] in erm the winter garden*
excerpt_11	*[…] I quite like the idea of stepping stones*

participants to identify the impact on different parts of the designed product such as doors, wreath court, the need for a bridge over the pond and what will be impact of having any kind of route over the pond on the people circulation. Again, coupled parametric models for the design embodiment and processes simulation will offer the participants the possibility to automatically explore various alternatives.

24.5 Conclusions

While design knowledge is developed through dialogues during the multi-party collaboration sessions, current human-computer interfaces still restrict the implementation of agreed solutions. The central thesis of this paper is represented by the idea that the computers can have a more ambitious role during these sessions by extracting and implementing the meaningful information directly in parametric models. Thus, the major concern oriented towards the existence of such information. After analysing meeting transcripts of two design meetings, we can conclude that parametric models can be steered based on the spoken dialogue. We were able to identify keywords and utterances that would allow to trigger parametric models and start simulation of various processes. Moreover, the conducted analysis shows that the embodiment of the design cannot be steered without meaningful input from the simulations models, as the participants always make connections to the related processes.

A limitation identified concerns the use of multi-modality during communication. As the example of the waiting room, the unclear location of possible extension indicated using the concept "here" while pointing at drawings. Without additional input to clarify "here", it makes it computationally impossible using only voice input. Another situation is when the designers present similar cases to support their design ideas. This can be seen in the example for the circulation routes, indicated as "winter garden". Computationally, a machine can reproduce the design intent of the given case if the information about the case is available. Of course, the results of this analysis are based on only two meetings, which we see as a limitation. Future data collection should focus on collecting more data from multi-disciplinary sessions, as well as from a wide variety of civil engineering projects.

The engineering models of products and processes represent an intricate network of components, subsystems, and systems. While the human mind can quickly understand the jump and transition from one element to another, mainly based on change of context, machines require training to recognize this kind of situations. Making sure that the changes are implemented on the right elements represent one of the current challenges. Future research should focus on training various models to identify when this transition occurs. Moreover, the good part of the conversation is noise and future research should train models to identify it. This will allow computers to identifying when actions are required from its side, and when nothing should happen.

References

1. Bernal, M., Haymaker, J.R., Eastman, C.: On the role of computational support for designers in action. Des. Stud. **41**, 163–182 (2015)
2. Burger, S., MacLaren, V., Yu, H.: The isl meeting corpus: the impact of meeting type on speech style. In: Seventh International Conference on Spoken Language Processing (2002)
3. Chen, K., Zhang, Z., Long, J., Zhang, H.: Turning from tf-idf to tf-igm for term weighting in text classification. Expert Syst. Appl. **66**, 245–260 (2016)
4. El-Assady, M., Gold, V., Acevedo, C., Collins, C., Keim, D.: Contovi: multi-party conversation exploration using topic-space views. In: Computer Graphics Forum, vol. 35, pp. 431–440. Wiley Online Library (2016)
5. El-Assady, M., Sevastjanova, R., Gipp, B., Keim, D., Collins, C.: Nerex: Named-entity relationship exploration in multi-party conversations. In: Computer Graphics Forum, vol. 36, pp. 213–225. Wiley Online Library (2017)
6. Fougeres, A.J., Ostrosi, E.: Intelligent agents for feature modelling in computer aided design. J. Comput. Des. Eng. **5**(1), 19–40 (2018)
7. Hirschberg, J., Manning, C.D.: Advances in natural language processing. Science **349**(6245), 261–266 (2015)
8. Kan, J., Gero, J.: Using the fbs ontology to capture semantic design information in design protocol studies. In: About: Designing-Analysing Design Meetings (2009)
9. Lloyd, P., McDonnell, J., Reid, F., Luck, R.: Dtrs7 dataset from 7th design thinking research symposium. http://design.open.ac.uk/dtrs7
10. Luck, R.: Does this compromise your design? socially producing a design concept in talk-in-interaction (2009)
11. McCowan, I., Carletta, J., Kraaij, W., Ashby, S., Bourban, S., Flynn, M., Guillemot, M., Hain, T., Kadlec, J., Karaiskos, V., et al.: The ami meeting corpus. In: Proceedings of the 5th International Conference on Methods and Techniques in Behavioral Research, vol. 88, p. 100 (2005)
12. McDonnell, J.: Collaborative negotiation in design: a study of design conversations between architect and building users. CoDesign **5**(1), 35–50 (2009)
13. McDonnell, J., Lloyd, P.: About: Designing-Analysing Design Meetings. CRC Press (2009)
14. McDonnell, J., Lloyd, P.: Beyond specification: A study of architect and client interaction. Des. Stud. **35**(4), 327–352 (2014)
15. Oak, A.: As you said to me i said to them: reported speech and the multi-vocal nature of collaborative design practice. Des. Stud. **34**(1), 34–56 (2013)
16. Pauwels, P., Zhang, S., Lee, Y.C.: Semantic web technologies in aec industry: a literature overview. Autom. Constr. **73**, 145–165 (2017)
17. Perry, M., Sanderson, D.: Coordinating joint design work: the role of communication and artefacts. Des. Stud. **19**(3), 273–288 (1998)
18. Ramos, J., et al.: Using tf-idf to determine word relevance in document queries. In: Proceedings of the first instructional conference on machine learning, vol. 242, pp. 133–142 (2003)
19. Ren, Z., Yang, F., Bouchlaghem, N., Anumba, C.: Multi-disciplinary collaborative building designa comparative study between multi-agent systems and multi-disciplinary optimisation approaches. Autom. Constr. **20**(5), 537–549 (2011)
20. Russell, S.J., Stuart, J.: Norvig. Artificial Intelligence: A Modern Approach. pp. 111–114 (2003)
21. Schultz, C.P., Amor, R., Lobb, B., Guesgen, H.W.: Qualitative design support for engineering and architecture. Adv. Eng. Inform. **23**(1), 68–80 (2009)
22. Silge, J., Robinson, D.: Tidytext: Text mining and analysis using tidy data principles in r. J. Open Source Software **1**(3) (2016)
23. Tixier, A.J.P., Hallowell, M.R., Rajagopalan, B., Bowman, D.: Automated content analysis for construction safety: a natural language processing system to extract precursors and outcomes from unstructured injury reports. Autom. Constr. **62**, 45–56 (2016)
24. Tur, G., De Mori, R.: Spoken Language Understanding: Systems for Extracting Semantic Information from Speech. John Wiley & Sons (2011)

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25 Detecting Falls-from-Height with Wearable Sensors and Reducing Consequences of Occupational Fall Accidents Leveraging IoT

Onur Dogan and Asli Akcamete

Abstract

Labor intensive and hazardous nature of the construction activities plays an important role on the increase of the amount of accidents and fatalities on sites. One of the most important sources of fatalities occurring on construction sites is falls-from-height (FFH). Despite the various efforts for the solution over decades, the yearly statistics still indicate high amount of fatalities and severe injuries due to FFH accidents on construction sites. Medical literature emphasize that the time passed after the accident is a critical factor for avoiding preventable deaths and permanent disabilities of trauma patients. The objective of this study is to timely detect FFH accidents on construction sites by using a wearable device and to provide a real-time notification to the emergency medical team (EMT) leveraging Internet-of-Things (IoT). This is expected to maintain the earliest possible medical intervention on site in order to help reducing fatal and severe consequences of FFH accidents for construction workers. Test results of the system evaluation show that the fall is detected correctly and the alert message is sent to the prescribed addresses with 100% sensitivity. The system has shown a good accuracy for true detection of the fall height with an overall error rate of 10.8%. Another metric which shows the detection of the disconnected network time of the system has been surveyed and the results are accurate with an overall error rate of 3.16%.

Keywords

Occupational health and safety • Falls-From-Height • Internet of things (IoT) • Wearable sensors and devices
Data acquisition

25.1 Introduction

Construction industry is known with its labor intensive and hazardous nature among the other industries. The risk-prone working conditions of construction industry lead to frequent accidents and health issues on construction sites. Hence, construction workers are exposed to occupational accident risks, and many of them are subject to lose their physical integrity, have permanent disabilities, or face death correspondingly. According to Bureau of Labor Statistics (BLS) [1], construction industry takes the lead among other sectors with 899 fatal injuries occurred in 2014, where the total number of the fatal occupational injuries was 4821 for all the industries in the US. Having 4386 fatal records for the whole private industry [2], with a share of 20.5%, construction industry seems to possess at least 1 out of 5 fatal injuries occurred in 2014 among the overall private industries in the US.

Risky working conditions on construction sites may result in several occupational accidents. Some of the well-known examples are fall-from-heights (FFH), being struck-by objects, electrocution, and caught in/between objects [3]. Indeed,

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Occupational Safety and Health Administration [4] has declared "*construction's fatal four*" which are responsible for more than half (64.2%) of the fatalities occur on construction sites in year 2015, and accordingly, falls are the leading causes of fatalities among all. Another statistics that prove falls are leading fatal occupational accidents is published by BLS [2], revealing that out of 899 deaths occurred in the US on construction sites in year 2014, 359 of them were due to falls which corresponds to the biggest amount of share. These statistics reveal the serious results of occupational fall accidents in construction industry. Moreover, health and safety countermeasures undertaken in construction sites unfortunately fall short of reducing or eliminating these numbers, apparently.

Conventionally, several safety countermeasures have been undertaken to prevent occupational fall accidents, such as on-site precautionary measures including use of Personal Fall Arrest Systems (PFAS), guardrails, safety nets, etc., educating and training of personnel in accordance with safety regulations, redesigning jobs in order to reduce the impact of FFHs, and promoting safety among workers [5]. However, these precious efforts do not provide satisfying results, and unfortunately, cannot prevent FFHs being the leading cause of deaths in construction sites for many years. Therefore, although construction industry has been implementing health and safety efforts and regulations against FFH accidents; fall accidents still remain as a persistent problem [6], and the available safety measures and techniques are not sufficient yet to decrease the amount of fatalities resulting from FFH [7]. Hence, until every influencing factor behind occupational falls and regarding issues are fully understood and addressed by deploying novel approaches and techniques, it will not be hard to predict that a lot more workers will be subject to FFH accidents and probably be exposed to permanent disabilities or deaths on construction sites.

25.2 Objective and Scope

Taking the fatality rates of occupational fall accidents into consideration, remediation of the results by preventing deaths and reducing the effects of injuries that occur in construction sites, deserves particular attention and vigorous efforts.

In medical emergency domain, time is a critical factor for patients who are exposed to trauma [8]. There is a well-known fact in the medical emergency lexicon called 'golden hour' which is the first hour right after the accident has happened [8]. In this very critical time, it is very important to intervene with the trauma patient as early as possible and give an appropriate definitive care, which may save lives of critical patients or avoid future disabilities [9]. Effective use of this time is expected to reduce the mortality and morbidity rates of trauma patients [8].

Considering abovementioned factors, in case of trauma it is obvious that every minute counts against the trauma patients' benefit, and every possible period of time should be efficiently utilized on behalf of the patient. Therefore, faster and true detection of the accidents gains much higher importance in order to provide an agile response to prevent deaths, disabilities and/or serious consequences. Hence, the accident has to be accurately detected and immediately reported to the emergency personnel in order to support them intervening with the trauma patient as fast as possible.

This study investigates a solution within this scope for occupational fall accidents occurring at construction sites. This solution will use a dedicated wearable sensor for true detection of the accident, by leveraging Internet-of-Things (IoT) to provide a connection and communication with emergency medical teams (EMT) immediately after the accident happens. Thus, workers that are subject to accident trauma would find a chance to meet early medical treatment while there is still an opportunity to recover unwanted consequences of the accident.

25.3 Background Review

25.3.1 Technology

IoT

IoT proposes an approach to connect things together to communicate within a network by leveraging emerging technologies which offer affordable low-cost solutions that are widely applicable. Gubbi et al. [10] defined IoT as an integrated framework which is enabling cross-platform innovative applications to share information through connected sensors and actuators. Sensors do the abstraction of data from the physical world and communication facilities provide connection between the things. Corresponding applications can be exemplified as smart grid and energy metering, smart homes/offices/cities, intelligent transportation and smart logistics [10, 11].

IoT based technological applications might offer a great potential for real-time tracking of progress and construction resources on site [12]. This may lower the costs of monitoring activities at construction sites when compared to the traditional operation handling, where responsible site personnel periodically collect and report the required information about the resources on construction sites. Efforts and resources required for the monitoring of the resources can be minimized by taking the advantage of reliable information obtained from the use of IoT implementations. In order to have better understanding about IoT concept and its applications, definitions, relevant technologies and exemplary use cases as well as challenges and its future directions, the reader is kindly referred to [13–15].

Wearable technology

With the technological advances in electronic products manufacturing industry components to any electronic device are getting much smaller in size. The compaction of these devices due to this development enables new approaches to facilitate them on a body as part of the wearable technology for different purposes such as monitoring and tracking of humans and animals. These systems typically consist of components such as sensors to gather data from the physical world, processors to interface and interpret the data and communication units to transmit the output of the system wirelessly to their correspondents. Several use cases of these devices can be exemplified as remote patient monitoring, health tracking, wellness applications, wireless activity monitoring, performance tracking in sports and fitness, and proximity warning systems in mining industry [16]. Devices that are facilitated as hardware platforms during these activities can be smart watches, wristband sensors, disposable sensing patches, augmented reality eyewear, brain-computer interfaces and smartphones with their peripherals [13].

Wearable technology is generally favored against other systems such as ambient type sensing using external sensors and vision-based type of sensing using camera and images with regard to its low-cost hardware configuration and ease of installation. The use of wearable technology provides relatively practical and cost effective solutions [17], whereas, obtrusiveness of the wearable devices is regarded as a drawback compared to aforementioned methods [17, 18].

25.3.2 Safety Related Technology Based Studies in Construction

As being one of the most important sub-disciplines in construction domain, researchers and practitioners of occupational health and safety (OHS) management sub-discipline have been seeking solutions against safety issues using various methods and technologies at construction sites. In a review study involving advanced technological applications conducted in construction safety management field between years 1986 and 2012, Zhou et al. [19] pointed out that real-time flow of information is a crucial factor to solve safety relevant issues on construction sites and technologies such that radio frequency identification (RFID) systems, sensors, global positioning system (GPS), and wireless systems have been used in this domain and gaining more attraction towards achieving effective safety management goals. Skibniewski [20] reviewed studies that were published between 2000 and 2014 regarding deployment of information technologies (IT) applications in construction safety engineering and management and similarly reported that researchers are seeking solutions to the safety issues on construction sites like proximity detection and early warning systems that are aimed to prevent collision of on-site resources and real-time positioning of workers to track their safety status indoors and outdoors.

Another study conducted by Marks and Teizer [21] investigated the usability, effectiveness and reliability of radio frequency (RF) based proximity and warning technologies in eliminating being struck by objects which is another significant source of fatalities on construction sites. Teizer [22] presented another study including an implementation named “SmartHat” in which sensors are attached to personal protective equipment (hardhat) and the system tracks RFID tags on workers using readers for proximity detection that triggers a sound warning system during alert situations. Zhong et al. [23] proposed an IoT solution to prevent the collisions of tower crane groups on construction sites by producing position data of the crane parts using sensors where it is able to make the cranes stop if the maximum acceptable level of proximity limit is reached during any operation.

With technological advances in recent years, technology based solutions are finding much more chance to be implemented into the studies regarding safety related problems of construction industry. In this study, an IoT based approach has been implemented by deploying a cost-effective wearable device. This study aims to contribute to the literature by detecting occupational falls on construction sites with relating key attributes such as fall height and fall time and providing EMT with corresponding information.

25.4 Detection of Occupational Falls

Existing methods of fall detection can be classified into three different approaches such as (a) using ambient sensors, (b) using vision based systems such as cameras and (c) using wearable devices [24]. Ambient sensing refers to the use of several external sensors deployed around the place of interest. These sensors provide data of the physical setting in order to capture the prospecting behavior of the corresponding phenomenon such as human activity recognition. Sensors used in this type of sensing method can be RFID tags that can help to identify the user and detect the proximity of the subjects, pressure sensors that detect the presence of a subject, thermal infrared (IR) sensors to detect presence, etc. As being unobtrusive to the user on one side, ambient type sensing requires too many sensors to be deployed all around the place of interest in order to increase the accuracy of fall detection. This will inflate the cost of installation as well as computational costs regarding a consistent fall detection system.

Another approach used in fall detection studies is computer-vision-based sensing. Computer-vision type of sensing uses camera-based solutions to capture streaming images for detecting anomalies or intended behavioral patterns using image recognition techniques. Useful information is extracted by deploying computational analysis on imagery data using computer-vision methods such as object detection, object tracking and action recognition [25]. Computer-vision approach needs to have a line-of-sight with the subject of interest in order to perform these methods. Therefore, the obstructions are one of the biggest problems in vision-based techniques since analysis regarding the subject will not be performed [26]. That is, construction sites will need particular attention due to possible interferences of different subjects within the sight when it is required to track multiple workers at the same time. Considering the dynamic nature of construction sites, progressive work environment limits the use of ambient-sensing and vision-based approaches and makes them unattractive.

Establishing a trade-off of selecting the best option among these alternatives, wearable device based approach is adopted in this study to detect occupational fall accidents on construction sites. Several studies [27, 28] have also used wearable devices in their fall related studies. With using wearable devices on workers connected to wireless networks, real-time tracking of multiple workers would be viable to accomplish as soon as they remain connected.

In several studies [27–30], smartphones are promoted for being used as a wearable device. However, owners of these devices are much likely to use them for their calls, messages and schedules, and most frequently as an entertaining medium connected to the internet. Therefore, people might want to put their smartphone into their pockets for easy access. These have a potential to interrupt the working conditions of the wearable device and when the designated position of the wearable device is changed it will not function properly for its intended use in detection systems. Habib et al. [31] reported that adequacy of the built-in sensors such as the dynamic reading range of accelerometers remains as a doubtful issue for most of the smartphones. It has also been denoted that typical acceleration limits of these built-in sensors fall short during fall detection. Another technical issue is the capacity of the batteries used in smartphones. Lifetime of a fully charged battery will depend upon the energy consumption and a smartphone battery will last only about a few hours with heavy usage [31].

Accounting these, smartphones as well as smart watches are not feasible alternatives of continuous safety monitoring devices. In these cases, selection process should favor dedicated wearable devices which are designed to fit specific requirements of the corresponding problem. With this study, a dedicated wearable device is used as a data acquisition and fall detection mechanism.

25.4.1 Proposed System

Method of study

A wearable device is developed to record the acceleration data of the workers during their jobsite activities which runs a threshold based algorithm at the background and processes the data to detect occupational fall accidents instantaneously in real-time. In order to develop an algorithm that detects FFH accidents on construction sites, physics of fall behavior is studied. According to Risser et al. [32], falls from height is defined as unrestricted drop of a body from a specific position to another crushing position. From this point of view, a subject that is exposed to a fall from height will initially show a free-fall behavior. Thus, free-fall due to gravity is decided to be investigated as a first matter to determine the fall pattern of the workers during an accident. An object that is exposed to free-fall is subject to the gravity acceleration towards earth's center of gravity is a well-known fact. As can be seen from Eq. 25.1, the velocity of this falling object will increase proportional to the time passed starting from the beginning of free-fall until the collision of the object with the ground.

$$a = \partial v / \partial t \quad (25.1)$$

The gained velocity right before the collapse will be decelerated to zero in a very short amount of time during the collision of the subject with the ground. Thus, the kinetic energy of the falling human body will be damped by the body itself to return to a static position during the collapse. This is the main reason behind the major trauma happened to the human body. While the height of fall (see Eq. 25.2) increases, the time spent during the fall increases which then will increase the instant velocity of the body right before the collision.

$$h = 1/2 * g * t^2 \quad (25.2)$$

Using accelerometer sensor integrated into the wearable device, acceleration data is collected and interpreted by the developed algorithm in real-time and in case of any accident, the detection of the FFH is realized.

System architecture

According to the system architecture, as can be seen in Fig. 25.1, the wearable system is attached to the worker's body and collects real-time acceleration values which are trained in the microcontroller by the developed algorithm at the background. If the algorithm detects any FFH accident, an instant notification is sent to the main control unit wirelessly. The control unit immediately generates an alert message through the custom terminal software including information about the actual accident time, fall height, and accident address and sends it to the EMT and corresponding prescribed personnel on the construction site in no time. Thus, prior to intervention with the patient, EMT can be provided with the information indicating that the emergency situation relates to an occupational fall accident. This could enable the opportunity for a definitive care with early preparation to the intervention with the patient at accident scene which might minimize the risks of fatality and permanent losses during the most critical time period (i.e. 'golden hour') of the accident.

In brief, the approach of the system architecture involves two major steps as one of them is true and timely detection of the fall accident using a wearable device, and the other is transmitting the alert message instantaneously to the control unit in order to contact with the EMT and corresponding personnel on site. The reliability of the system exactly depends upon the output of the first step. In the next section, the developed algorithm of this study for true detection of FFH accidents on construction sites is explained.

Fall detection algorithm

This study refers to a multi-phase threshold based fall detection algorithm that trains the real-time streaming acceleration data generated due to the movements of the workers on construction sites. In order to distinguish the fall behavior from the normal work activity patterns of the worker and eliminate false positives, three successive interrogation and verification steps are applied.

Accordingly, as a first step, the first query of this algorithm surveys the continuous real-time acceleration data that is produced as a result of magnitude value of each axis to detect and verify 'free fall' behavior which is the acceleration towards earth's gravity center with gravitational force—zero g.

When free fall is detected, the next interrogation as a second step comes into play and surveys the data stream for 'collision' to the ground which yields a peak acceleration value (i.e. 4 g) as threshold in this study. In case the collision is detected, third interrogation looks for the 'steadiness' detection of the subject who is anticipated to stay motionless due to

Fig. 25.1 System architecture

being exposed to major trauma. Between the second and third steps, delay timing (i.e. 1 s) is required to prevent erroneous results such as exiting the algorithm due to possible fluctuations in acceleration data during the crash with the ground. After observing dedicated amount of steadiness of the subject, the algorithm decides upon occupational fall accident and generates an alert notification indicating the details of the accident. In order to obtain reliable results, acceleration and time values are being used as threshold parameters which are based upon findings of pre-evaluation fall tests.

25.4.2 Implementation of the System

While using on a human body, the use of wearable devices should satisfy several considerations in order to facilitate their ultimate goal. Some of these required characteristics of a wearable device are size and weight of the device, location and mounting of the sensor, power supply, processing capabilities, wireless transmission range and storage of the device [16].

The wearable device should not interfere with the worker's activities for getting a desired performance. Moreover, size and weight of the device should be as small as possible. Having out-to-out dimensions of 11.4 cm by 8.2 cm by 3.2 cm, the wearable device developed for this study consists of a tri-axial accelerometer sensor (i.e. ADXL345 $\pm$ 16 g), microcontroller unit (i.e. Arduino Nano with Atmel ATmega328), wireless communication module (i.e. XBee Series2 radio with uFL antenna), storage module (i.e. MicroSD card module), a step-down voltage regulator and a power supply module containing 2600 mAh Li-ion rechargeable batteries inside. It should be noted that the power demand of any system determines the number and size of the batteries to be used and therefore, the most influential part which controls the size and weight of a wearable device is the power supply module.

Aiming higher accuracy for detecting occupational falls, the wearable device is planned to be positioned on the waist of the worker with a fastener belt tape. In similar studies, waist is used as the most common location for positioning of the wearable device [17]. The main reason for this is collecting the overall acceleration of the worker body as much as possible instead of being deceived by the free motion of body extensions during activities and to prevent false positives of the system outputs due to job activities performed using these extensions.

As mentioned above, the system uses XBee radio modules to communicate with the main control unit over a proprietary Zigbee network protocol. The system records acceleration data to a Micro SD card in order to provide data for further feature extractions regarding the accident and/or worker movements. The system is installed with a mesh networking configuration using XBee Series2 radios. The coordinator radio, installed on the main control unit side, expects alert notifications from the router nodes which are installed on the wearable devices. The system is configured to maintain the connection between nodes as much as possible. In case of any accident, alert notification can be sent to the coordinator using every node in the coverage area of the victim node.

25.4.3 Test Results

The developed system has been tested in a controlled office environment in order to obtain the preliminary results from the system in terms of fall detection sensitivity and fall height accuracy. Corresponding results are shown in Table 25.1. The results shown in the table reveal that the system is able to detect the falls from a predetermined height with 100% sensitivity. The height data output that the system calculates and sends via alert message is also obtained with good accuracy indicating an overall error rate of 10.8%. Additional tests are also planned to be performed on construction sites to emulate FFH accidents.

In case of accident detection, the system stamps time on the main control unit. However, if any connectivity issues occur between the victim node and the main control unit, the wearable system logs the duration of disconnected time in order to provide EMT with the actual accident time and reports it whenever the system provides a connection again. In Table 25.2 delay results revealed from a controlled test are shown. Connection between the wearable device and main control unit was disconnected from the network on purpose for the amount of times indicated in the second row, and then the reported delay duration from the alert message for each case was noted. The disconnection time is detected accurately with an overall error rate of 3.16%.

Table 25.1 Test results

Test case	Drop height (m)	Fall detection	Reported height (m)	Average (m)	Error %	Overall error %	Fall detection sensitivity %
1	1.50	Yes	1.251	1.341	10.6	10.8	100
2	1.50	Yes	1.266				
3	1.50	Yes	1.286				
4	1.50	Yes	1.538				
5	1.50	Yes	1.362				
6	2.00	Yes	2.028	1.779	11.1		
7	2.00	Yes	1.754				
8	2.00	Yes	1.736				
9	2.00	Yes	1.650				
10	2.00	Yes	1.725				

Table 25.2 Delay results

Test case	1	2	3	4	5
Disconnected duration (s)	30	60	90	120	180
Reported delay (s)	33	60	93	123	180
% Error	10.0	0.0	3.3	2.5	0.0
Overall error %	3.16				

25.5 Conclusions

Despite many valuable prevention strategies and efforts implemented against occupational fall accidents on construction sites, the fatality rate records do not indicate a significant decrease. Using this wearable system, physiological status of workers will be monitored using a wearable device using a tri-axial accelerometer that is developed for detecting occupational fall accidents on construction sites within the scope of safety monitoring on construction sites leveraging IoT. The ultimate expectation is to detect inevitable FFH accidents and provide an opportunity for notifying EMT in-time, in order to save lives and eliminate permanent disabilities of construction workers who are subject to FFH accidents. Another main contribution would be the information about the key attributes of the accident that is provided to the EMT such as fall height and true accident time, which might supply EMT with the crucial information for providing a true definitive care to the patient. Indeed, Locker and Morris [9] suggest that the height of fall can give information about the injury mechanism and trauma situation.

The developed system and its data can be used in forensic analysis against any possible fraud attempts that hide the accident information. As offering an imperative solution, it is designed to prevent delays that may occur due to poor site organizations. Also in case of any unfortunate events resulting with death, this data might be a useful source for further analysis that will be performed by the authorities to discover the fall pattern.

As an ethical issue, tracking of workers might be a source of concern for their privacy. In order to address this, in the proposed system the device has got its own ID rather than having an assigned personal information. Also, the location information is not monitored continuously but only automatically reported to EMT services as soon as the fall detection occurs. Thus, personal privacy of the users is taken into account during the development of the system.

The initial tests on the system have been performed by dropping the device from designated heights. The results are satisfying as findings ensure that the fall is detected correctly (100%) and the message with true fall detection time and height is sent to the prescribed addresses. The corresponding fall test heights are detected with an overall error rate of 10.8%. Another metric that shows the detection of the disconnected network time of the system has been surveyed and the results are accurate with an error rate of 3.16%. As future work, additional tests to emulate FFH accidents are planned to be performed on construction sites using dummies in order to optimize the threshold values in the algorithm and improve the outputs of the system and present an applicable and reliable solution to the problem. These test case results are expected to be discussed as part of a further study paper.

References

1. Bureau of Labor Statistics: 2014 Census of Fatal Occupational Injuries (revised data) (2016)
2. Bureau of Labor Statistics: Fatal Occupational Injuries by Industries and Event or Exposures - all United States (2014)
3. Wu, W., Yang, H., Chew, D.A.S., Yang, S.H., Gibb, A.G.F., Li, Q.: Towards an autonomous real-time tracking system of near-miss accidents on construction sites. Autom. Constr. **19**, 134–141 (2010)
4. Occupational Safety and Health Administration: Commonly Used Statistics, https://www.osha.gov/oshstats/commonstats.html
5. Nadhim, E.A., Hon, C., Xia, B., Stewart, I., Fang, D.: Falls from height in the construction industry: a critical review of the scientific literature. Int. J. Environ. Res. Public Health. **13**, 638 (2016)
6. Siddiqui, S.: US construction worker fall accidents: Their causes and influential factors. http://digitalcommons.fiu.edu/cgi/viewcontent.cgi?article=2203&context=etd, (2014)
7. Chan, A.P.C., Wong, F.K.W., Chan, D.W.M., Yam, M.C.H., Kwok, A.W.K., Lam, E.W.M., Cheung, E.: Work at height fatalities in the repair, maintenance, alteration, and addition works. J. Constr. Eng. Manag. **134**, 527–535 (2008)
8. Harmsen, A.M.K., Giannakopoulos, G.F., Moerbeek, P.R., Jansma, E.P., Bonjer, H.J., Bloemers, F.W.: The influence of prehospital time on trauma patients outcome: a systematic review. Injury **46**, 602–609 (2015)
9. Locker, T., Morris, F.P.: Pre-hospital Care, Triage and Trauma Scoring. Surg. **21**, 197–201 (2003)
10. Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M.: Internet of Things (IoT): a vision, architectural elements, and future directions. Futur. Gener. Comput. Syst. **29**, 1645–1660 (2013)
11. Vermesan, O., Friess, P.: Internet of things applications—From research and innovation to market deployment. (2014)
12. IEEE: Examples of IoT Applications, http://sites.ieee.org/rww-2018/examples-of-iot-applications/
13. Swan, M.: Sensor Mania! The internet of things, wearable computing, objective metrics, and the quantified self 2.0. J. Sens. Actuator Netw. **1**, 217–253 (2012)
14. Want, R., Schilit, B.N., Jenson, S.: Enabling the internet of things. Computer (Long. Beach. Calif). **48**, 28–35 (2015)
15. Razzaque, M.A., Milojevic-Jevric, M., Palade, A., Clarke, S.: Middleware for internet of things: a survey. IEEE Int. Things J. **3**, 70–95 (2016)
16. Awolusi, I., Marks, E., Hallowell, M.: Wearable technology for personalized construction safety monitoring and trending: review of applicable devices. Autom. Constr. **85**, 96–106 (2018)
17. Pannurat, N., Thiemjarus, S., Nantajeewarawat, E.: Automatic fall monitoring: a review. Sensors (Basel). **14**, 12900–12936 (2014)
18. Lara, O.D., Labrador, M.A.: A survey on human activity recognition using wearable sensors. IEEE Commun. Surv. Tutorials **15**, 1192–1209 (2013)
19. Zhou, Z., Irizarry, J., Li, Q.: Applying advanced technology to improve safety management in the construction industry: a literature review. Constr. Manag. Econ. **31**, 606–622 (2013)
20. Skibniewski, M.: Research trends in information technology applications in construction safety engineering and management. Front. Eng. Manag. **1**, 246 (2014)
21. Marks, E.D., Teizer, J.: Method for testing proximity detection and alert technology for safe construction equipment operation. Constr. Manag. Econ. **31**, 1–11 (2013)
22. Teizer, J.: Wearable, wireless identification sensing platform: self-Monitoring Alert and reporting technology for hazard avoidance and training (SmartHat). J. Inf. Technol. Constr. **20**, 295–312 (2015)
23. Zhong, D., Lv, H., Han, J., Wei, Q.: A practical application combining wireless sensor networks and internet of things: safety management system for tower crane groups. Sensors **14**, 13794–13814 (2014)
24. Mubashir, M., Shao, L., Seed, L.: A survey on fall detection: principles and approaches. Neurocomputing **100**, 144–152 (2013)
25. Seo, J., Han, S., Lee, S., Kim, H.: Computer vision techniques for construction safety and health monitoring. Adv. Eng. Inform **29**, 239–251 (2015)
26. Delahoz, Y.S., Labrador, M.A.: Survey on fall detection and fall prevention using wearable and external sensors. Sensors (Switzerland). **14**, 19806–19842 (2014)
27. Dzeng, R.J., Fang, Y.C., Chen, I.C.: A feasibility study of using smartphone built-in accelerometers to detect fall portents. Autom. Constr. **38**, 74–86 (2014)
28. Fang, Y.C., Dzeng, R.J.: Accelerometer-based fall-portent detection algorithm for construction tiling operation. Autom. Constr. **84**, 214–230 (2017)
29. Abbate, S., Avvenuti, M., Bonatesta, F., Cola, G., Corsini, P., Vecchio, A.: A smartphone-based fall detection system. Pervasive Mob. Comput. **8**, 883–899 (2012)
30. Akhavian, R., Behzadan, A.H.: Smartphone-based construction workers' activity recognition and classification. Autom. Constr. **71**, 198–209 (2016)
31. Habib, M., Mohktar, M., Kamaruzzaman, S., Lim, K., Pin, T., Ibrahim, F.: Smartphone-Based Solutions for Fall Detection and Prevention: Challenges and Open Issues. Sensors **14**, 7181–7208 (2014)
32. Risser, D., Bönsch, A., Schneider, B., Bauer, G.: Risk of dying after a free fall from height. Forensic Sci. Int. **78**, 187–191 (1996)

Using Augmented Reality to Facilitate Construction Site Activities

26

Serkan Kivrak and Gokhan Arslan

Abstract

Using augmented reality in construction applications can be a beginning of a new era in the construction industry. This advanced technology has the potential to provide significant benefits to construction companies. Since it is a relatively new technology, the application areas in the construction industry are rather limited. Parallel to the development of augmented reality, it is envisaged that applications will be grow up in the construction sector besides automotive, advertising, food, media, film and many other sectors in the near future. Therefore, it is very important for the construction companies to adapt this technology as fast as possible in order not to lose the competitive advantage in the future. In this study, an augmented reality system is developed for facilitating construction site activities. The system enables managers, engineers and construction workers to follow each step of the construction activities that they are responsible for. Users can access information on training materials and construction methods related to the activities. Thus, the risk of making mistakes in site activities will be minimized. Using smart glasses, the system is tested for steel fixing and brick wall construction. The developed system has the potential to improve the quality and productivity of construction site activities and therefore, provide significant contributions to the construction industry.

Keywords

Augmented reality • Construction site activities • Smart glass

26.1 Introduction

Mistakes in construction site activities affect the quality of projects, cause delays, increase costs, and lead to disputes between the employer and the contractor [1]. In addition, mistakes in construction site activities are one of the important factors that cause structures to be damaged in earthquakes. In order to overcome these problems, it is very important for construction workers to access accurate information about construction site activities. Effective use of information technology in the construction phase significantly affects the efficiency of projects, quality, health and safety, and consequently the project cost and duration, positively. Within this context, augmented reality (AR), which brings a new perspective to information technologies, has a significant potential to improve construction site activities.

AR is the enrichment of the real world with information from the virtual world [2]. According to a common definition, AR is to increase the real world reality phenomenon boarded the virtual world objects on the display of real-world objects [3, 4]. AR is one of the innovative technologies that has a great potential in applications in almost every area. AR is a variation of virtual reality (VR). VR is a computer-generated simulation of the real world. In AR, the real world is much closer to virtual reality [5]. Milgram et al. [6] defined the relationship between reality-virtual continuity. At one end of this continuity

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is a world we perceive without the use of any equipment, while at the other end there is a world of computer production altogether. Intermediate transitions are defined as mixed reality where real and virtual media objects are presented together. The real environment in AR is more dominant than virtual environment. Unlike VR, AR allows the user to perceive the real world combined with virtual objects.

AR is foreseen to use in almost all sectors in the near future. For example; car maintenance in automotive industry, operations in medicine, visualization of books in education, advertising, home furniture placement, visualization of architectural designs, display of inter-vehicular distances in traffic are potential future applications of the AR technology. However, the construction industry is one of the sectors that do not use this promising technology's applications effectively. Within this context, in this study, an AR system, by which workers, equipment operators, engineers and managers can easily access to relevant information about the site activities they are responsible for, was developed. It was aimed to contribute to the literature and sector in this area. The system has the potential to improve construction site activities.

26.2 Augmented Reality in Construction

Researches on AR applications in construction have been increased in the recent years [7]. Constantly increasing hardware development and monitoring techniques motivate AR applications in the construction industry [8]. The use of AR provides significant advantages to this sector. Agarwal [9] mentioned the advantages of AR use in civil engineering as error reduction, better marketing, review of the project, saving of man-hours, and cost reduction. Computer interface design and new advances in hardware power have developed AR research prototypes and test platforms for architecture, engineering and construction applications. However, most of these laboratory-based prototypes and concepts are explored by computer science or engineering researchers, who choose architecture, engineering and construction applications randomly to develop test scenarios and to prove the availability and efficiency of AR concept as the subject. As a result, the prototype tests cannot reach the level to be ready for the field tests [2].

Behzadan and Kamat [10] tried to transfer the construction site activities to civil engineering students via AR technology. Another study on the use of advanced technologies in education was carried out by Gul et al. [11]. The researchers have studied the design students on using 3D VR technology. Chi et al. [12] investigated the potential future applications of AR technology in the construction industry. According to the results of the investigation, they specified that the use of mobile devices in the future will be more effective and cheaper foreseeing the AR technology will increase the application of these devices. Wang et al. [13] examined articles published between the years 2005 and 2011 related to AR in construction. The researchers stated that the majority of AR technologies are based on laboratory studies and it is still insufficient to apply to the real construction projects. As a result, researchers have noted that AR technology needs for research that can be applied in real projects rather than laboratory-based researches.

Park and Kim [14] have developed a safety management and visualization system (SMVS) that integrates AR, location tracking, building information modeling (BIM) and gaming technologies. They have developed a prototype system on their research and tested the system with an identifier accident scenario. The purpose of their study was to get continuous processes such as planning of safety, training and control processes under a framework. They used AR technology on real-time and location-based safety management in their study on smartphones and tablet computers. Employees can see augmented safety information on their devices, when they walk around in the construction site. With this approach, researchers aimed to avoid accidents before accidents may occur at construction sites.

The researches described above and many other studies [15–18] are important studies especially in the last five years in terms of the development of AR technology in the construction sector. However, although there are numerous publications on the use of AR technology in other sectors and their contributions to these sectors, the use of this technology in the construction sector is still relatively limited. As mentioned in the literature review, the construction industry needs AR applications especially for construction sites, instead of laboratory-based studies [13]. Thus, the proposed system in this study can provide significant contributions to the construction industry when considering its application potential.

26.3 Method

The main aim of this study is to develop a system using AR to facilitate construction site activities. The system enables construction workers, equipment operators, engineers and managers to follow each step of the construction site activities that they are responsible for. Thus, all phases of construction site activities can be made in a more efficient manner. Within this scope, steel fixing and brick wall construction, which are commonly used site activities in construction projects, were selected. These activities were determined together with construction companies providing technical support to this study. In order to comply with the standards in the construction methods of each site activity, training materials developed by the Turkish Ministry of Education and INTES (Employers' Union of Construction Industry Employers) within the scope of the 'Project for Strengthening the Vocational Education and Training System' have been utilized [19]. In the first stage of the study, the production methods and training materials of these selected activities are prepared. Animation models of each activity were created in accordance with the construction methods. Animation models have been designed using 3ds Max and Maya programs to show all phases from the beginning to the end of the activities, in accordance with the standards selected. The system was developed after completing the models. In the third phase of the study, the AR software was adapted to the smart glass. In the fourth phase, the AR system was tested. At this phase, mistakes, errors and deficiencies of the AR system have been identified and consequently the system has been revised.

26.4 System Development

In the development phase; AR platform software, the Maya program to create 3D models, the Unity program to render models, the Xcode and Android SDK programs to develop softwares, the AR camera Vuforia SDK, and Android Studio and C++ software languages to make smart glasses compatible with Android 4.04 operating system were used. Smart glasses have been used as mobile devices. Each phase of the construction site activities are determined and integrated into the AR system. Applications for each phase are created and buttons are prepared for transitions between the steps.

The AR system was designed using the following methods:

- Image Tracking

In the image tracking method, the area, previously scanned digitally, is used. The scanned area is saved in the AR platform software. The models are placed and the image is saved in the scan area database and prepared in apk format compatible with the Android system in the Android Studio software language. Then the setup is performed by transferring to the smart glass.

- Extended Tracking

In extended tracking, instead of a specific area, a wide area scanning is performed and transferred to the AR software platform. It is the process of placing 3D models in the specified locations of the modules depending on the movement of the person. The AR model is prepared in apk format compatible with the Android system in the Android Studio software language and is installed by transferring it to the smart glass.

- Object Tracking

In object tracking, a captured object is recorded in the database and the QR (Quick Response) code is transferred to the AR platform software. This method is valid for standing objects. 3D modeling is placed on the transferred object and it is prepared in apk format compatible with Android system in Android Studio software language and transferred and integrated to the glasses. By looking at the object modeled with smart glasses, one can follow the steps of the construction activities.

- Face Tracking

In face tracking, 3 dimensional models are placed on the face model in the AR platform and adjusted to the face of the person. Relevant codes are prepared using C++ software. The AR model is prepared in apk format compatible with the Android system in the Android Studio software language and transferred to the glasses for installation.

- Marker Tracking

In marker tracking, a marker is prepared specifically for each AR model. The marker recorded in the database is transferred to the AR platform and added to the desired 3D model when the marker is received. Using relevant codes, Android Studio is prepared in apk format compatible with the Android system in the software language and is installed to the smart glass.

For construction site activity applications, first, the real images which will be integrated into the AR system are photographed with object tracking method. 3 dimensional models of construction site activity productions are prepared and AR mobile platform was developed. The 3D models of the photographs were prepared in Maya program in *.obj and *.flx formats. Each phases of construction site activities are prepared in the AR development program. Application area for each stage was designed and forward-backward buttons were created for transitions between the phases. Then, 3 dimensional models are transferred into the AR development program. The imported models and object tracking images are saved in the development program database. The models are designed using 3ds Max and Maya programs to show all phases of the site activities from the beginning to the end in accordance with the required building standards. In Fig. 26.1, a rebar model used in steel fixing is illustrated.

In the AR development program, 3D images prepared in the Maya program were transferred onto the image that was transferred as object tracking. Then x, y, z coordinate settings and the model matching were completed (Fig. 26.2). In order to achieve effective results in model matching, distance and height arrangements of the model are performed.

After the model matching process, applications, prepared with Android SDK mobile software, need to be coded according to the platform where they will be integrated. Once the codes for the Android platform have been prepared, transfers will be made in the AR development program according to the selected platform. When the created application file is executed after being transferred to the mobile device, the 3D model appears on the screen. The match occurs when the actual model comes at the front of the image display.

Using smart glasses, the system is tested for steel fixing and brick wall construction on a real construction site. For brick wall construction, a marker was attached on the ground. Once the marker is detected by the camera, the phases of brick wall construction are displayed on the screen of the smart glass. Figures 26.3 and 26.4 illustrate some views of the brick wall construction phases taken from the smart glass. As Figs. 26.3 and 26.4 illustrate, 3D models and the phases of brick wall construction were displayed in a real environment and the users are guided to carry out this task from the beginning to the end.

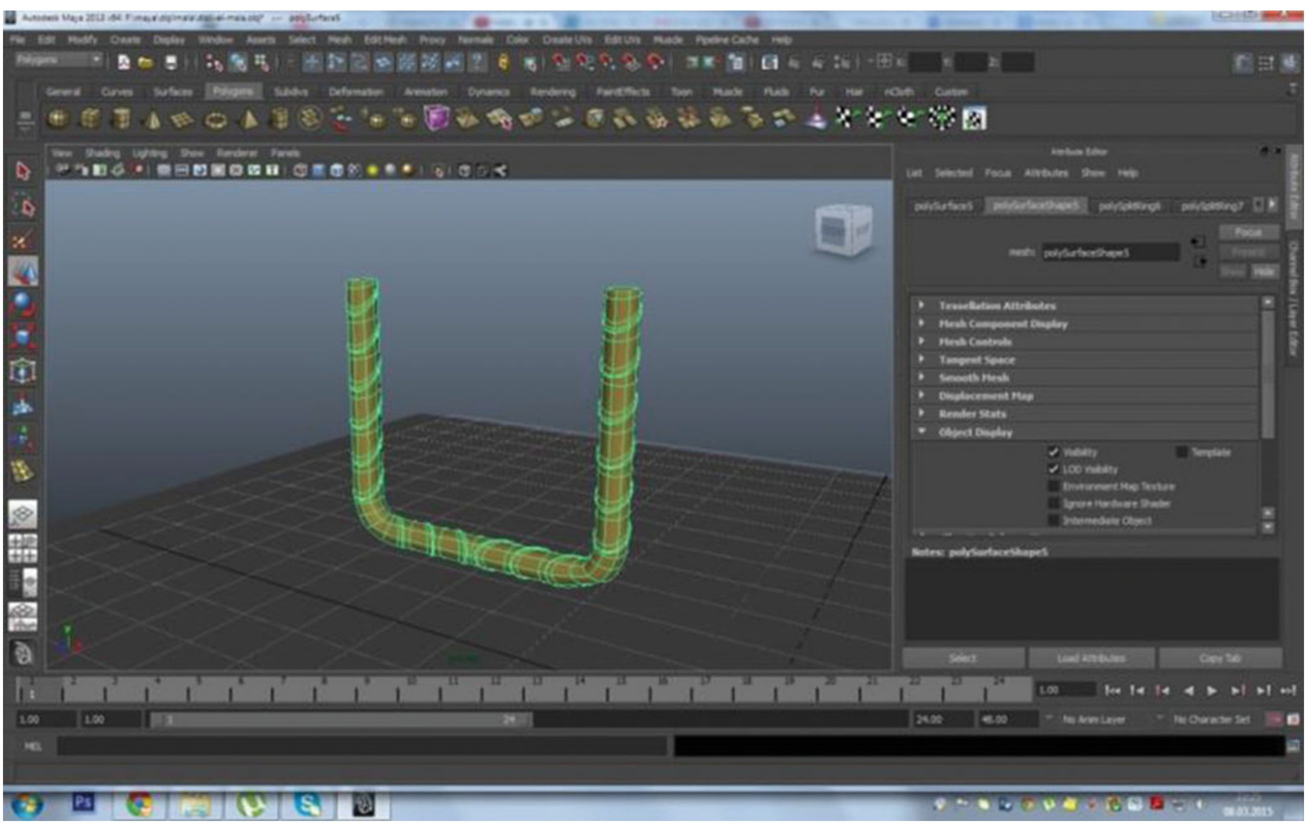

Fig. 26.1 Rebar 3D model

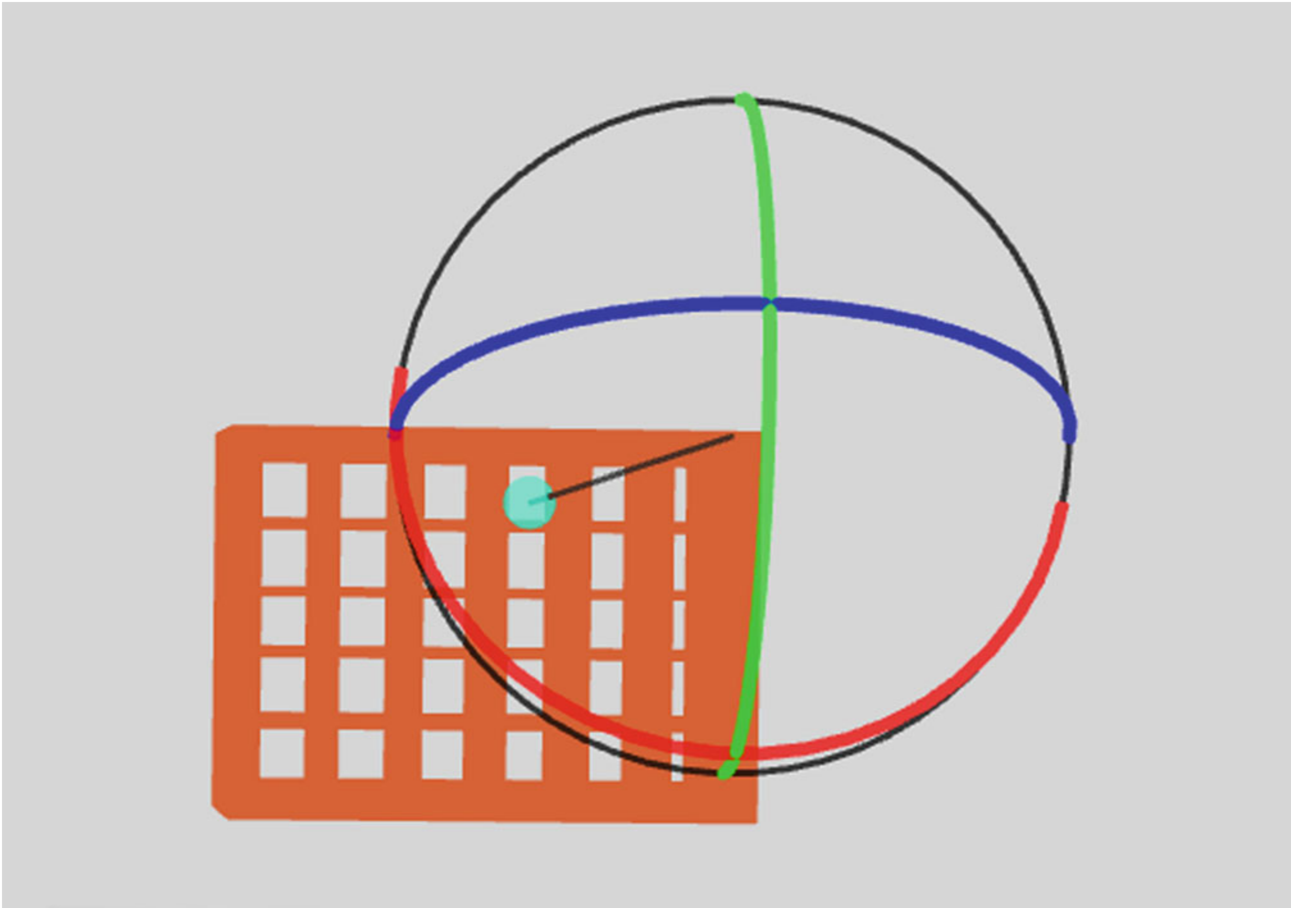

Fig. 26.2 Transferring brick model into the AR development program

Fig. 26.3 Testing the system using smart glass-I

Fig. 26.4 Testing the system using smart glass-II

26.5 Conclusions

Effective use of rapidly developing information technologies in construction projects has become one of the factors directly affecting the efficiency, quality, health and safety of the projects and consequently the project success. In this context, it is anticipated that AR technology applications, which bring a new perspective on information technologies, will provide significant contributions to companies operating in the construction sector. As AR is a relatively new technology, the application areas in the construction industry are rather limited. However, this promising technology has the potential to be implemented in many different areas of the industry. Parallel to the development of AR technology, it is envisaged that applications will be grow up in the construction sector besides automotive, advertising, food, media, film and many other sectors in the near future. Therefore, it is very important for the construction companies to adapt this technology as fast as possible in order not to lose the competitive advantage in the future. Utilizing AR technology in construction will be a beginning of a new era in this sector.

In this study an AR system was developed. By using this system, managers and construction workers can get relevant information, from the beginning to the end, about construction site activities they are responsible for. With this system, the risk of construction activity mistakes can be minimized as workers can obtain all information relevant to the activity. Thus, completing the activities according to the standards can ensure the required quality of the production. For example, a construction worker can learn how to make correct steel fixing and how to construct a brick wall in accordance with the standards by following the phases of the activity through the smart glasses. Inexperienced workers can be trained in a faster and cheaper way through a user-friendly system. On the other hand, experienced workers will have the opportunity to correct their mistakes and incorrect applications or enhance their performance by improving the critical phases in site activities through details reflected in the smart glasses.

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References

1. Gordon, C., Akinci, B., Garrett, J.H.: Formalism for construction inspection planning: requirements and process concept. J. Comput. Civ. Eng. **21**(1), 29–38 (2007)
2. Wang, X., Dunston, P.S.: Design, strategies, and issues towards an augmented reality-based construction training platform. ITcon **12**, 363–380 (2007)

3. Azuma, R.T.: A survey of augmented reality. Teleoperators Virtual Reality **6**(4), 355–386 (1997)
4. Shin, D.H., Jung, W., Dunston, P.S.: Camera Constraint on Multi-range Calibration of Augmented Reality Systems for Construction Sites. ITcon **13** (2008)
5. Kuo, C., Jeng, T., Yang, I.: An invisible head marker tracking system for indoor mobile augmented reality. Autom. Constr. **33**, 104–115 (2013)
6. Milgram, P., Takemura, H., Utsumi, A., Kishino, F.: Augmented reality: a class of displays on the reality-virtuality continuum. In Proceedings SPIE, Telemanipulator and Telepresence Technologies, vol. 2351, pp. 282–292 (1994)
7. Kwon, O.S., Park, C.S., Lim, C.R.: A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. Autom. Constr. **46**, 74–81 (2014)
8. Jiao, Y., Zhang, S., Li, Y., Wang, Y., Yang, B.M.: Towards cloud augmented reality for construction application by BIM and SNS integration. Autom. Constr. **33**, 37–47 (2013)
9. Agarwal, S.: Review on application of augmented reality in civil engineering. In: International Conference on Inter Disciplinary Research in Engineering and Technology, pp. 68–71 (2016)
10. Behzadan, A.H., Kamat, V.R.: Enabling discovery-based learning in construction using telepresent augmented reality. Autom. Constr. **33**, 3–10 (2013)
11. Gul, L.F., Gu, N., Williams, A.: Virtual worlds as a constructivist learning platform: evaluations of 3D virtual worlds on design teaching and learning. ITcon **13** (2008)
12. Chi, H.L., Kang, S.C., Wang, X.: Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. Autom. Constr. **33**, 116–122 (2013)
13. Wang, X., Kim, M.J., Love, P.E.D., Kang, S.C.: Augmented reality in built environment: classification and implications for future research. Autom. Constr. **32**, 1–13 (2013)
14. Park, C.S., Kim, H.J.: A framework for construction safety management and visualization system. Autom. Constr. **33**, 95–103 (2013)
15. Irizarry, J., Gheisari, M., Williams, G., Walker, B.N.: Info SPOT: a mobile augmented reality methods for accessing building information through a situation awareness approach. Autom. Constr. **33**, 11–23 (2013)
16. Zhou, Y., Ding, L.Y., Chen, L.J.: Application of 4D visualization technology for safety management in metro construction. Autom. Constr. **34**, 25–36 (2013)
17. Guo, H., Yua, Y., Skitmore, M.: Visualization technology-based construction safety management: a review. Autom. Constr. **73**, 135–144 (2017)
18. Huang, W., Sun, M., Li, S.: A 3D GIS-based interactive registration mechanism for outdoor augmented reality system. Expert Syst. Appl. **55**, 48–58 (2016)
19. Turkish Ministry of Education: Construction Technology, Ankara (2012)

Semantic Frame-Based Information Extraction from Utility Regulatory Documents to Support Compliance Checking

27

Xin Xu and Hubo Cai

Abstract

Computer-aided compliance checking is always a challenge in the Architecture, Engineering, and Construction (AEC) domain. In recent years, semantic compliance checking has gained a lot of attention. As the critical ingredient of the checking system, rule information needs to be extracted from regulatory texts and be formalized into machine-readable format. This paper proposed a semantic frame-based information extraction method with a focus on domain semantics and lexical semantics. The extraction process is characterized by the enrichment of lexical semantic frames and the mapping with the domain semantic framework. Natural language processing (NLP) and machine learning (ML) techniques were used to implement the extraction mechanism. The preliminary experiment shows a promising performance when extracting rule information from Indian Utility Accommodation Policy.

Keywords

Compliance checking • Semantic framework • Semantic frame • Natural language processing (NLP)

27.1 Introduction

Research of computer-aided compliance checking is always a challenge, which has been studied and developed over the last four decades, with a focus on buildings and the built environment [1]. In recent years, computational implementation and tools (e.g., Solibri Model Checker, Jotne EDModelChecker, FORNAX, and SMARTcodes) have been developed by practitioners and software developers, adopting a variety of approaches including the widely popular rule-based systems [2]. One of the most important steps in a rule-based compliance checking system is the rule requirement analysis, which targets at the extraction of rule knowledge from regulatory documents. However, most current initiatives rely on manual efforts to extract requirements from regulatory documents and encode these requirements in a machine-interpretable format, which is time-consuming, costly and error prone [3]. Moreover, rule knowledge is conventionally represented in natural language texts and formalized in various formatting and semantic structures. Even in a single regulation, the formatting and semantics of the provisions could vary from one chapter to another. Consequently, the task of information extraction from regulatory documents is very complicated. In the Architecture, Engineering and Construction (AEC) domain, several approaches that aim at interpreting regulatory documents, extracting rule knowledge, and representing rules in a standard format have been attempted, including the use of document markup techniques to aid navigating the document structure and the integration of natural language processing (NLP) algorithms and semantic web technologies to facilitate syntactic and semantic interpretations of regulatory sentences [3–7].

Since more and more design and construction data is represented in the Resource Description Framework (RDF) data model [8], the underlying semantic and logical basis can provide an effective platform for implementing semantic compliance checking, as proposed by Pauwels et al. [9]. To ensure an effective semantic checking performance, the extracted rule

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information needs to follow a formalized representation format that aligns well with RDF-based design and construction data model. To achieve this goal, this paper proposed a novel approach to extract the rule information from regulatory documents by using NLP techniques and integrate domain-level semantic framework and sentence-level semantic frames. The application is targeted at checking the underground utility spatial configuration against the utility accommodation policy to identify potential utility conflicts.

27.2 Methodology

Substantial efforts on information extraction exist outside the AEC domain [10–12]. They focus on named entity extraction, attribute extraction, relation extraction, and event extraction [13]. Rule-based and machine learning-based approaches are frequently used for text processing. Semantic approach (using meaning/context-related features captured by a domain ontology) is expected to enhance the information extraction performance over the existing approaches [10]. In the AEC domain, similar research efforts, especially the ontology-based information extraction, are very limited. To take a step further, the proposed methodology in this paper used sentence-level semantic frames to boost the rule information extraction together with a domain semantic framework (a domain ontology).

27.2.1 Semantic Framework and Semantic Frames

In urban infrastructure domain, relevant work has been untaken to develop an ontology for products [14], processes [15], and actors [16]. Salama and El-Gohary [6] proposed a semantic framework for the compliance checking knowledge in the construction domain. By combining the existing ontological models, a semantic framework in the context of utility compliance checking was developed. A partial view of the semantic framework (ontology) is shown in Fig. 27.1. The development process is outside of the scope of this paper and is explained in Xu and Cai [17].

The developed ontology includes concepts applicable in the context of utility compliance checking and categorized into four main top-level concepts, namely, Utility Element, Surrounding Element, Rule Element, and Compliance Checking Element. This ontology also remains flexible and extendable. Most of the concepts and instances observed in this application domain can be organized and represented within this semantic framework. More efficient rule information extraction algorithms can be devised under the guidance of this framework as discussed in 27.2.3.

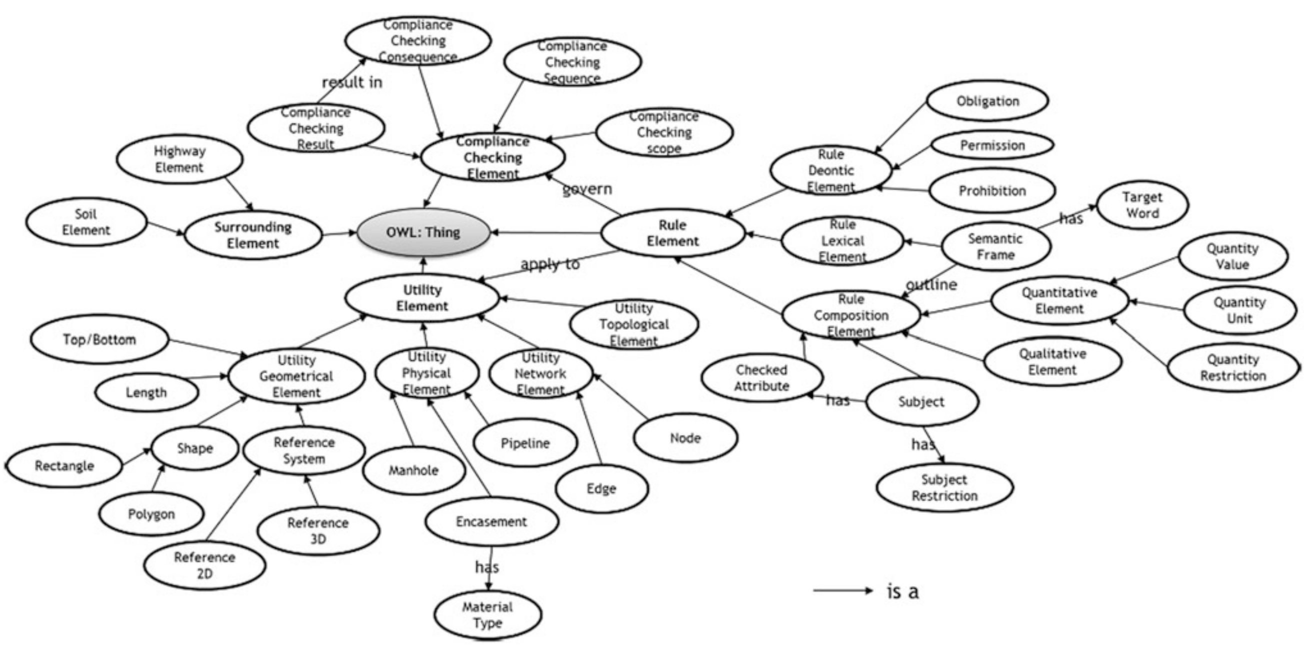

Fig. 27.1 Partial view of the ontology

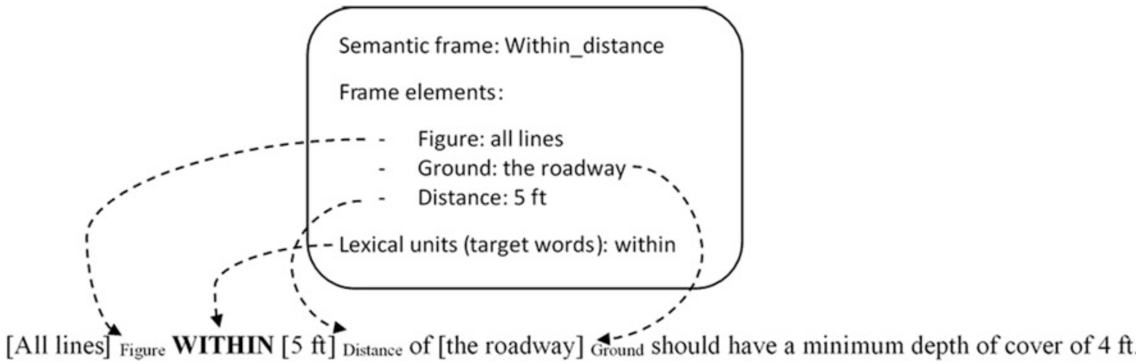

Fig. 27.2 Semantic frame filled with information extracted from rule clause

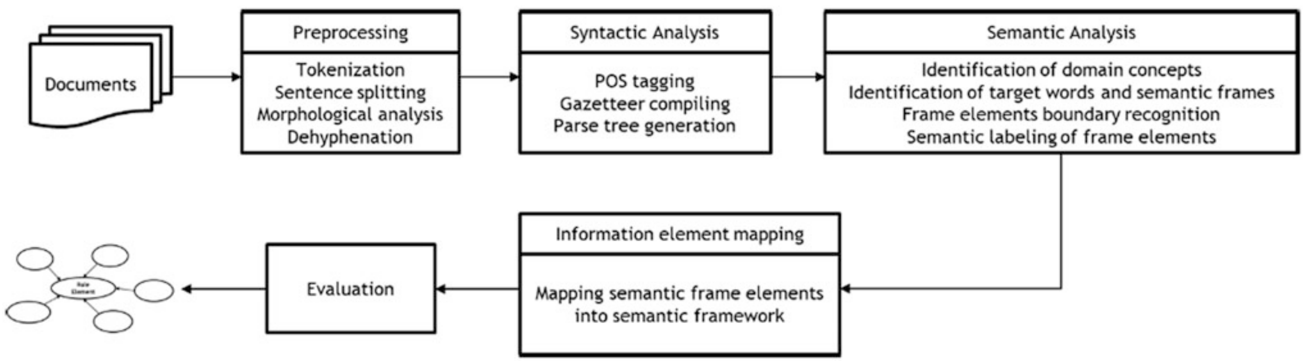

Fig. 27.3 Proposed information extraction methodology

Unlike other rule information extraction methods, this paper also added sentence-level semantic frames into the semantic framework to capture rule lexical elements. Semantic frame is a description of a type of event, relation, or entity and the participants in it, on basis of which sentences can be best understood [18]. Within a semantic frame, several core frame elements exist to contain important information entities extracted from sentences. Words that evoke the frame are called lexical units or target words. An excerpt from Indiana utility accommodation policy, all lines within 5 ft of the roadway should have a minimum depth of cover of 4 ft, can be partially interpreted via the within_distance semantic frame as in Fig. 27.2.

The readers are referred to the FrameNet project (https://framenet.icsi.berkeley.edu/fndrupal/) for detailed explanations. FrameNet has begun to annotate some continuous texts, as a demonstration of how frame semantics can contribute to text understanding and this style of annotation typically involves marking frame elements of frames evoked by target words in each sentence. Therefore, FrameNet can provide sufficient annotated training data for extracting frame elements from rule sentences. To this end, the procedure of semantic frame-based information extraction is summarized in Fig. 27.3.

27.2.2 Preprocessing

This phase is used to prepare the raw texts from regulatory documents for further processing. The rule sentences selected from utility accommodation polies were preprocessed following the procedure of tokenization, sentence splitting, morphological analysis, and de-hyphenation.

Tokenization is the process of splitting the raw texts into tokens, where a token is a word, a number, a symbol, or a whitespace [19]. Sentence splitting aims at detecting sentence boundary indicators (i.e., periods, exclamation marks, and question marks) and recognizing each sentence of the texts [13]. Morphological analysis aims to map the different forms of a word (e.g., plural form of a noun) to its lexical form (e.g., singular form of a noun) [20]. De-hyphenation is to remove hyphens that are used to continue a word across two lines. To illustrate, the same excerpt, all lines within 5 ft of the roadway should have a minimum depth of cover of 4 ft, was preprocessed as shown in Fig. 27.4.

Fig. 27.4 Illustrative example of preprocessing

Original text:
All lines within 5 ft of the roadway should have a minimum depth of cover of 4 ft.
Preprocessed text:
<sentence>
<Token>all</Token><Token>line</Token><Token>within</Token>
<Token>5</Token><Token>foot</Token><Token>of</Token><Token>the</Token>
<Token>roadway</Token><Token>should</Token><Token>have</Token>
<Token>a</Token><Token>minimum</Token><Token>depth</Token>
<Token>of</Token><Token>cover</Token><Token>of</Token><Token>4</Token>
<Token>foot</Token>
</sentence>

27.2.3 Syntactic Analysis

This phase is used to analyze the syntactic features of the preprocessed texts, which consists of part-of-speech (POS) tagging, gazetteer compiling, and parse tree generation.

POS tagging is to assign parts of speech to each word based on its syntactic word category, such as NN (singular nouns), DT (determiner), JJ (adjectives), VB (verb), and CD (cardinal number). The readers are referred to the Penn Treebank Project (https://www.ling.upenn.edu/courses/Fall_2003/ling001/penn_treebank_pos.html) for the complete list of POS tags. Figure 27.5 demonstrates the tagged result of the same excerpt using Stanford Parser.

Gazetteer compiling aims to group a set of terms based on any specific commonality possessed by these terms. By investigating the regulatory texts in the application domain, the negation gazetteer list (e.g., no, not), comparative relation gazetteer list (e.g., less than, greater or equal, minimum), and unit gazetteer list (e.g., foot, meter) were compiled, as similar as proposed by Zhang and El-Gohary [3]. If a word or a phrase is found within the compiled gazetteer list, a specific tag will

POS tagged text:
All/DT lines/NNS within/IN 5/CD ft/NN of/IN the/DT roadway/NN should/MD have/VB a/DT minimum/JJ depth/NN of/IN cover/NN of/IN 4/CD ft/NN.

Fig. 27.5 Illustrative example of POS tagging

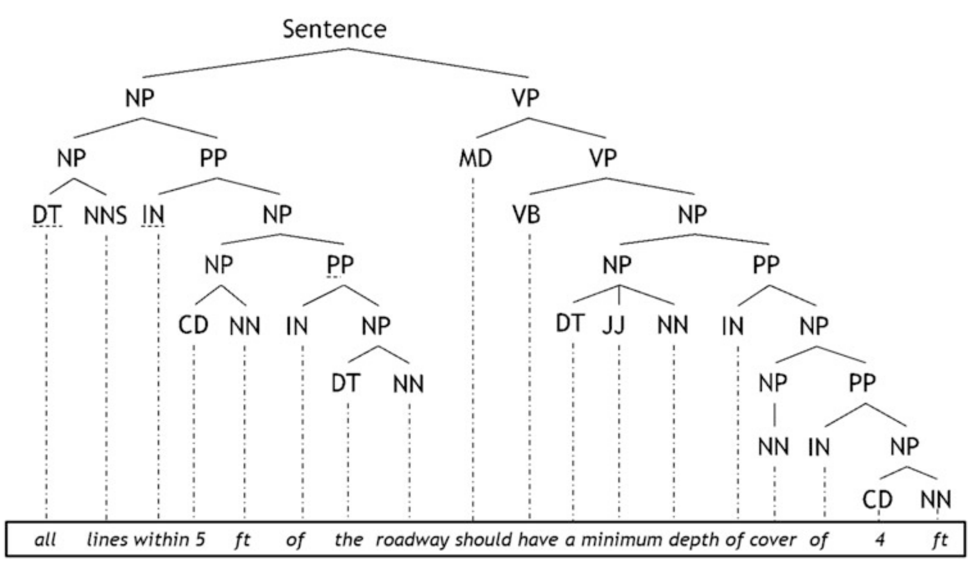

Fig. 27.6 Illustrative example of generated parse tree

be assigned. For example, in the POS tagged text, “minimum” was detected by gazetteer lookup then was labelled as CR (comparative relation gazetteer). The gazetteer tags together with POS tags can assist in subsequent information extraction phases, which are discussed in the following sections.

Parse tree is an ordered, rooted tree that represents the syntactic structure of a sentence according to some context-free grammar (CFG), starting from Sentence and ending in POS tagged words. The parse tree of the same excerpt was generated using Stanford Parser, as illustrated in Fig. 27.6.

The terminals (POS tags) are chunked into phrasal tags such as NP (noun phrase), VP (verb phrase) and PP (prepositional phrase) based on CFG following the bottom to up direction. Once rule clauses are decomposed into parse tree, rule information entities can then be extracted on the basis of their phrasal tags. In addition, the tree path (up or down) would be very helpful in assigning semantic roles to frame elements, which are discussed in 27.2.4.

27.2.4 Semantic Analysis

This phase is used to analyze the semantic features of the syntactically processed texts based on domain-level semantics (ontology) and lexical semantics (semantic frames). The goal is to identify the domain concepts structured in the semantic framework and to fill the semantic frames evoked by target words that are detected in the texts.

Identification of domain concepts. Since the ontology captures the concepts related in the context of utility compliance checking, it can be regarded as a gazetteer list populated with domain concepts, thus assisting the extraction of relevant information with domain-specific meanings from the texts. In previous work, the authors proposed an ontology to capture the concepts about utility physical products and attributes, which can be incorporated under the concept of utility physical element. For instance, the “pipeline” concept is a “utility physical element” concept. The “depth of cover” concept is a utility attribute concept that can be linked with the “pipeline” concept using the “has” relationship. Using these concepts modeled in the ontology, “lines” and “depth of cover” can be extracted from the same excerpt, “all lines within 5 ft of the roadway should have a minimum depth of cover of 4 ft”, by matching with the concepts of “pipeline” and “depth of cover” respectively. By this way, domain semantic tags can be added into the syntactically processed texts. Moreover, cross-concept relationships like the “is a” relationship and the “has” relationship defined within the ontology can aid in the semantic labeling of frame elements, which is discussed in the following sections.

Identification of target words and semantic frames. In the proposed methodology, lexical semantics was incorporated into the semantic framework by analyzing the target words and the evoked semantic frames. Given a sentence, once the target words are identified and the corresponding semantic frames are filled with core frame elements, the sentence can be interpreted from the lexical perspective. Information entities and relations can also be extracted based on the filled semantic frames. Following this direction, the authors investigated the utility accommodation policies of six states (Indiana, Tennessee, Illinois, Ohio, Michigan, and Kansas) to observe the rule clause patterns. With reference to semantic frames built in the FrameNet, three applicable semantic frames to the utility accommodation policy sentences are summarized in Fig. 27.7. Core frame elements and possible target words are also listed in Fig. 27.7. One observation was found in the preliminary investigation that a single rule sentence may hold multiple semantic frames associated with multiple target words. In order to extract all rule information entities and relations, all applicable semantic frames must be filled. In 27.2.1, the excerpt was interpreted using the semantic frame of “within_distance” evoked by the target word of “within”. What is still missing is the “deontic_rule” semantic frame evoked by the target word of “should”. Only by enriching these two semantic frames can all the rule knowledge within the excerpt be extracted.

Frame: Locative_relation	Frame: Within_distance	Frame: Deontic_rule
FEs:	FEs:	FEs:
- Figure	- distance	- Subject
- Ground	- Figure	- Theme
- Distance	- Ground	- Degree
Target words:	Target words:	Target words:
under. prep	Locate. v	Shall/Should
above. prep	place. v	Must
Beyond. Prep	Within. prep	Will

Fig. 27.7 Examples of applicable semantic frames

Analysis of lexical semantics starts with the identification of the target words, then the selection of applicable semantic frames, and lastly the enrichment of the semantic frames. To identify the target words, the highest ranked word in the sentence is selected by ranking all sentence words by semantic similarity to the evoking words listed in FrameNet [21]. Semantic similarity is computed following the same procedure as reported in [22]. In the case of this paper, the authors enumerated all the semantic frames with all the possible target words formalized in a lookup table. Then the target word in a given sentence can be found by simply referring to the lookup table. Correspondingly, evoked semantic frames can be matched. The following procedure is to fill the applicable semantic frames with frame elements, which is discussed in next two sections.

Recognition of frame elements boundary. After generating a set of syntactic features (e.g., POS tags, gazetteer tags, and phrasal tags) and domain semantic features (domain semantic tags), some frame elements boundary can be easily detected based on these features. For instance, domain semantic tags and gazetteer tags are often assigned to frame elements. POS tags following a specific sequence can also form a frame element, which plays a similar role as phrasal tags. Quite a few studies used regular expressions to encode the sequence patterns of POS tags [3, 7, 23]. The detailed explanation for the syntax of regular expressions is given in [24]. The NP tag corresponds to a list of POS tags matching the pattern (<DT|CD>? <JJ>*<NNS>). The phrases in the excerpt, *all lines* and *the roadway* are examples that satisfy the pattern and they are both frame elements in the "within_distance" frame. Another way of detecting the boundary of frame elements is to check the relative location with the target word, which can be analyzed along the generated sentence parse tree. The search path can be expressed as a sequence of non-terminal nodes of the parse tree linked by direction symbols (up or down). For instance, search along the path of "within" ↑ PP ↓ NP ↓ NP for the frame element of "5 ft". When the sentence structure gets much complicated, a collection of sample sentences is required to develop a set of reliable heuristics for targeting the boundary of those frame elements.

Semantic labeling of frame elements. As described previously, multiple core frame elements exist in a semantic frame. In the "within_distance" frame, "figure", "ground", and "degree" are three semantic roles labeled to the frame elements (see Fig. 27.2). Once the frame elements are recognized, semantic role labels are required to assigned to them, which is also critical to interpret their relations.

Research on semantic role labeling has been studied for long in the area of computational linguistics [21, 25]. Recently, a number of researchers have used machine learning techniques to build system which can be trained on FrameNet annotation data (as described in 27.2.1) and automatically produce similar annotation on new (previously unseen) texts [25, 26]. This process is called automatic semantic role labeling. In the case of this paper, the task of semantic role labeling is to classify the recognized frame elements into their corresponding semantic roles. The authors used a collection of annotated data from FrameNet to train a probability model that can be relied on to annotate new data from utility rule clauses. Features that are used in the probability model are summarized in Table 27.1. Some features were first designed in [27]. The examples in Table 27.1 all refer to the same excerpt from utility accommodation policy and some features are generated from the syntactic processing phase.

Table 27.1 Feature set

Feature type	Description
Phrase type	This feature indicates the syntactic type of the phrase recognized as a frame element, e.g., NP for "all lines" labeled as the role of "Figure"
Parse tree path	This feature contains the path in the parse tree between the recognized frame element and the target word, expressed as a sequence of nonterminal labels linked by direction symbols (up or down), e.g., NP ↑ NP ↓ PP for "all lines" labeled as the role of "Figure"
Position	This feature indicates if the frame element appears before or after the target word in the processed sentence, e.g., "all lines" appears before the target word "within"
Voice	This feature distinguishes between active or passive voice for the target word
Target word	This feature indicates the target word identified in the sentence with the case and morphological information preserved
Domain concept class	This feature indicates the concept class that the recognized frame element belongs to, e.g., "all lines" belongs to the concept class of pipeline in the semantic framework
Domain relationship class	This feature indicates the possible domain relationship the recognized frame element holds to the target word or other frame elements, e.g., "all lines" and "depth of cover" may be linked with a "has" relationship in the semantic framework
Gazetteer class	This feature indicates the prebuilt gazetteer class that the recognized frame element belongs to

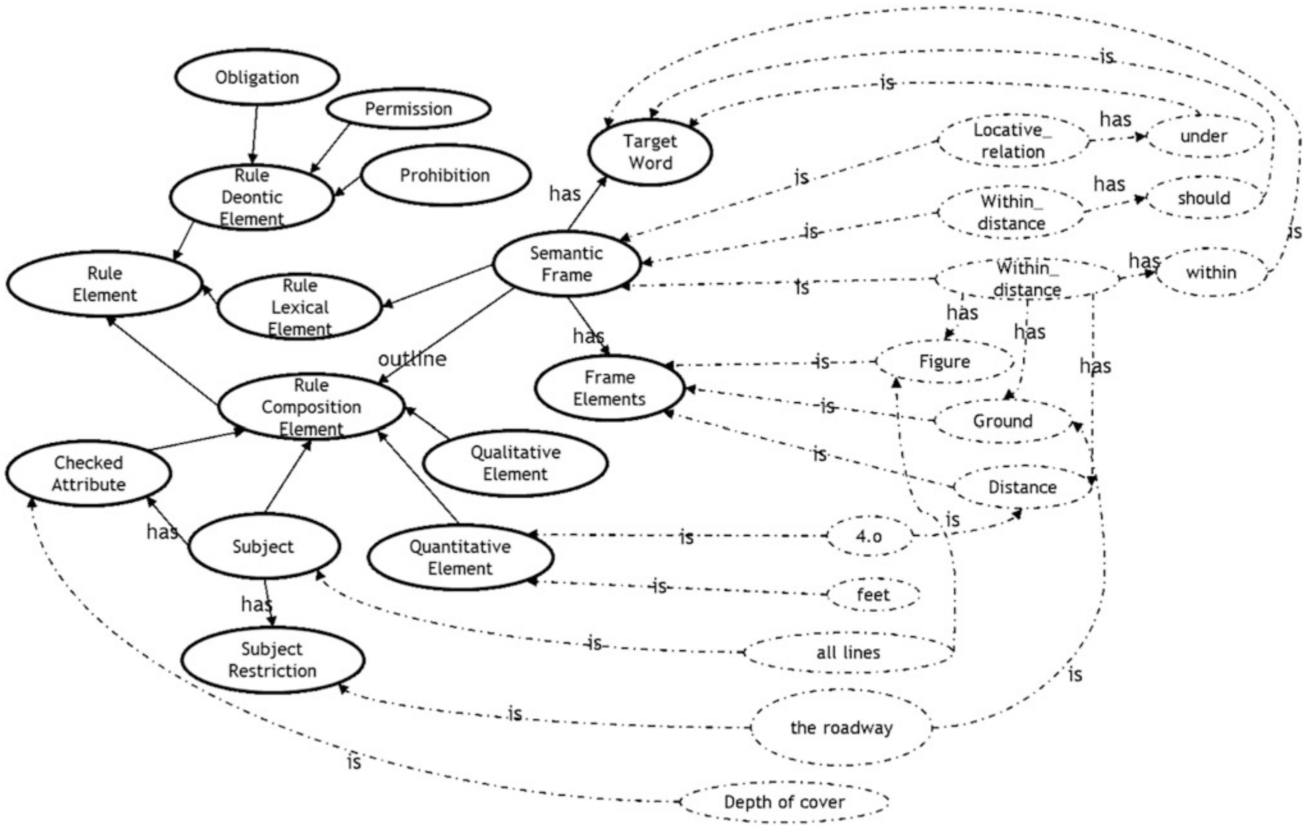

Fig. 27.8 Partial view of the mapping result

In FrameNet, a semantic frame has also a description that defined the relations holding between its frame elements, which is called the scene of the frame. For example, the scene of the "within_distance" frame is defined as: the "Figure" holds a "within" spatial relationship with the "Ground" and the distance between them is the "Distance". Once all the frame elements are labeled with semantic roles using the machine leaning-based system, the semantic relationships between frame element can be extracted correspondingly.

27.2.5 Information Element Mapping

The last step of the semantic frame-based information extraction is to map the semantic frame elements into the semantic framework in a unified knowledge representation format, which is required by semantic-based checking mechanism. The mapping process can be regarded as the process of adding instance data extracted from regulatory texts into the semantic schema. Figure 27.8 gives an example for the mapping result of processing the same excerpt (solid circles hold the semantic concepts and dash circles hold the instance data). Different semantic frames may have different mapping rules. The mapping can be done through comparing lexical semantics with domain semantics and linking them with predefined domain relationships.

27.3 Conclusion

As described previously, semantic frame-based information extraction is more suitable for semantic-based compliance checking. In the context of semantic checking, either fact knowledge or rule knowledge is represented in RDF graph. An RDF graph is constructed by applying a logical AND operator to a series of logical statements containing concepts and their relationships, similar as Figs. 27.1 and 27.8. These logical statements are often referred to RDF triples, consisting of a subject, a predicate, and an object. It is observed that the structure of the semantic frames displays a Subject-Verb-Object dependency with the target word. Given one sentence, all Subject-Verb-Object triples can be collected by identifying all the frame elements of all applicable semantic frames. Therefore, semantic frame-based information extraction serves as a starting point for semantic-based compliance checking, which gains a lot of popularity in recent years in AEC domain [2, 9].

The authors' preliminary experiment demonstrates the promising performance of the semantic frame-based information extraction method. The authors tested the method in extracting rule information from Indiana Utility Accommodation Policy using the semantic frame of "within_distance" with the target word of "within". The extracted rule information is concerned about the spatial relation between utility assets and their surrounding infrastructure including their relative distance. The precision is 92.32%. It can be expected that when more semantic frames are involved, the performance will deteriorate. Therefore, future experiments of rule information extraction using multiple semantic frames simultaneously are needed to improve the proposed methodology.

References

1. Dimyadi, J., et al.: Computerizing regulatory knowledge for building engineering design. J. Comput. Civil Eng. **30**(5) (2016)
2. Eastman, C., et al.: Automatic rule-based checking of building designs. Autom. constr. **18**(8), 1011–1033 (2009)
3. Zhang, J., El-Gohary, N.M.: Semantic NLP-based information extraction from construction regulatory documents for automated compliance checking. J. Comput. Civil Eng. **30**(2) (2013)
4. Abuzir, Y., Abuzir, M.D.O.: Constructing the civil engineering thesaurus (CET) using ThesWB. In: Computing in Civil Engineering, pp. 400–412 (2002)
5. Al Qady, M., Kandil, A.: Concept relation extraction from construction documents using natural language processing. J. Const. Eng. Manage. **136**(3), 294–302 (2009)
6. Salama, D.A., El-Gohary, N.M.: Automated compliance checking of construction operation plans using a deontology for the construction domain. J. Comput. Civil Eng. **27**(6), 681–698 (2013)
7. Zhou, P., El-Gohary, N.: Ontology-based automated information extraction from building energy conservation codes. Autom. Const. **74**, 103–117 (2017)
8. Manola, F., Miller, E., McBride, B.: RDF primer. W3C recommendation (2004)
9. Pauwels, P., et al.: A semantic rule checking environment for building performance checking. Autom. Const. **20**(5), 506–518 (2016)
10. Soysal, E., Cicekli, I., Baykal, N.: Design and evaluation of an ontology based information extraction system for radiological reports. Comput. Biol. Med. **40**(11–12), 900–911 (2010)
11. Sapkota, K., et al.: Extracting meaningful entities from regulatory text: Towards automating regulatory compliance. In: Requirements Engineering and Law (RELAW), 2012 Fifth International Workshop on IEEE, pp. 29–32 (2012)
12. Hogenboom, A., et al.: Semantics-based information extraction for detecting economic events. Multimed. Tools Appl. **64**(1), 27–52 (2013)
13. Jurafsky, D., Martin, J.H.: Speech and language processing. Pearson, London (2014)
14. El-Diraby, T.E., Osman, H.: A domain ontology for construction concepts in urban infrastructure products. Autom. Const. **20**(8), 1120–1132 (2011)
15. El-Gohary, N.M., El-Diraby, T.E.: Domain ontology for processes in infrastructure and construction. J. Const. Eng. Manage. **136**(7), 730–744 (2010)
16. Zhang, J., El-Diraby, T.E.: Mapping actors and roles in construction knowledge. In: Construction Research Congress 2009: Building a Sustainable Future, pp. 936–945 (2009)
17. Xu, X., Cai, H., Chen, K.: An ontology approach to utility knowledge representation. Const. Res. Congr. **2018**, 311–321 (2018)
18. Fillmore, C.J., Baker, C.: A frames approach to semantic analysis. The Oxford handbook of linguistic analysis (2010)
19. Moens, M.F.: Information extraction: algorithms and prospects in a retrieval context. Springer Science & Business Media (2006)
20. Fautsch, C., Savoy, J.: Algorithmic stemmers or morphological analysis? An evaluation. J. Assoc. Inf. Sci. Technol. **60**(8), 1616–1624 (2009)
21. Moschitti, A., Morarescu, P., Harabagiu, S.M.: Open Domain Information Extraction via Automatic Semantic Labeling. In: FLAIRS conference, pp. 397–401 (2003)
22. Barzilay, R., Elhadad, M.: Using lexical chains for text summarization. Advances in automatic text summarization, pp. 111–121 (1999)
23. Li, S., Cai, H., Kamat, V.R.: Integrating natural language processing and spatial reasoning for utility compliance checking. J. Const. Eng. Manage. **142**(12) (2016)
24. Thompson, K.: Programming techniques: regular expression search algorithm. Commun. ACM **11**(6), 419–422 (1968)
25. Das, D., et al.: Frame-semantic parsing. Comput. Linguist. **40**(1), 9–56 (2014)
26. Roth, M., Lapata, M.: Context-aware frame-semantic role labeling. Trans. Assoc. Comput. Linguist. **3**, 449–460 (2015)
27. Gildea, D., Jurafsky, D.: Automatic labeling of semantic roles. Comput. linguist. **28**(3), 245–288 (2002)

Ontology-Based Semantic Retrieval Method of Energy Consumption Management

28

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Abstract

A large number of different forms of energy consumption information are generated during facility management. In addition, due to the uncertain and ambiguous external and internal environment of construction project, it is an important issue in energy consumption for operation staff to query required information efficiently. Moreover, implementations of BIM technology can provide visualization and integrated information models for FM. In view of the above two aspects, this paper introduces ontology as the modeling approach for information exchange and put forward a semantic retrieval method based on ontology for building energy management. Then this paper realizes the integration between ontology based semantic retrieval system and energy consumption information under BIM environment. In the case study, this paper constructs a domain ontology of energy consumption and then conducts retrieval expansion based on this information model, and the discussion of example provides support for further research.

Keywords

Ontology • Energy consumption • BIM • Query language

28.1 Introduction

A relevant fraction of worldwide energy consumption is tightly related to indoor systems for residential and commercial buildings; it has been estimated that these buildings are responsible for about 20% of the world's total energy consumption today [1, 2]. Take into consideration the whole Building Lifecycle (BLC), construction and operation of the built environment account for at least 50% of all energy consumption in Europe [3]. The EU has established the Energy Performance of Buildings Directive, which aims to promote conservation and rational use of energy in buildings. New solutions to reduce energy consumption in the O&M phase are important to achieve this goal.

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In the future, some integrated systems which monitor and display the different factors that contribute towards building energy consumption, while also be capable of automatically retrieving the information required and provide knowledge about the entire built environment for enhanced decision support, are required [4]. This kind of method is considered in the literature important as the conventional thermal insulation of walls or insulating glazing to improve energy efficiency in buildings [5]. The basis of intelligent control to support energy management is visualizing actuators status and historical data

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based on different time stamps and ranges. Due to the uncertain and ambiguous external and internal environment of construction project, it is an important issue in energy conservation for operation staff to query required information efficiently.

In this paper, ontology is considered as the modeling approach for information exchange and put forward a semantic retrieval method based on ontology for energy consumption information. The information model is used in the knowledge base that allows intelligent analysis on the relations between energy consumption, building related information (geometry, boundary conditions, etc.) and surrounding factors, such as temperature, weather condition, and operating status of equipment. The knowledge base is represented using ontologies. Ontology can be used as generic model to facilitate the integration [6]. The ontology is not only used to describe functionalities of building automation systems, but also to represent states of building. The core link model is represented with OWL, which includes the capabilities of model management and decision support [7].

To support the integration of multiple data sources and achieve information retrieval, the solution makes use of building information modelling (BIM) principles and ontologies in the form of a holistic knowledge base. The paper is structured as follows: the following section discusses relevant existing work. Next, the requirements and implementation of the integrated system are presented. Finally, an example of energy analysis through ontology query will be evaluated given.

28.2 Existing Researches

Within the existing research, numerous methodologies have been proposed to provide different kind of intelligent control to support energy management [1]. In order to achieve comprehensive energy management by taking into account as much as related data resources and factors, an integration of building energy information model is required. Building energy management systems (BEMS) data integration requires consideration of the data structure and their representation. Building Information Modelling (BIM) describes an integrated approach to structuring all information relevant to the BLC. The Industry Foundation Classes (IFC) [8] standard, an open and neutral data file format for data sharing and exchange within AEC, is the leading standard developed around the concept of BIM. IFC is an object-oriented data standard that can describe physical objects, such as ducts and pipelines, as well as abstract concepts, such as space, organization, relationships, and processes. Modelling all this data remains a challenge, particularly for older buildings where the issue of fragmented and hard to access building data increases. Linked Data (LD) refers to the recommended best practices for exposing, sharing, and connecting data on the Web [9]. In particular, on the Ontology Web Language (OWL) as a data model for representing structured content. OWL languages do not contain any information about the content in the information sources, and hence can be used to represent general information queries from various domains. Ontology language OWL is based on RDF and provides information framework for representing ontology. This kind of structured ontology can be queried with SPARQL query language [10].

Using OWL as a schema modelling language, transforming EXPRESS schemas into ontologies was proposed by numerous authors [5, 11–14]. Ontology can be used as generic model to facilitate the integration [6]. Some scholars [15] gives a literature overview of semantic web technologies' potential applications, while referring to numerous example implementations worldwide. This paper summarizes examples in three categories: (1) interoperability, (2) linking data across domains, and (3) logical inference and proofs. The usage of semantic web technologies appears to achieve more in the latter two categories. The generic ontology represents domain knowledge for building holistic energy management. It contains definitions, and taxonomies that are aligned with IFC. The ontology is not only used to describe functionalities of building automation systems, but also to represent states of building, and relations with behavior model and surrounding factors. In this paper, an ontology model is proposed for building energy management data based on user events and building specific information.

To monitor the built environment and provide information for management, BEMS data integration requires a sensing infrastructure to measure data such as temperature, humidity, CO_2, and occupancy. This is achieved through the use of sensing technologies like thermostats, CO_2, ultrasound, cameras, and tag based system, like RFID, Bluetooth [16, 17], etc. A multi-scale BIM management system was developed for FM of large public buildings based on a self-developed graphic engine, containing the upstream and downstream relationship management of MEP components [18]. The basic management of these measured data can adapt device behavior to reduce energy consumption, some of MEP subsystems can also maintaining comfort levels, for example, the automatic control of HVAC based on a desired temperature. A common issue for commercial BEMS is the limitation of the sensing infrastructure [19]. For example, the data abstracted from different

MEP subsystems is unable to management in an integrated commercial system, and movement detection for calculating numbers of occupants is difficult.

The above researches about energy consumption do not strongly consider the alignment of existing standards, such as IFC, with the integrated information model. They do not include the modeling of occupant behavior as one of the factors that affects the energy consumption. This paper proposes an approach that addresses these points.

28.3 An Integrated BIM System to Query Sensor Data Based on Ontological Knowledge

In this study, an intelligent system which integrate many kinds of sensor data with BIM is proposed to help users to have an overview of energy data collected from different sensor in their building. With the help of domain query language and BIM, operation staff can query required information efficiently within visualized and integrated information models for FM. Figure 28.1 depicts the proposed approach of the intelligent system developed in this paper.

The generic ontology represents domain knowledge for building holistic energy management. It contains definitions, and taxonomies that are aligned with IFC. The generic ontology created by domain experts should be applicable in most kinds of building. The development of ontology will be discussed further in Sect. 28.3.1.

Another important module is the data collector and aggregator which is developed for collecting monitoring data from different building automation systems installed in the building. It contains an interface to communicate with different building automation logic control units or gateways via web services. The module is also responsible to integrate different kinds of data in BIM. For this, a BIM-based interface to collect energy data is developed. Section 28.3.2 will specify the realization of collecting sensor data within BIM environment.

The sensor data are collected and stored in a database. For the sake of visual representation of related data, pre-processing is necessary for data such as removing singular point, data transformation, data selection and data conversion. The data are prepared for further analysis in different criteria based on relation between rooms, appliances, time, and so on. Therefore, it

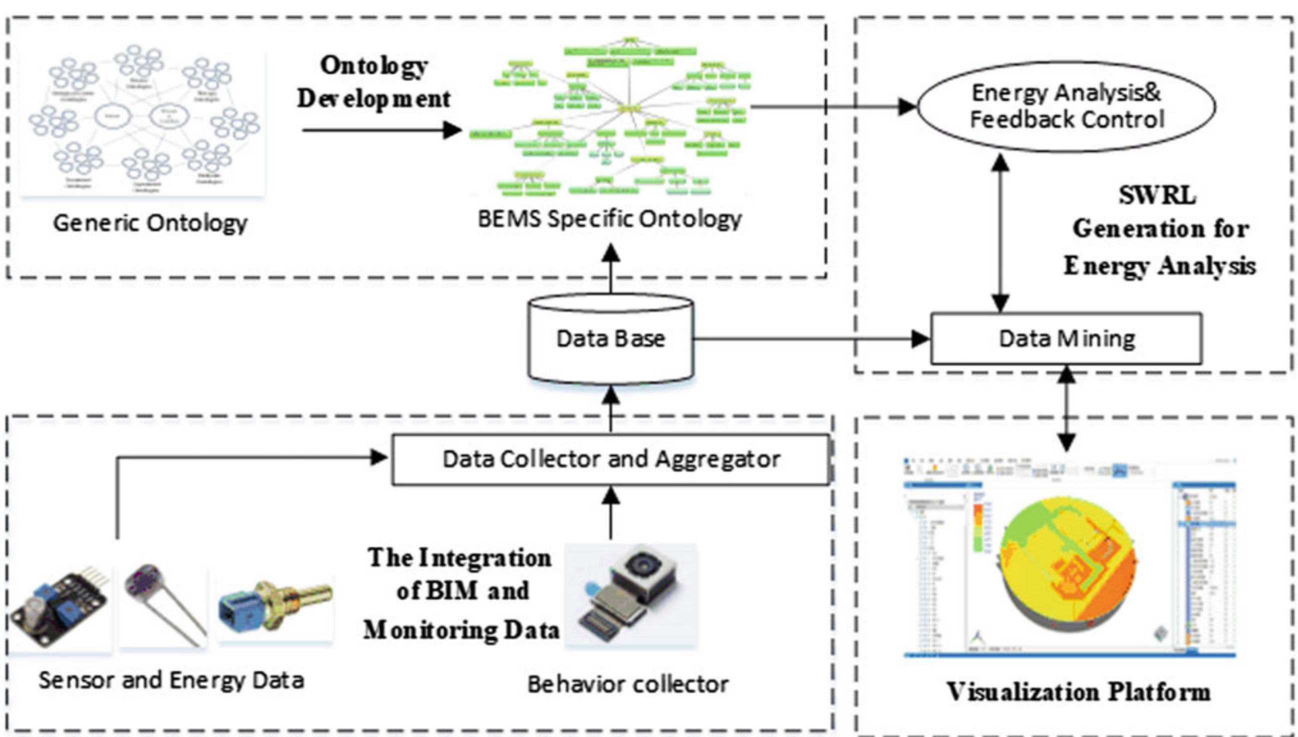

Fig. 28.1 The framework of building energy management with ontology knowledge

allows a data-driven analysis that is conducted directly on the collected data by performing SQL-query, simple calculation, or visualization. The ultimate goal of data-driven analysis is to provide efficient decision support for reducing energy consumption.

The visualization and analysis tool facilitates the visual interaction between the user and the system. The BIM provides geometry information for 3D visualization. In addition, users can query the ontology by using the tool, the facility manager is able to identify sensor data, to examine the building states, e.g. the light of which room is on, etc. The tool also allows the building occupants to have better understanding of the current building environment of the zones, where he is responsible for, thus it empower their engagement in balancing comfort and energy efficiency.

28.3.1 Building Energy Management Specific Ontology Development

Ontology classes and their properties as well as relationships representing the resources required for building energy management are developed firstly. The ontologies that contain basic elements are called generic ontologies. It only contains the ontological classes that describe the knowledge structure, definitions and terminology. Ontology main classes for the energy management in building are shown in Fig. 28.2.

The class MonitoringData models the sensor data that are collected, examined and analyzed in energy management activities. The class BuildingElement and its sub classes represent the fundamental of BIM. It is aligned with the domain layer in IFC4. The class BuildingControl indicates the entities related to building automation system elements in the building. It represents the sensors, actuators, controller, alarm, etc., which are elements of a building automation system. It

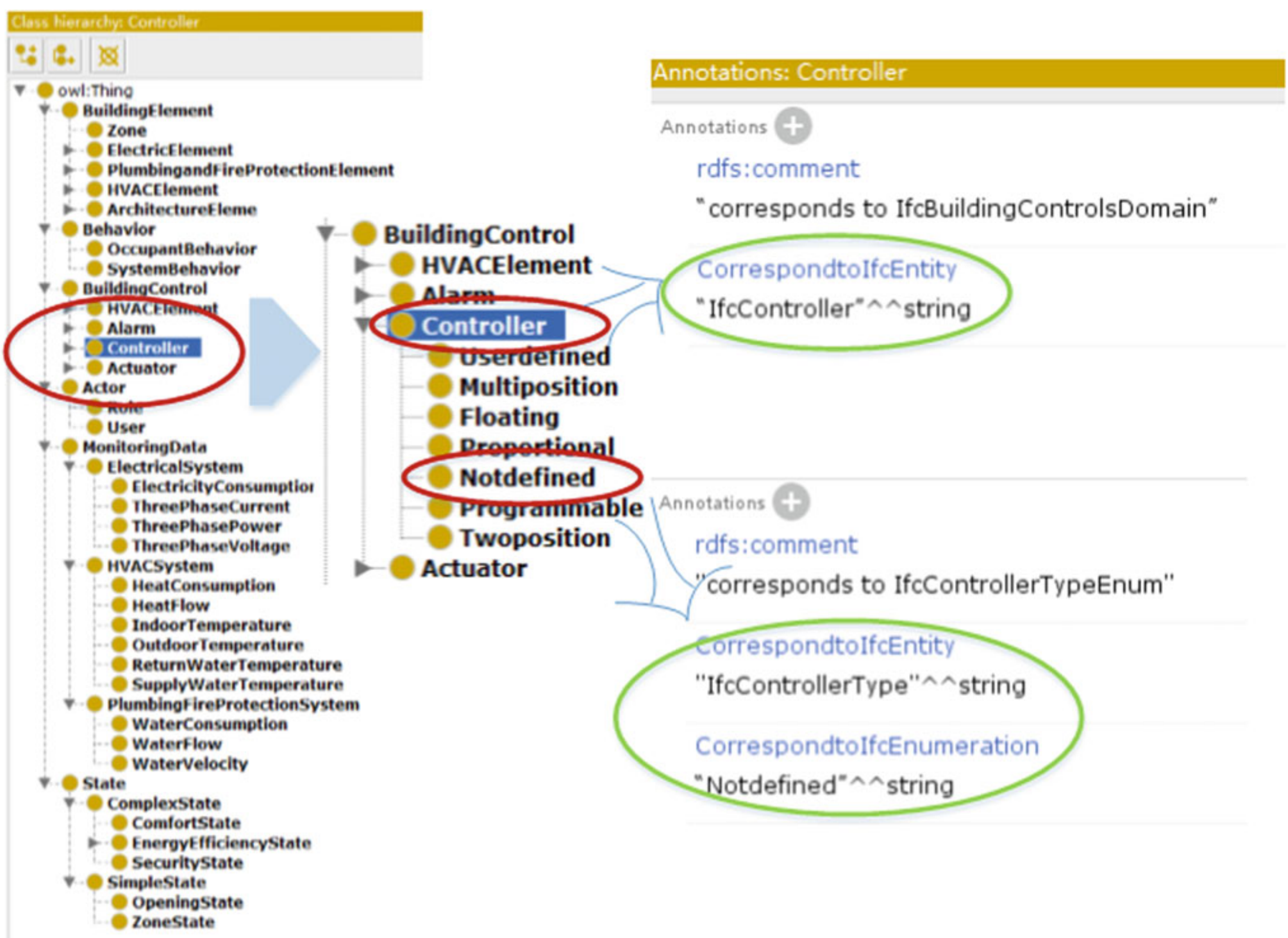

Fig. 28.2 Ontology main classes

has capabilities to measure, to observe, and to control the state of BuildingElement. It aligns with entities in the IFC4 domain IfcBuildingControlsDomain.

The class Actor defines all actors or human agents involved in a project during its FM. It is aligned with the IfcActorResource in IFC4. The class Behavior represents behavior performed by Actor, such as working, sleeping, etc. The Behavior can affect the state of BuildingElement. The class State represents the state of BuildingElements. It can be divided as ComplexState and SimpleState. Examples of ComplexState are ComfortState and EnergyEfficiencyState, whereas examples of SimpleState are WindowState, LightState, etc.

28.3.2 The Integration of BIM and Monitoring Data

The monitoring information of the MEP equipment of the building contains two aspects: the sensor information and the monitoring data. The sensor information of monitoring points contain is the description of the characteristics of information of MEP equipment monitoring subsystem including the basic information of monitoring points: location description, system, equipment type, equipment number, and feature information of monitoring points: monitoring point description, data point type, data point numerical range, alarm value, data length, information object address, etc. In MEP monitoring system, the monitoring point information is usually stored and transmitted in the form of point table. There is usually a fixed point table format which can be developed as interface for transition, monitoring point information is stratified according to building, system, zoon, equipment, monitoring point.

The monitoring data is the current and historical data of the monitoring points of the MEP equipment. The type of monitoring data includes digital quantity and analog quantity, namely discrete quantity and continuous quantity, in which digital quantity can be a switch quantity containing only two kinds of value states or a combination of multiple switches. Monitoring data are usually stored in the controller or database of electromechanical monitoring system. There are differences between different monitoring systems or related database.

In the process of data fusion, the monitoring point is the main body, and the BIM information as well as monitoring data are related to the MEP equipment. The relationship between the model information of MEP equipment and the monitoring point is many to one. Each device in the monitoring point can correspond to multiple BIM entities or regions. For the structure of monitoring point, each device can contain multiple monitoring points, for example, one air conditioning unit has many monitoring points, such as temperature, humidity, air volume, and so on. The relationship between the monitoring point structure and the monitoring data is one to many. For each monitoring point, the monitoring data is a number of records in the database.

28.3.3 SWRL Generation for Energy Analysis

In this paper, energy consumptions that do not occur normally in the building should be recognized. To finish this task, it is necessary to discuss how energies are consumed normally regarding occupant events and surroundings. For example, normally when an occupant is currently sleeping or left, or intensity of illumination in the room is enough for working, for instance greater than 100 lx, the light should be turn off. If in the same pre condition, the light in the room switching state is on, then it is considered as a usage anomaly.

It is not friendly for users if they always have to input their activities. The system contains simple sensors like different kinds of cameras to recognize user activities automatically. For instance, a camera can strongly give a clue whether somebody is currently sleeping, working or left. Of course it should be combined with some algorithms of appliance image recognition.

The query of ontology is based on SWRL language which consists of two main parts connected with the symbol "→", antecedent and consequent, both of them are collection of atoms. For example, the created rule represents a condition that if the activity is working while inside intensity of illumination is greater than 100 lx with the light in the room is on would normally occurs. The rule is transformed to (2), in order to represent an anomaly condition, by negating the consequent part of the rule.

$$\begin{aligned} \text{Event} = \text{``working''} \wedge \text{InsideIllumination} \geq 100 \\ \rightarrow \text{SwitchingofLight} = \text{On} \end{aligned} \tag{28.1}$$

Table 28.1 Competency questions to get states

Question	Competency questions	Example of answers
Q1	Which lights are currently in energy inefficient state in the zone?	Light2, Light4
Q1.1	Which lights are currently switched on?	Light1, Light2, Light4
Q1.2	Which users are currently sleeping?	User2, User3, User4
Q1.3	Which lights and users are currently located in the same zone?	Light1&User1, Light2&User2, Light3&User3, Light4&User4

$$\begin{aligned} &\text{UserBehavior}(?e)\wedge\text{``hasName}(?e,\text{working})''\wedge\text{InsideIllumination}(?ii)\\ &\wedge\text{hasValue}(?ii,?iit)\wedge\text{swrlb:greaterThanOrEqual}(?iit,100)\\ &\wedge\text{Light}(?l)\wedge\text{hasValue}(?l,?iit)\wedge\text{swrlb : Equal}(?l,1)\\ &\rightarrow \text{UsageAnomaly}(?e) \end{aligned} \tag{28.2}$$

The intelligent achieve the interaction between OWL knowledge base, SWRL rule, and rule engine through SWRL API. The SWRL API implements the retrieval of the OWL knowledge base using SWQRL. Furthermore, BIM data is integrated into the application framework and automatically processed by the relevant data mining algorithms to generate ontology knowledge.

28.4 Energy Analysis Through Ontology Query

In knowledge base represented in ontology, all conditions of energy wasting and anomalies are represented as SWRL. Real-time monitoring data extracted from building automation system will integrate with ontology information. These data given by installed monitoring point used to correspond to different kind of states, simple state or complex state.

The SWRL illustrated in (28.3) implies a complex state of energy inefficiency, if a user is sleeping, a light is turned on, and they both are located in the same zone. The necessary classes are created based on the formulated competency questions. For example, as seen in Table 28.1, the classes LightSwitchedOn and Sleeping are created based on competency questions Q1.1 and Q1.2. The simple state class LightSwitchedOn is represented as axiom.

$$\begin{aligned} &\text{Q1.1LightSwitchedOn}(?l)\wedge\text{Q1.2Sleeping}(?s)\wedge\text{Inside}(?z)\\ &\wedge\text{Q1.3isLocatedIn}(?s,?z)\wedge\text{Q1.3isLocatedIn}(?l,?z)\\ &\rightarrow \text{Q1EnergyInefficient}(?h) \end{aligned} \tag{28.3}$$

Under BIM environment, data processing program provides the interface of retrieval rules definition. When the rules are required to be executed, the BIM data engine extracts spatial and monitoring information based on the TBox (shown in Fig. 28.3) and the rules engine has semantic reasoning. After that the new value of attribute that are made will be set into the OWL ontology class through the SWRL query. For example, if camera attached to office space gives the occupant a state "sleeping", then the attribute has Value of corresponding ontology instance of concept UserBehavior is set to "sleeping". After the rule engine executes the SWRL rules, the instance of class Light is additionally assigned to EnergyInefficient class as shown in Fig. 28.3.

According to the above design, when the occupant is asleep in the office, the light in the relevant area will be automatically closed. In addition, if there are energy inefficient conditions, the related equipment or zone will be marked in different colors under BIM environment to be recognized by user. In addition, the historical monitoring data can also be retrieved with ontology knowledge. With this mechanism, user can have more directly understanding of management and have a better performance of energy conservation.

28.5 Conclusions

In this paper a system of intelligent energy analysis based on ontology is proposed under BIM environment. In the developed system, BIM information is combined with knowledge-driven energy analysis through ontology query. The ontology supported analysis approach provides intelligent assistance to improve energy efficiency in buildings, by strongly

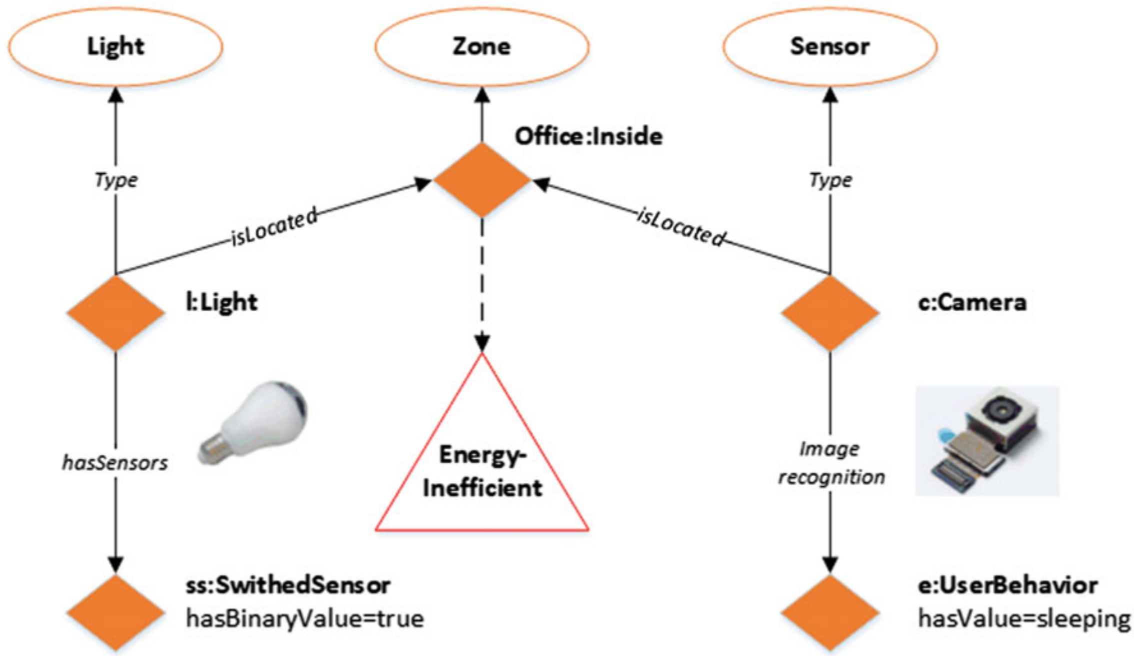

Fig. 28.3 Example of energy inefficiency identification with ontology knowledge

considering user behavior and real-time states in the building. The system will give out the energy usage pattern through monitoring data, and notify user whether energy inefficient conditions occur.

An approach is proposed to develop the ontology as the knowledge base of the intelligent energy management system. There are different methods and steps to generate building specific ontology containing the building specific information. It achieved the integration of BIM system and monitoring data. The monitoring point structure and query of monitoring information is also discussed in this paper.

Future works will focus on improving the accuracy of the approach and exploring efficient control methods of energy conservation combined with BIM models and ontology theories. Based on the experiences gained from this application, additional functions can be developed for energy management depending on a thorough exploration and comprehensive application of BIM and related information technology.

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References

1. Alessandra, D.P., Marco, O., Giuseppe, L.R., Giuseppe, A., Sajal, K.D.: Intelligent management systems for energy efficiency in buildings: a survey. ACM Comput. Surv. **47**(1), 1–38 (2014)
2. Wong, J.K.W., Zhou, J.: Enhancing environmental sustainability over building life cycles through green BIM: a review. Autom. Constr. **57**, 156–165 (2015)
3. Yuce, B., Rezgui, Y., Mourshed, M.: ANN–GA smart appliance scheduling for optimised energy management in the domestic sector. Energy Build. **111**(1), 311–325 (2016)
4. McGlinn, K., Yuce, B., Wicaksono, H., Howell, S., Rezgui, Y.: Usability evaluation of a web-based tool for supporting holistic building energy management. Autom. Constr. **84**, 154–165 (2017)
5. Hendro, W., Preslava, D., Polina, H., Sven, R.: Methodology to develop ontological building information model for energy management system in building operational phase. Knowl. Disc. Knowl. Eng. Knowl. Manage. **454**, 168–181 (2015)
6. Reinisch, C., Granzer, W., Praus, F., Kastner, W.: Integration of heterogeneous building automation systems using ontologies. In: Proceedings of 34th Annual Conference of the IEEE Industrial Electronics Society (IECON 2008), pp. 2736–2741 (2008)

7. Guruz, R., Katranuschkov, P., Schrerer, R.J., Kaiser, J., Grunewald, J., Hensel, B., Kabitzsch, K., Liebich, T.: Ontological specification for the model integration in ICT building energy systems, EEBuilding data models—energy efficiency vocabularies and ontologies. In: Proceedings of the European Conference of Product and Process Modelling, Reykjavik, Iceland, pp. 6–29 (2012)
8. buildingSMART.: IFC4 Release Candidate 4. Retrieved from buildingSMART website: http://www.buildingsmart-tech.org/ifc/IFC2x4/rc4/html/index.htm. Accessed on 24 Sept. 2015 (2013)
9. Tom, H., Christian, B.: Linked data: evolving the web into a global data space, Synthesis Lectures on the Semantic Web: Theory and Technology, Morgan & Claypool, pp. 1–136 (2011)
10. W3C.: SQARQL query language for RDF specification. http://www.w3.org/TR/rdf-sparql-query/. Accessed on 15 Jan. 2013 (2011)
11. Hans, S., Robin, D.: Converting the industry foundation classes to the web ontology language. In; Proceedings of the First International Conference on Semantics, Knowledge and Grid, IEEE Computer Society, Washington, D.C., pp. 556–560 (2005)
12. Carlos, A., Moisés. D., Ricardo. J.G., Parisa. G. and Adolfo. S.G.: EXPRESS to OWL morphism: making possible to enrich ISO10303 Modules. In: Complex Systems Concurrent Engineering, pp. 391–402 (2007)
13. Raphael, B., Sylvere, K., Sudarsan, R., Anantha, N., Xenia, F., Sebti, F., Ram, D.S.: OntoSTEP: enriching product model data using ontologies. Comput. Aided Des. **44**(6), 575–590 (2012)
14. Pieter, P., Walter, T.: EXPRESS to OWL for construction industry: towards a recommendable and usable ifcOWL ontology. Autom. Constr. **63**, 100–133 (2016)
15. Pieter, P., Zhang, S.J., Lee, Y.C.: Semantic web technologies in AEC industry: a literature overview. Autom. Constr. **73**(1), 145–165 (2017)
16. Thomas, W., Yuvraj, A.: From buildings to smart buildings–sensing and actuation to improve energy efficiency. IEEE Des. Test Comput. **29**(4), 36–44 (2012)
17. Timilehin, L., Zeiler, W., Boxem, G., Yang, Z.: Occupancy measurement in commercial office buildings for demand–driven control applications: a survey and detection system evaluation. Energy Build. **93**(4), 303–314 (2015)
18. Hu, Z.Z., Zhang, J.P., Yu, F.Q.: Construction and facility management of large MEP projects using a multi-Scale building information model. Adv. Eng. Softw. **100**(11), 215–230 (2016)
19. Yuvraj, A., Bharathan, B., Rajesh, G., Jacob, L., Wei, M., Weng, T.: Occupancy–driven energy management for smart building automation, Proceedings of Acm Workshop on Embedded Sensing Systems for Energy-efficiency in Building. Zurich, pp. 1–6 (2010)

29 Visualisation of Risk Information in BIM to Support Risk Mitigation and Communication: Case Studies

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Abstract

In recent years, Building Information Modelling (BIM) has been attracting increasing research interest for construction project risk management. However, very few studies exist that explore how to manage and visualise risk information within BIM environment. To overcome this gap, this paper introduces a method that establishes an active link between risk data and BIM, and illustrates and tests the proposed linkage approach by using two case studies to gain a practical understanding on the existing technical limitations and future research opportunities. The first case describes the presentation of risk information as visual objects in a 3D BIM of a highway project in Finland. The second case discusses potential of integrating and visualising risk information into 4D BIM of a footbridge in the UK. Results show the proposed linkage approach could facilitate better communication of risks within multi-disciplinary team; understanding of exact locations of risks, and transparency of risk communication and information management.

Keywords

Building information modelling (BIM) • Risk management • Construction engineering and management

29.1 Introduction

Construction projects are exposed to various risks (e.g. financial, health and safety, cost, environmental related risks) during their project lifecycle and the importance of risk management for any projects has been recognised worldwide. To identify and mitigate any risks successfully, it is important to establish a common understanding and communicate the project and risk information throughout the multi-disciplinary project team before any adverse consequences of the risks come up [1]. However, in current practice risk information has not been communicated, used and recorded effectively. For example, 2D drawings only contain limited information but are often used as design and construction solutions by engineers for risk identification and communication [2]. In addition, risk register as a master document containing information about identified risks and corresponding mitigation solutions is created at an early stage of a project but often has no linkage to the design and construction solution [3, 4].

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Building Information Modelling (BIM) is a new technology in the construction industry that refers to the process of generation and management of digital representations of physical and functional characteristics of a building, and in recent years it has been attracting increasing research interest for project risk management [2–4]. The main advantage of integrating BIM with risk management are twofold. Firstly, the visualisation features of BIM enable the project team to identify foreseeable risks and discuss possible solutions based on a better understanding of the project details, construction activities and sequences [5]. Visualising risks in 3D/4D BIM will help distribute knowledge of risks as widely as possible. Secondly, BIM is a shared data platform and repository serving the lifecycle of a project, and can be extended for risk information analysis and management [6]. However, very few studies [4, 7, 8] exist that can explain how to manage and visualise risk information within BIM environment and what benefits can be achieved.

To overcome this gap, this paper presents a method that stores risk information in a separated database and establishes an active link between risk data and 3D/4D BIM. The method is examined in two case studies—a highway project in Finland and a bridge project in UK—to gain a qualitative understanding on the existing technical limitations. Based on the proposed method and case studies, the paper also discovers a number of new research topics and opportunities.

29.2 Literature Review

29.2.1 BIM-Based Risk Management Research

Risk is an event that has either positive or negative impacts on the set goals [9]. In recent years, risks in construction projects have gradually increased due to the complexity of the structures and the size of the project, as well as the introduction of new and difficult building methods. There is a wide scale of project risks such as structural, construction, health and safety, financial and environmental risks. As a result, all project participants need to improve their ability, knowledge and experience to manage the risks throughout the project lifecycle to ensure a safe, successful and sustainable project [10]. Risk management is critical to the success of any construction projects and current risk management methods are highly dependent on multidisciplinary knowledge and experience [8]. In recent years, the use of information modelling has grown rapidly. It provides potential for cooperation and communication, improving productivity and quality, reducing project cost and implementation time [11]. A data-based collaboration and communication environment could facilitate early identification and reduction of risks [12, 13].

Several studies [5, 14–16] have shown challenges in current risk management methods that are largely dependent on experience and multidisciplinary knowledge. BIM has become a systematic method and process that changes the presentation of the project [17], design [18], and communication [19]. Many publications utilize BIM as a tool for managing project risks, related to design errors, occupational safety, quality and budget, but they often do not refer directly to the concept of risk management. Risk management will play a more valuable role when project participants start using these latest technologies as part of their daily work. Most current BIM-based risk management efforts are technology-driven. Only a few studies (e.g. [10, 14]) show how new technologies, traditional risk management methods and processes can be integrated systematically and efficiently into information-based risk management.

29.2.2 Highlighting Risks in 3D BIM

Research about the presentation of risks or hazards in BIM is often focused on occupational safety. Virtual reality (VR), 4D CAD, BIM, sensitivity/warning technologies or their combinations are often used to manage hazards and prevent accidents [14, 20]. According to a study by Enshassi et al. [21], BIM is currently one of the best available application tools to improve workers safety in the building industry. Fall hazards can be checked against computer readable algorithms and visualized objects of risk can be automatically generated in BIM [22]. The benefits of BIM on site safety were already reported in 2009, including safety planning, identification of hazards and risk assessment, work guidance and information on topical work, dangers and security arrangements [23]. Visualisation of safety risks enables designers and engineers to better understand the importance of ‘Design for Safety’ (or ‘Safety in Design’ and ‘Prevention through Design’).

The most recent observation is the Publically Available Specification (PAS) 1192-6 standard issued by the British Standards Institute in February 2018 [24]. The PAS defines the requirements for sharing work safety information throughout the project lifecycle. Its appendix “Representation of risk information” contains examples of how to store the risk information in the element attribute and visualize hazards using the objects in the BIM. According to this PAS, visualisations should be used to emphasize the elevated risks.

29.2.3 Promoting Risk Visualisation in 4D BIM

Four-dimensional (4D) model is an important concept of BIM, where the fourth dimension refers to the time- and schedule-related information [25]. Risks in construction are highly relevant to particular tasks or activities, and visualising risk information in 4D BIM throughout the construction process could effectively facilitate the understanding and communication of what and when any risks may come to place. It is also an effective way to help recall previous knowledge and experience for identifying and mitigating potential risks [4, 26, 27]. For example, Sacks et al. [28] proposed a model that informs risk levels of each floor of a building in a 4D animation using different colours to help plan and filter tasks for safety risks. In order to facilitate the risk identification and communication process in 3D/4D BIM, Zou et al. [4, 8] developed a framework that integrates a project's Risk Breakdown Structure and Work Breakdown Structure into BIM environment. In addition, Ding et al. [7] successfully implemented linking risk knowledge and information to BIM objects in 4D in a tunnel project to support its risk mitigation and communication.

29.3 Method and Case Studies

29.3.1 The Proposed Linkage Approach

To enable the visualisation and management of risk information in BIM, this paper proposes a method that stores risk information in an external database and establishes an active link between the risk data and BIM. Specifically, 3D/4D BIM can provide a visual information-rich environment for the multi-disciplinary team to understand and communicate the project goals, construction logics, and potential risks, etc. A user interface within 3D BIM environment can be established to help end users to input and manipulate risk data. The risk data is then stored in an external database, which, at the same time linked to BIM objects and construction schedule. Integrating the risk information needed into 3D BIM will help the project team to extract their best knowledge and experience to communicate the potential risks in a visualised 3D environment. Risk data can be then further visualised and highlighted in 4D BIM. The following two sections will present two case studies of implementing this method, and the next chapter will connect recent literature and technologies to discuss benefits and technical obstacles summarised from the two case studies, and a number of promising research directions in this area.

29.3.2 Case Study 1: Managing Risks in 3D Highway BIM

A highway project in Finland, called E18 Kausela-Kirismäki was selected as the first case study. The use of BIM in risk management was based on experiences from the Finnish Transport Agency in two railway projects in 2016. The experiences were positive, and all project partners realized that BIM improved the risk management. In those two railway projects, however, there was no link between the risk database and the BIM models. Instead, data were manually transferred to the BIM as objects. As a result, the workload was big and the implementation was time-consuming. In this case study, a link was created between the risk information and the BIM and hence the previous workload issues were largely resolved. The main purpose was to explore the benefits of presenting risk information as visual objects in a BIM model and identify the practical challenges related to implementation.

The project is located a one and half hour drive away from Helsinki to the west. The state-owned road section called E18 Kausela-Kirismäki is 9 km long and improvement work will be carried out during years 2018-2021. The road section is part of the international TEN-T Scandinavian-Mediterranean core corridor. The project involves a four-lane TEN-T road. Construction costs are estimated at about EUR 65 million.

Implementing risk assessment and modelling was done by Finnmap Infra Company. The company developed a plugin for Bentley PowerCivil software that transfers information between the modelling software and the risk database which is described in Fig. 29.1. A total number of 41 project risks were identified and added to the risk database, and 20 of these risks could be located and identified with a visual object in the BIM. The plugin retrieves the risk information from the database based on the risk number on the user's screen so that the user can also update the information via the plugin.

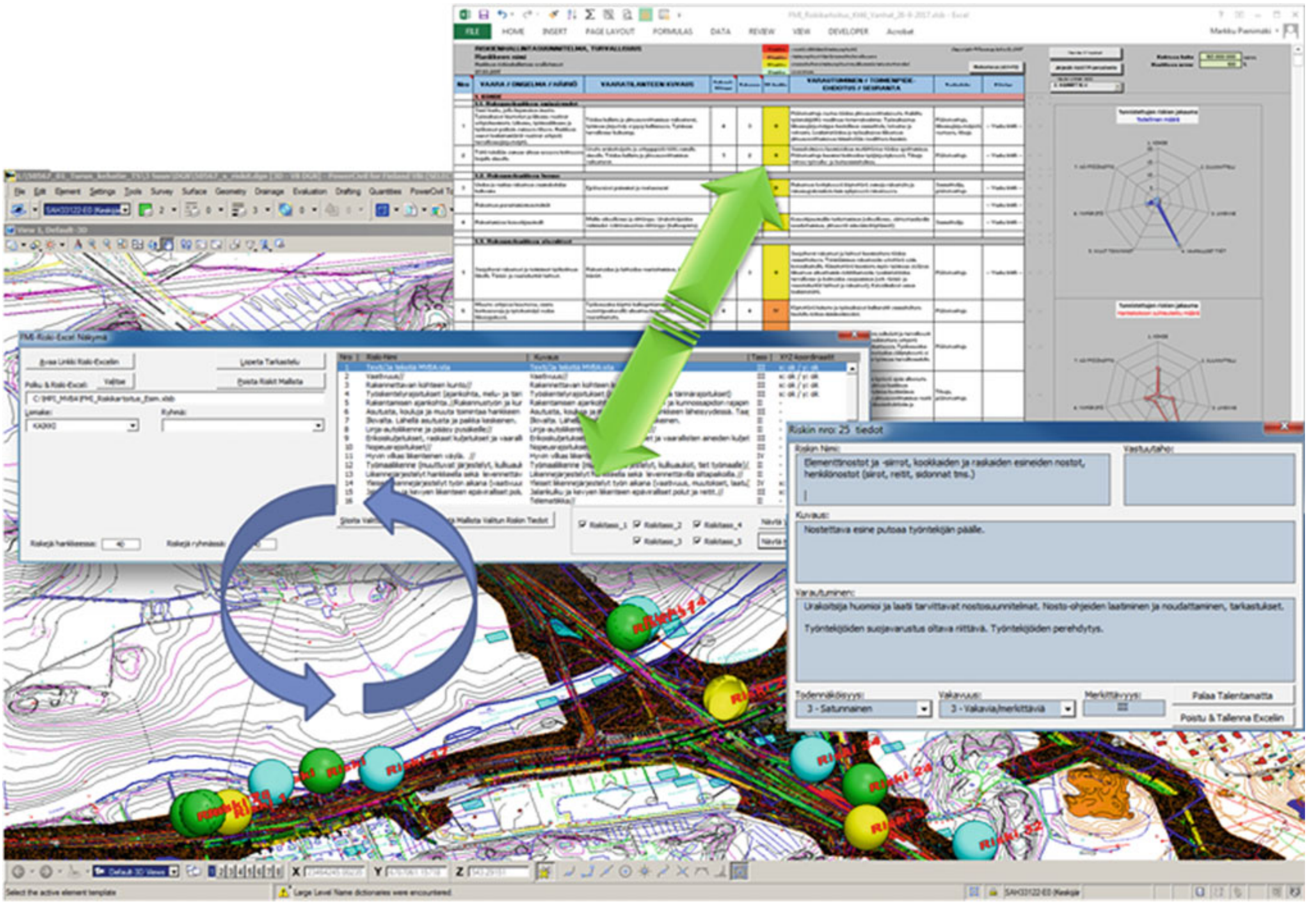

Fig. 29.1 Plugin communicates between the design software and the risk database

The targeted risks were described in the BIM with a vector-type ball object. The shape of the balls was designed based on a simple rule to assist easy risk visualisation and model producing. The colour of the ball was determined by the classification of each risk. The classification and colour scheme are based on guidelines issued by the national Finnish Transport Agency. Additionally, the plugin adds a text object to the ball object, where the number of the targeted risk is described. This way, the information model can be used to read the risk locations and risk number information on other design platforms as well without plugins (Fig. 29.2).

Most of the project risks were distributed over the whole project. However, in some cases, the locations of the risks were very close together. Closed ball objects almost overlap if two or more risks are closely related to each other. This may cause challenges for users to read. The factors affecting this are the size and shape of the object. With a smaller object, the information is more readable, but it is more difficult to notice when viewed from a large perspective. If the three-dimensional object consists only planar surfaces, then the locally accumulating information can be more readable.

It was observed from this study visualising risks in 3D BIM can facilitate the risk identification process. Previously, the risk location was not accurately defined and a risk management expert needed to analyse all risks in order to locate it in a specific location of the BIM. Around half of the location-based risks had more than one location associated with them. The most frequently repeated risk occurred in ten different locations in BIM. But this case study did not investigate how risks that are non-location-based in nature can be taken into account in the project. In the next project phase, BIM will provide a visual overview of the risks of the project to the new project team. The risks information can be easily transferred from one phase and team to another.

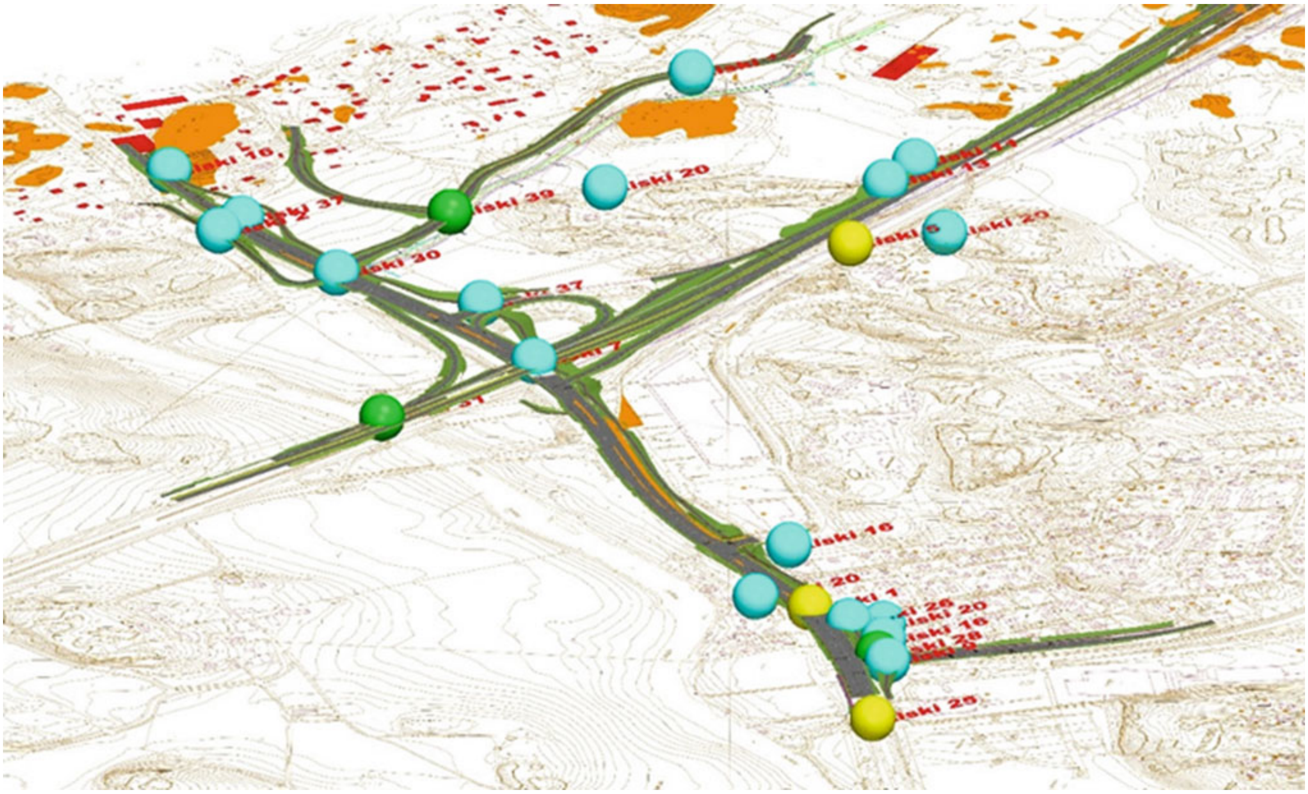

Fig. 29.2 Visualised risks of the E 18 Kausela-Kirismäki project

29.3.3 Case Study 2: Visualising Risks in 4D Steel Bridge BIM

A footbridge named Dunmow Footbridge was selected as the second case. This bridge has a span of 56 m and is a steel tied-arch bridge spanning over the M60 motorway in the UK. The bridge has been completed in 2004 as part of a large motorway widening project and there is no existing 3D graphical model available.

The purpose of this case is to examine the feasibility, benefits and technical obstacles of integrating and visualising risk data into 4D BIM. Autodesk Navisworks 2017 was selected as the main BIM platform for implementation, and a plugin was developed within Navisworks environment to help users to input and manipulate risk data and link risk data to BIM objects and construction activities, where risk data is stored in Microsoft SQL Server database.

In the initial stage, a set of construction drawings were obtained and a 3D BIM was created manually by using Autodesk Revit 2016. The Revit model was then exported to Navisworks as a 3D BIM and the construction schedule information of the bridge was brought into Navisworks to develop the 4D model. The construction of this bridge consists of three main processes: (1) on-site fabrication of the arch and deck, (2) construction of the bridge abutments, and (3) move and installation of the bridge structure.

With the 3D/4D BIM, several industry experts were invited to review the project, its surroundings, and construction schedule in the computer-based virtual environment, and a number of risks were identified associated with their affected construction activities. Risk information was manually input into 3D/4D BIM through using the proposed plugin tool. In this process, each risk's information was stored in the database and a link was established between the risk data and BIM. By taking the on-site fabrication of the arch and deck as an example, three risks relating to time, personnel safety and the structure respectively were identified according to the authors' and invited experts' experience. As the risks had been linked to their affected construction phases in the data input stage, they were then visualised in 4D scheduling (see Fig. 29.3). Specifically, risk information were linked to existing objects or new risk objects. For those risks (e.g. time-related) that are not easily linked to any objects, they were summarised in a popped up tabular form.

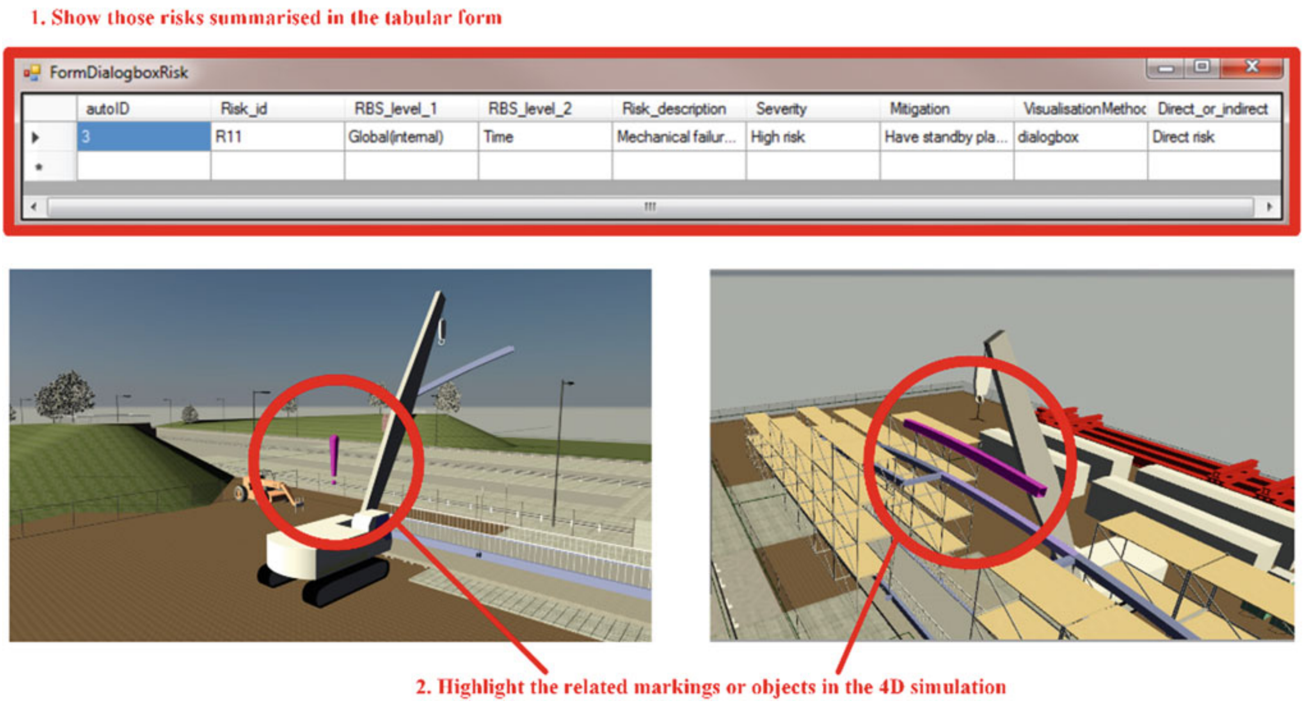

Fig. 29.3 Examples of visualising different types of risk in 4D BIM

29.4 Discussion and Conclusion

This paper presents a method for risk information management in BIM that a linkage can be established between risk data and 3D/4D BIM. It further illustrated and tested the proposed approach through using two case studies. To better understand the benefits and challenges of the proposed approach, this paper conducted a SWOT (Strengths, Weaknesses Opportunities, Threats) analysis on the case studies and its results are presented in Fig. 29.4. Specifically, main strengths of the linkage approach include, for example: (1) risk information can be visualised and highlighted in 3D BIM environment and 4D animation for better communication of risks within multi-disciplinary team; (2) visualising risks in BIM could facilitate the understanding of exact locations of risks, (3) it facilitates the concept of identifying risks at an early stage and improves the transparency of risk communication and information management. The main weakness observed from the two case studies is the lack of a well-accepted method for visualising different types of risk in BIM. For example, some structural risks can be linked to structural elements directly; however, some other types of risks such as potential coordination risks between different design teams are not object-dependent and therefore difficult to be linked to any BIM objects. To overcome this weakness, the next step of this research will investigate the use of applied semiotic to develop a general method or framework for risk signs in BIM [29]. Future opportunities of the proposed method include: (1) the quality of risk management will be improved, (2) risk documentation can be enhanced, and (3) risk management can be facilitated to support the development process of a project. The main threat behind the proposed method is currently there is a lack of method that can update linkage when BIM models are progressing. For example, when a BIM is transferred from one platform to another platform, the established linkages are not transferred.

Acknowledgements The highway project BIM in Finland used in first case study was provided by Finnmap Infra Oy. The bridge BIM used in second case study was produced by James Walsh as an output of his final-year undergraduate project at the University of Liverpool.

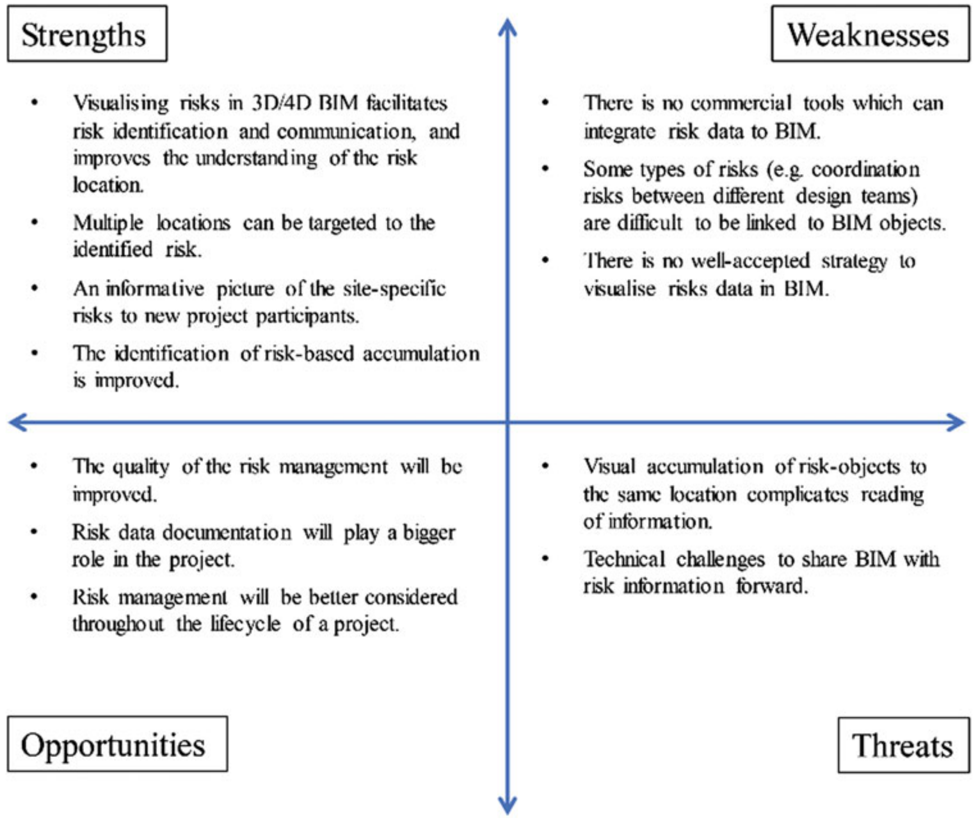

Fig. 29.4 SWOT analysis results

References

1. International Organization for Standardization (ISO): IEC 31010:2009 Risk Management—Risk Assessment Techniques. Geneva, Switzerland (2009)
2. Ding, L.Y., Yu, H.L., Li, H., Zhou, C., Wu, X.G., Yu, M.H.: Safety risk identification system for metro construction on the basis of construction drawings. Autom. Constr. **27**, 120–137 (2012)
3. Patterson, F.D., Neailey, K.: A risk register database system to aid the management of project risk. Int. J. Project Manage. **20**(5), 365–374 (2002)
4. Zou, Y., Kiviniemi, A., Jones, S.W.: Developing a tailored RBS linking to BIM for risk management of bridge projects. Eng. Constr. Archit. Manage. **23**(6), 727–750 (2016)
5. Hartmann, T., Van Meerveld, H., Vossebeld, N., Adriaanse, A.: Aligning building information model tools and construction management methods. Autom. Constr. **22**, 605–613 (2012)
6. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Wiley, Hoboken, New Jersey (2011)
7. Ding, L.Y., Zhong, B.T., Wu, S., Luo, H.B.: Construction risk knowledge management in BIM using ontology and semantic web technology. Saf. Sci. **87**, 202–213 (2016)
8. Zou, Y., Jones, S.W., Kiviniemi, A.: BIM and knowledge based risk management system: A conceptual model. In: Hore, A., McAuley, B., West, R. (eds.) CITA BIM Gathering 2015, pp. 63–68. The Construction IT Alliance, Hoboken, New Jersey (2015)
9. PMI: A guide to the project management body of knowledge (PMBOK Guide). Project Management Institute (PMI), Newtown, Pennsylvania (2004)
10. Zou, Y., Kiviniemi, A., Jones, S.W.: BIM-based risk management: challenges and opportunities. In: J. Beetz, L.v. Berlo, T. Hartmann, R. Amor (eds.) 32nd CIB W78 International Conference 2015, pp. 847–855. Eindhoven (2015)
11. Azhar, S.: Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. Leadersh. Manage. Eng. **11**(3), 241–252 (2011)
12. Dossick, C.S., Neff, G.: Messy talk and clean technology: communication, problem-solving and collaboration using building information modelling. Eng. Proj. Organ. J. **1**(2), 83–93 (2011)
13. Grilo, A., Jardim-Goncalves, R.: Value proposition on interoperability of BIM and collaborative working environments. Autom. Constr. **19** (5), 522–530 (2010)
14. Zou, Y., Kiviniemi, A., Jones, S.W.: A review of risk management through BIM and BIM-related technologies. Saf. Sci. **97**, 88–98 (2017)

15. Shim, C.-S., Lee, K.-M., Kang, L.S., Hwang, J., Kim, Y.: Three-dimensional information model-based bridge engineering in Korea. Struct. Eng. Int. **22**(1), 8–13 (2012)
16. Zhang, L., Wu, X., Skibniewski, M.J., Zhong, J., Lu, Y.: Bayesian-network-based safety risk analysis in construction projects. Reliab. Eng. Syst. Saf. **131**, 29–39 (2014)
17. Porwal, A., Hewage, K.N.: Building information modeling (BIM) partnering framework for public construction projects. Autom. Constr. **31**, 204–214 (2013)
18. Liu, W.P., Guo, H.L., Li, H., Li, Y.: Using BIM to improve the design and construction of bridge projects: A case study of a long-span steel-box arch bridge project. Int. J. Adv. Rob. Syst. **11**, 125 (2014)
19. Hardin, B.: BIM and construction management: proven tools, methods, and workflows. Wiley, Indianapolis, Indiana (2011)
20. Zhou, W., Whyte, J., Sacks, R.: Construction safety and digital design: a review. Autom. Constr. **22**, 102–111 (2012)
21. Enshassi, A., Ayyash, A., Choudhry, R.M.: BIM for construction safety improvement in Gaza strip: awareness, applications and barriers. Int. J. Constr. Manage. **16**(3), 249–265 (2016)
22. Zhang, S.J., Teizer, J., Lee, J.K., Eastman, C.M., Venugopal, M.: Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules. Autom. Constr. **29**, 183–195 (2013)
23. Kiviniemi, M., Sulankivi, K., Kähkönen, K., Mäkelä, T., Merivirta, M.-L.: BIM-based safety management and communication for building construction. VTT, Finland (2011)
24. BSI: PAS 1192–6:2018 Specification for Collaborative Sharing and Use of Structured Health and Safety Information using BIM. The British Standards Institution (BSI), London (2018)
25. Hartmann, T., Gao, J., Fischer, M.: Areas of application for 3D and 4D models on construction projects. J. Constr. Eng. Manage. **134**(10), 776–785 (2008)
26. Goh, Y.M., Chua, D.: Case-based reasoning for construction hazard identification: case representation and retrieval. J. Constr. Eng. Manage. **135**(11), 1181–1189 (2009)
27. Goh, Y.M., Guo, B.H.: FPSWizard: A web-based CBR-RBR system for supporting the design of active fall protection systems. Autom. Constr. **85**, 40–50 (2018)
28. Sacks, R., Rozenfeld, O., Rosenfeld, Y.: Spatial and temporal exposure to safety hazards in construction. J. Constr. Eng. Manage. **135**(8), 726–736 (2009)
29. Hartmann, T., Vossebeld, N.: A semiotic framework to understand how signs in construction process simulations convey information. Adv. Eng. Inform. **27**(3), 378–385 (2013)

Team Interactions in Digitally-Mediated Design Meetings

30

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Abstract
The complexity of multi-disciplinary design increasingly relies on the use of digital media to support design team interactions to communicate and understand the design. Digital media are often employed in design process to facilitate team interactions by allowing the team members to visualize and virtually walk through digital information. Hence, it is assumed that these spaces facilitate activities such as authoring, visualizing and sharing design information, as well as establishing mutual understanding of design content among team members. However, detailed understanding of how the design team interact to communicate and understand design information and how specific features of the digital media support activities and actions of the team during architectural design meetings within the context of practice appear to be limited. This study seeks to understand how the design team interact in digitally mediated spaces to communicate and understand design information and how salient features of the digital space mediate activities that emerge during collaborative design task. This paper describes initial analysis of design team activities in digitally mediated design meetings in an architectural design office in UK. The main empirical video recording of de-sign team meetings is ongoing. Initial results reveal that members in design teams accomplish task through sharing of information, description and explanation of design details, evaluation and prediction of alternative solutions, decision making, as well authoring, visualisation and navigation of design data. The paper concludes that design teams interact differently across varying digital media and associated data set and that task performance appears to be higher in digital spaces with varying features and rich data set.

Keywords
Team interaction • Digital media • Media use

30.1 Introduction

The increasing demand for effective collaboration among team members in the design process has made the team interaction critical in multidisciplinary collaborative design discourse. Team interaction is fundamental to accomplishing design goals as contributions of team members are harnessed in the creation of sound design solutions [1, 2]. Achieving effective team interaction in the design development process emphasizes the need to communicate and understand design content among multi-disciplinary team members [3]. The inherent complexity of multi-disciplinary design coupled with the challenge of their management has resulted in an increasing reliance on use of digitally supported collaborative media to mediate interactions of design team members [8].

Digitally-enabled collaborative media are means through which people generate, share and use information [4]. These spaces have emerged as powerful platforms, often employed in the design process to mediate team interactions by allowing the team members to visualise, virtually walk through and modify digital information to inform de-sign decisions [5–8].

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Hence, it is assumed that these media facilitate activities such as authoring, visualizing and sharing design information, as well as establishing mutual understanding of design content among team members. Consequently, growing efforts are being intensified to promote their integration into current collaborative design practices. Prior studies on mediated team interactions and role of digital media in collaborative design practice established that digital media support communication of design information to multi-disciplinary team members, and that teams better work together using variety of media, hence teams that often mediate their activities and actions with the use of media attain greater synergy in team work [6, 7, 9]. Others have observed that use of media in team interaction is underpinned by the complexity in work context [6, 8].

However, there is limited discussion on how the specific features of the media such as visualisation, interactivity and navigation functionalities and the associated data or information are used to facilitate activities of design teams during collaborative task performance within the context of architectural design practice. Digital media employed to facilitate collaborative team activities encompass both the medium of representation and the information or data communicated. Hence, features of the media become critical to understanding possible set of activities and actions enabled by the media and its consequence use in team interaction. Knowledge on what are the salient features of the media and the role of dataset to supporting activities of design teams within the context of practice are thus imperative to promote collaborative design task accomplishment. The goal of this study is to understand how the design team interact in digitally mediated spaces, and how use of salient features of the media and the dataset conveyed may shape emergence of the activities during collaborative accomplishment of tasks in architectural design meetings. Specifically seeking to explore the patterns of interactions among design team members across different mediated spaces, as well as interactions with media use and design data set.

30.2 Background

30.2.1 Team Interaction

Team interaction is considered as a prerequisite in design collaboration, since through it individual team members integrate their expertise to create a design solution [1]. The concept of interaction has been conceptualized in varying dimensions. McGrath [10] argues that team interaction is a continuous process involving communication and task performance among design teams. Through these engagements, members in a project team accomplish the goals of the project. Hence, in realising this, team members communicate and act together through verbal and non-verbal means. However, Liston [8] argues that project teams also interact with the materials and tools within their work environment to accomplish project tasks. Hence conceptualisation of team interaction needs include how technologies are employed to support team actions and activities [8]. The current study aligns with this position on the premise that, interaction in AEC project teams, being it design or construction stretches beyond communication and performance of task to encompass media use. Practitioners, in attempting to communicate and act together rely on the material environment of the task at some point to share and create information, and develop understanding of the design. Hence, this study posits that discussions on team interaction be extended to cover the use and features of the media and the embedded data set to provide a comprehensive understanding of the phenomenon. However, whilst Liston's assertion is deemed appropriate, her conceptualisation of mediated team interaction failed to account for how specific features and de-sign information contribute to use of the media. The premise being that types of actions carried out with the support of technology, coupled with how people use the media is contingent on media features and information. Hence, the current study seeks to extend Liston's proposition by investigating the role of media features and associated dataset in team interaction within the context of practice to reveal in-depth knowledge how people interact in mediated environments.

This study thus positions itself within the larger literature of technology use and social action in organisations. Specifically, the study draws on DeSanctis and Poole [8] Adaptive Structuration Theory (AST) to empirically investigate the interplay between digitally-enabled collaborative media and team interaction. The perspective of AST is that technology possesses structures which stimulate emergence of social actions. Hence, these structural features are key to influencing use of technology.

In communicating to execute project goals, team members interact to exchange in-formation and knowledge about the content of the design as well as construct mutual understanding of the design [11–13]. In the view of Haberman [11], information sharing is key to achieving effective discussions among team members towards realisation of the team task. Several studies investigating group interaction process have considered exchanges among team members in terms of information and knowledge sharing, critical to the execution of the collaborative task [4, 8]. This is due the fact that member's ability to contribute to the interaction process is partly linked to their awareness and understanding of the task content. This assertion about communication in team interaction is considered relevant in developing empirical understanding of design team inter-actions. The premise is that a lot of design activities rely on availability and adequacy of design data, and thus need to be supported for effective interaction. Again, design team members whether within the same discipline or different disciplines are meant to work together to deliver a shared design solution. Hence, individual understanding of the design content need to be realigned to reflect the team's overall view [2, 10–13].

Consequently, developing a common understanding among team members about content of the task and expected solution becomes relevant for effective team interaction and as such key to contributing to the project goals. In addition to building mutual understanding about the details of the design, team members also carry out tasks such as decision making, problem solving and generating alternatives to accomplish project goals. Since teams interact for specific purpose, members' actions towards realisation of the team's goal become essential in the work of the members. These constructs relate specifically to task performance where behaviours and actions of members in the team results in a specific outcome or product. This study adopted the constructs such as decision making, creation/generation, due to their relevance to the discourse of team interaction in design team meetings. This was done on the premise that members in design teams interacting to deliver a collaborative solution, often generate and choose alternatives considered relevant towards delivering the design product [2, 8, 13].

30.2.2 Mediated Team Interactions in AEC

Several studies have been conducted to investigate team interactions in mediated environments. Whilst a lot of studies have sought to investigate role of media features in collaborative activities, variations of the medium and dataset have not been decoupled and interrogated [4, 6, 13]. Although, features of the medium provide useful insight to understanding set of actions promoted, the data set as argued possess varying forms of information relevant to stimulate different engagements with users in the interaction process [6, 8]. Hence, stand to engage differently with different form and state of design data. Whist some studies have considered both the characteristics and use of media, others have aligned mainly to media use [4, 9, 13]. For instance, Liston [11], building on DeSanctis and Pooles' [8] Adaptive Structuration Theory (AST), developed Mediated Interaction Approach (MIA) framework to investigate role of media use in team interactions. MIA considers the role of media in the interaction process. It provides a set of media use concepts such as communicative, information sharing and decision making, as well as purpose of media which are relevant in capturing instances of media use in team meetings. However, MIA does not address key aspects of media such as features and the data set, which are considered key in the AST conceptualization of media use [8]. Hence, this study extends discourse of role of digitally-enabled collaborative media by incorporating features of media, model content and the work context to empirically capture how specific features of the media as well as content of data represented are used to mediate team activities. The current study considers investigation of the medium and design information as relevant for deepening understanding of role of media in team activities.

Despite these variations, studies on use of digital media in team interactions have contributed to the debate on media use in team activities. For instance, in a study con-ducted by Liston [8] on role of media in shaping team meetings, within the environment of multiple media use, it was observed that team interaction changes across different medium. Liu [7] in evaluating effect of virtual reality (VR) on design review for post-occupancy analysis where he compared VR with other media concluded that interactions vary across different range of media. However, issues on how the specific features of the media and associated data set are used to support actions and activities of team members within the context of architectural design practice have not received much discussion in these prior investigations. This development makes discourse on the interplay between team interaction and use of media inclusive. This study seeks to address these limitations by providing a detailed investigation on how design team members interact across different media with varying characteristics and dataset to accomplish collaborative design task.

30.3 Methodology

30.3.1 Research Design

The purpose of this research is to investigate how design teams interact to undertake collaborative task, communicate and understand design information and how specific features of digital media mediate the activities and actions in design team meetings. The research was conducted in a large architectural design firm based in UK with involvement in digital design practices. The study used video and audio recordings of three design meetings involving architects, and structural engineers. The design teams employed different types of digital media including 3D virtual walkthrough model, mo-bile devices and interactive display screens to mediate their activities. Data was collected over a period of three months, spanning between January and March 2018. The sessions produced 6 h of video and audio recordings. Two video cameras fixed on tripods, were positioned to capture activities at the workspace as well as interactions of participants with various digital media. Additional sound recorder was used to record verbal interactions of team members. The sound recorder was placed on top of the desk. Before recording commenced, the purpose of the study was explained, and participants' consents were sought as part of ethics requirements.

The data was segmented and transcribed in line with analytic interest of the study, which seeks to capture instances of verbal and non-verbal actions of design teams as they interact to accomplish collaborative design task. The transcription was done using a qualitative video transcription software called Transana Professional 320. Data was analysed through iterative processes of coding and continuous refinement to achieve inter-coder reliability. Mediated Interaction Analytic coding scheme [9] was adapted and modified to include features of the media and the embedded design dataset (see Table 30.1).

30.3.2 Results

The main empirical video recording of design team meetings in a digitally-mediated space are ongoing. Initial findings of a six-hour transcribed data are presented. The results are presented in line with the key concepts in the analytic coding scheme (see Table 30.1). The analysis seeks to understand how design teams engage with salient features of digitally-enabled collaborative media and design information during task accomplishment.

Features of media: Design teams incorporate varying forms of digital media with unique features in their task performance activities. The findings revealed that design teams significantly employed wide range of digitally-enabled collaborative media, such as multi-display projector screens, wall displays, interactive screens, mobile devices and 3D models to mediate activities. These media had varying features and capabilities, with which the design team relied to support activities during design meetings. The observations showed that capability to support multiple activities, and interactivity of display interface appeared to regulate set of actions enabled by the media (see Fig. 30.1). Remarkably, clear majority of actions engaged by the team seemed to emerge from the multi-display projector mediated design meeting. This suggests that participants had opportunity to leverage on walkthrough, 3D mark-up and annotation functionalities to perform different activities. Whilst these features provided opportunities for different sets of actions and activities to be enacted, the observation revealed that design teams employed other traditional media, such as 2D paper drawings to augment use of digital media during task performance. This development could be attributed to constraints imposed by the media. The indication is that, opportunities in digital interventions introduced to mediate team activities spread across variety of media, each with unique potentials. As asserted by Liston [9] and Fard [4], needs of the team in accomplishing design task vary, and unpredictable, hence should be supported through multiple means.

Interaction with media: Collaborative design teams interact, both with technologies within their work environment, and with each other via features of the media. In ascertaining how participants engaged with media, the analysis revealed that design teams interacted with media mainly in four differently ways. These interactions ranged from viewing/pointing, navigating, annotating, and authoring. From the observations, viewing/pointing activity appeared as dominant whilst authoring occurred occasionally during the meeting process (see Fig. 30.2). However, mode of visualisation seemed to differ

Table 30.1 Analytic coding scheme (Adapted and modified from Liston [9]; Leicht et al. [13]; DeSanctis and Poole [8])

Communicative/task activities	Interactions with media/design information	Media feature/capability	Design information
Exchanging	Viewing/pointing	Media type	Form/nature of design information
Understanding	Navigating	Level of sophistication-complex/simple	Level of detail
Problem solving	Annotating/mark-up	Level of interactivity	Availability/access
Decision making	Authoring content	Data display	
	Purpose of media use		

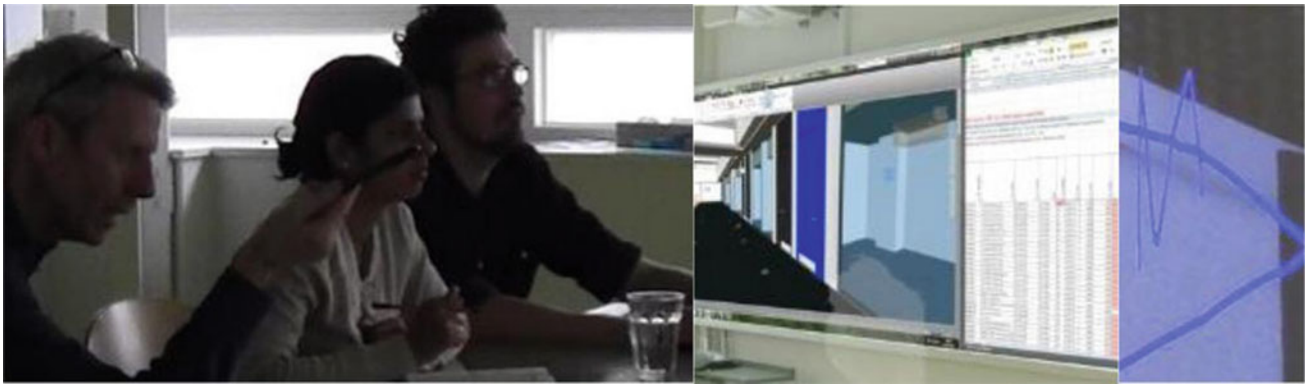

Fig. 30.1 Design team leveraging on multi-display capability of media to visualise multiple set of data simultaneously, and perform 3D mark-up activities

Fig. 30.2 Participants interacting with digital media via viewing, pointing and annotating during design meetings

across different mediated meeting environments. For instance, while the team in digitally-enabled multi-display supported meeting had opportunity to view variety of information simultaneously, the case of the was different. The overemphasis of visualisation activity could be that, participants had a need to thoroughly comprehend the design, and make informed decisions. Visualising design information aids understanding of design information thereby reducing cognitive load of members and improve deliberations in design meetings [7].

Purpose of media use: In terms of purpose, media primarily was used to support undertaking of activities such as visualisation, information seeking, referencing and authoring of design data, as well as managing the transitions in the interaction process. Through visualisation of design information, participants in the collaborative design work obtained better understanding of the content and details of the design data and thus provided contributions to enrich the conversations around the design. These are considered healthy since they enhance the team's understanding of the design, consequently contributing to better informed design decisions [14, 15]. As part of the demands of the task, where the team sought to critically appraise the proposed design solutions, the analytic potential of the media, especially, the 3D virtual walkthrough model, was seen instrumental in addressing project goals. Consequently, design teams are provided with opportunity to scrutinize design options, hence delivering better solutions.

Engagement with design information: How the design team interacts with information remains essential in understanding the interplay between technology and social interaction, since data communicated via a medium possesses unique characteristics sufficient to stimulate emergence of social action [8]. Initial findings in this study revealed that, participants in the design team engaged with different information, varying both in content and level of detail to accomplish a collaborative activity (see Fig. 30.3). However, the observations indicate variations in the way participants engaged with the design information. Interestingly, the team appeared to engage more with the 3D walkthrough virtual model compared to other forms of information. This could be attributed to the fact that walkthrough capability of virtual model afforded the team an

Fig. 30.3 Design team engaged with different forms of design information

opportunity to access various dimensions of information embedded in the model. Be-sides, since 3D virtual walkthrough model possesses large amount of spatial information, participants occasionally had to reference or query content of information as they built understanding and developed the design. Prior studies, for example, Liu [7] in his investigation on post-occupancy VR supported design meetings, observed that participants undertaking team activities engaged with different forms and content of design information to address specific purposes. Hence, use of multiple of set of information become critical to facilitating collaborative activities due to their complementary role in participants' information needs.

Communication activities: This study describe communication activities as exchange and development of understanding toward enhancing design solutions during meetings. The analysis characterised two key types of communicative activities-exchanging, understanding, and which we discuss below.

Information exchanges: In team interactions, how team members exchange information among themselves is considered critical since participants rely on available information to understand and meaningfully contribute to team deliberations. The observations revealed that design teams as part of their activities seek to share information considered relevant in advancing team activities. Interestingly, participants across different mediated meetings observed had to exchange information generated at individual and sub-group levels among the entire team. However, the analysis indicated that participants in most often struggled to make their ideas visible to the team. This means that digital media employed to support team activities probably lacked capability in aiding communication of information from individual and sub-group to the larger team. Fard [4], in similar studies, observed that exchange of information generated by individuals appear to suffer since digital resources provided in mediating interactions lacked that functionality.

Developing understanding: The findings revealed that team members devoted most of their efforts in design meetings developing understanding through description and ex-planation of the design content. However, the observations indicated evidence of variations across different mediated design meetings. From the analysis, descriptive activities appeared to be dominant in design meetings mediated by mobile devices such as tablets, iPad and smart phones, whereas explanation activities featured prominently in BIM and 3D virtual walkthrough model mediated meetings (see Fig. 30.4). In design meetings, participants are often provided with orientations and explanation surrounding the content and rationale of design decisions to enable them familiarise with the task, and make meaningful contributions. This finding appears to be consistent with earlier studies that teams spent most of their activities in design meetings building collective understanding of the design, since the requirement of delivering shared design solutions tied to the overall team performance [4, 7].

Task performance activities: Analysis of the video data indicated that design teams mainly resolve design problems and take informed decisions during the design meeting. In all the cases, design team members resolved problems identified in the design model through extensive discussions and generation of alternatives. Although, decision making and problem-solving activities were witnessed in these meetings, the observations showed variations in their emergence. For instance, in the 3D BIM model mediated design meeting, participants engaged in a wide range of decision making and problem-solving activities compared to the other settings. This could be attributed to the fact that, nature and complexity of the design task

Fig. 30.4 An instance of design team developing mutual understanding of design content and intent through engagement with media and with the members during a design meeting

coupled with content of the design information stimulated the discussions. These observations were anticipated, since prior studies report of existing variations in meeting task performance, which according them emanate from differences in information content, context and task complexities [6, 9]. Hence, the media employed to facilitate accomplishment of collaborative design task needs to be aligned with the task characteristics and the need of the team members.

30.3.3 Conclusion

The findings indicate that design team interaction involves constant exchanges, development of understanding, decision making as well as engagement with multiple digitally enabled collaborative media and design information during design meetings. The design team interactions were accomplished through sharing of information, descriptions and explanations of design details, evaluation and prediction of design options, decision making, authoring, visualisation and navigation. The study reveals differences in team interaction across different media and design information with varying characteristics and level of detail. The study also highlights variations in design team interaction with media and information when communicating and developing understanding of the design. Again, the study shows that level of sophistication and interactivity, coupled with display features of the media, as well as design information contribute to higher task performance. The study seeks to leverage on practical implications of using digital media to support collaborative design tasks, thus contributing to organisation of collaborative work around mediated environments. These findings which are initial result of an ongoing study draws on video and audio data. Supplementing this data with follow up interviews with the team members involved in the interaction process might enhance understanding of phenomenon under investigation.

References

1. Kvan, T.: Collaborative design: what is it? Autom. Constr. **9**(4), 409–415 (2000). https://doi.org/10.1016/S0926-5805(99)00025-4
2. Kalay, E.Y.: The future of CAAD: from computer-aided design to Computer-aided collaboration. In: Augenbroe, G., Eastman, C. (eds.) CAAD 2 Futures' 99 on Conference. Springer, Boston (1999). https://doi.org/10.1007/978-1-4615-5047-1_2
3. Gray, C., Hughes, W.: Building Design Management. Butterworth Heinmann, Oxford (2001)

4. Fard, M.G.: Assessment of Collaborative Decision-Making in Design Development and Coordination Meetings. MAS Thesis, The University of British Columbia, Vancouver, BC, Canada (2006)
5. Whyte, J., Nikolic, D.: Virtual Reality and the Built Environment, 2nd edn. Routledge, London (2018)
6. Moum, A.: Design team stories. Exploring interdisciplinary use of 3D object models in practice. Autom. Constr. **19**(5), 554–565 (2010). https://doi.org/10.1016/j.autcon.2009.11.007
7. Liu, Y.: Evaluating design review meetings and the use of virtual reality for post-occupancy analysis. Pennsylvania State University, College of Engineering, Pennsylvania (2017)
8. DeSanctis, G., Poole, M.: Capturing the complexity in advanced technology use: adaptive structuration theory. Organ. Sci. **5**(2), 121–124 (1994)
9. Liston, K.: A mediated interaction approach to the study of the role of media use in team interaction. Department of Civil and environmental engineering, Stanford University. PhD: 225 (2009)
10. McGrath, J.E.: Groups: Interaction and Performance. Prentice-Hall Inc, New Jersey (1984)
11. Habermas, J.: Reason and the Rationalization of Society, Volume 1 of The Theory of Communicative Action, English translation by Thomas McCarthy. Beacon Press, Boston (originally published in German in 1981) (1984)
12. Valkenburg, R.C.: Shared understanding as a condition for team design. Autom. Constr. **7**, 111–121 (1998)
13. Leicht, R.M., Maldovan, K., Messner, J.: A Framework to Analyse the Effectiveness of Team Interactions in Virtual Environments. University Park, PA, USA (2007)
14. Liston, K.: Assessing and Characterizing the use of Visualization Techniques for AEC Decision Making Tasks. Ph.D. Thesis Proposal, Stanford University (2000)
15. Maftei, L., Harty, C.: Designing in caves: using immersive visualisations in design practice. Int. J. Archit. Res. **9**(3), 53–75 (2015). https://doi.org/10.26687/archnet-ijar.v9i3.693

User Perceptions of and Needs for Smart Home Technology in South Africa

31

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Abstract

Homeowners are often frustrated in trying to understand and control the use of energy within the home especially in tracking monthly usage and the impact of a change in habit on their bills. Recent advances in computing power and sensing technologies required to implement a smart home energy management system mean small, low price and sustainable devices are available for wider adoption. But how ready are homeowners to allow these devices into their homes to collect personal data? This study attempted to understand users' perceptions and requirements of smart home systems in order that these may be more readily integrated into new and existing homes. A quantitative approach using self-administered questionnaires was distributed to a random selection of respondents falling within the sample population of households who have access to the internet at home within the Republic of South Africa. Conclusions are that homeowners need to be aware that if they do not implement smart home technology to improve their home management, they will in all likelihood end up paying more or even facing resource shortages due to the inefficiencies of the current methodologies used for managing their homes.

Keywords

Internet of things • Smart home • Sustainability • Energy management

31.1 Introduction

In the world we live in, we are constantly battling to achieve a manageable work-life balance, find time for social interaction alongside attainment of financial as well as environmental sustainability, requiring us to squeeze evermore into our congested days. Homeowners are often frustrated in tracking monthly usage or in trying to control the use of energy within the home, especially the impact a change in habit is having on their bills. Having to 'manage' energy efficiency in our homes or businesses, using time-consuming manual systems and requiring a facilities management 'degree', has led to much interest and media attention placed on the potential for smart building technologies to play a decisive role in achieving this in a more efficient manner.

The recent introduction of off the shelf solutions into the South African consumer market by major technology companies has provided an opportunity for a range of smart home devices to interact with one another to create a smart home environment. As revealed in a study by the South African Department of Energy [1], South African households spend upward of 14% of their total monthly household income on energy needs. When compared with the international average of

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10%, it means consumers are constantly seeking options to reduce their energy consumption, providing opportunity for technological solutions within an African environment.

According to Madakam et al. [2], smart home technology is the future of home energy management, allowing homeowners the opportunity to be completely in control of their own homes, as smart home devices will possess an Internet of Things (IoT) protocol to communicate their status to the homeowner in a real-time accessible manner, allowing informed management decisions. Taking into considerations some of the additional challenges in the African energy sector including rolling power outages and fluctuations in power, the ability to be able to control in particular the technology reliant on that energy, provides an added incentive to consider the use of these devices.

The aim of the study was to determine homeowners' perceptions of and needs for smart home technology in order to manage and monitor a home more efficiently and sustainably. The objectives were to determine why homeowners struggle to monitor energy/resource consumption; whether homeowners would use smart home technologies to do this; if this would have an impact on the homeowner's awareness of energy consumption, and if there were any potential monetary savings a homeowner may achieve using smart home technology.

31.2 Background

The home is a very personal and vulnerable space and it is therefore imperative that smart home system providers understand users' perceptions towards the technology to ensure greater acceptance and implementation of the technology. That need is very real, in South Africa due to a more than 300% increase in the price of electricity in the past decade [1]. The strategy employed by almost half of South Africans to cope with the rising electricity costs was to reduce the amount of electricity used, which can be further facilitated and expedited through the implementation of smart home technology to assist with the identification and monitoring of energy consumption within the home.

31.2.1 Energy Consumption Monitoring

Using existing metering technology, homeowners are only able to view their monthly consumption rate and kilowatt-hour charges by recording this visually or from their utility bill. Using this method homeowners are unable to gain real-time data of their consumption, individual appliance consumption and 'live' monthly consumption patterns. Froehlich et al. [3] believe that through disaggregated energy consumption data, detailed information of all home appliances in real-time can be provided by a smart home system to homeowners to better monitor their peak energy consumption and consumption patterns. Homeowners with this data clearly accessible will proactively improve their energy efficiency strategies and consumption patterns, ultimately reducing their overall energy consumption [4].

31.2.2 Energy Consumption Awareness

According to Abdelmohsen et al. [5] household electricity meters appear confusing to homeowners as the meter provides a reading of the electrical energy consumption of the home with the use of a moving dial. For a homeowner to determine their daily electrical energy consumption they would have to, without fail, read and record the electricity meter at the same time each day and manually calculate and compare the electrical energy usage [5].

The results of a study conducted by Brounen et al. [6] in the Netherlands indicated that energy awareness among homeowners was low, as just 56% of the respondents were aware of their monthly energy consumption usage and cost. A study conducted by Rihar et al. [7] found evidence that those homeowners who take note of energy efficiency and conservation, realise the opportunity a smart home system presents to achieve additional savings from efficient energy consumption in their homes.

31.2.3 Energy Inefficiencies in Current Homes

Meyers et al. [8] revealed evidence that a substantial amount of energy consumption within a home delivers amenities and comfort to occupants in an inefficient manner. A summary of energy wasted in the five identified categories of inefficient delivery and conversion of amenities is illustrated below in Table 31.1.

Table 31.1 indicates that 39.7% of primary residential energy use in the home is wasted, due to inefficient delivery and conversion of energy. This is because the climate in unoccupied homes or rooms is not controlled, continuing to feed switched-off appliances, and not varying energy supply with the changing needs of occupants over the course of the day [8]. Similarly, Williams et al. [9] observed that an estimated 41% of energy consumption is wasted based on the same factors.

This is in addition to energy loss from the likes of hot water storage devices, influenced by the lack of control of energy use. This is due to no attempt being made to regulate the flow of electric current to the heater, other than by the thermostat, meaning the water contained within the heater remains at or near the "set" temperature 24 hours a day regardless of the use of Zero, Small, or large Volumes of water [10].

Automatically determining when to turn on/off the electric current to such heaters, to reduce the expenditure for electricity without compromising the users requirement for hot water, can produce savings of between 12 and 14% in energy use [11, 12].

31.2.4 Knowledge as a Barrier for Better Home Management Through Technology

According to Scott [13], homeowners were not demanding smart features before 2007, whilst residential property developers had no concern for the sustainable performance of a home once it sold, therefore negatively affecting the possibility of installing energy management smart systems in new homes? In a survey in 2007 among home building contractors observing the potential market for smart homes, the majority of participants felt that smart home technology would remain a niche system focused on upmarket homes [13].

Meyers et al. [8] identified a lack of knowledge about energy management among homeowners in a study conducted in 2010, especially as payback times from energy savings are measured in months or years. This is difficult for homeowners to comprehend and does not always provide a compelling reason to invest a large amount of money initially. Energy conservation for most remained a mental challenge and often thought of as being too expensive for the minimal reduction in energy consumption [8]. They also identified a lack of knowledge among professionals on the associated costs and benefits of different kinds of Home Energy Management Systems (HEMS). In addition, there was a lack of compelling datasets informing professionals as to which system is most effective and sustainable from an energy and cost perspective.

In a South African study conducted by Nel et al. [14] participants encountered difficulty understanding their geyser's energy consumption. Additionally, nearly 30% of participants are unsure of the potential energy and cost savings that can be realised through the switching on and off intermittently of their geyser [14]. Ford et al. [15] suggest that the full potential of smart home technology systems is limited by the conflicting information provided by professionals relating to energy consumption savings and the value proposition aligned to that.

Table 31.1 Energy wasted in inefficient delivery and conversion in homes

Factor	Base case % wasted (%)
Unoccupied homes	4.2
Unoccupied rooms	16
Thermostat oversetting	2.5
Leakage current	3
Appliance choice	14
Total	39.7

Adapted from [8]

31.2.5 Energy Savings from Smart Home Technology

According to Rihar et al. [7], implementing energy conservation specific smart home technology, as part of a HEMS, will enable homeowners to achieve substantial energy savings. Williams and Matthews [9] project, based on their research within the smart home technology field, that energy savings are positively correlated to the degree of connectivity within the smart home technology system. Ford et al. [15] consider that evidence for energy savings associated with the HEMS capabilities of smart home technology systems as ever increasing.

31.2.6 Privacy and Security Concerns Relating to Smart Homes

Horne et al. [16] suggest that if energy usage information and data is analysed to reveal personal details of a homeowner or occupants home life, which can be sold on to third parties, or if energy utility organisations are capable of controlling appliances within the home remotely, anti-smart home technology perceptions and advocacy may increase among the public, negatively impacting the adoption of these smart home technologies within the home.

The perceived difficulty in achieving security within home network environments has been identified by Jacobsson et al. [17] as one of the top barriers in preventing the adoption and implementation of smart home technology systems. This underlines that privacy and security is an important element in the successful adoption of smart home technology by homeowners. Jacobsson et al. [17] suggest the need for the integration of security in the design phase of smart home technology system development processes, using a model for security and privacy in design.

31.3 Methodology

The researchers employed a quantitative research method to gather data from homeowners, using self-administered questionnaires distributed to a random selection of the sample population identified from the 1.6 million (9.5%) households who have access to the internet at home, a subset of the 16.7 million households within the Republic of South Africa [18]. The sample size identified was statistically calculated by establishing a confidence level of 90% and a desired margin of error of six, which resulted in a sample size required of 200 respondents out of the sample population of 1.6 million. A random selection method was employed to ensure each respondent in the population was not chosen in predetermined manner to avoid the skewing of the findings and to eliminative any bias in the choice of respondents for the study.

The research questionnaire was distributed via e-mail to 200 respondents, of which 136 usable responses were received, a response rate of 68%. The questionnaire consisted of eighteen questions, five of which were demographics related; twelve were five-point Likert scale questions, whilst the last question was open-ended, allowing respondents to provide general comments that were not addressed previously.

The analysis of the data consisted of the calculation of descriptive statistics in the form of frequency distributions and a measure of central tendency, based upon the percentage responses to the points on the respective scales. This enabled interpretation of the responses and to rank factors where necessary, in order to calculate mean scores (MSs). For this study, the Likert scale points form a scale that ranges from one to five, 1 being not important to 5 very important, in order to calculate the mean scores.

31.4 Findings

Of the 136 respondents, 83% of respondents have owned or rented a residence for more than 5 years and 69.8% in excess of 10 years, with nearly 90% (89.7%) owning or renting a freestanding house. Respondents were then asked to indicate the extent to which an existing home's appliances have an impact on the use of the home based on a scale of 1 (minor) to 5 (major), with the results tabulated in Table 31.2.

It is notable that 10 out of the 12 questions (83.3%) had mean scores greater than 3.00. Time saving ranked first based on a resultant mean score (MS) of 3.76, with Ease of use (MS3.71) following closely behind. Living environment, Safety and security and Life satisfaction were perceived to have between some extent to a near major extent a positive impact on the use of the home.

Table 31.2 How existing home's appliances impact the use of the home

Factor	U	Response (%)					MS	Rank
		Minor	…			Major		
		1	2	3	4	5		
Time saving	2.2	2.2	8.8	24.3	37.5	25.0	3.76	1
Ease of use	2.2	2.2	3.7	31.6	42.6	17.6	3.71	2
Living environment	4.4	2.9	2.9	33.8	39.0	16.9	3.67	3
Safety and security	2.2	8.8	9.6	21.3	28.7	29.4	3.62	4
Life satisfaction	5.9	5.1	10.3	28.7	33.1	16.9	3.49	5
Happiness	4.4	5.9	14.0	29.4	36.0	10.3	3.32	6
Resource usage	9.6	5.9	11.9	34.1	25.9	12.6	3.30	7
Monetary expenses	2.9	8.1	11.8	33.8	33.1	10.3	3.27	8
Socialisation	3.7	9.6	15.4	26.5	33.8	11.0	3.22	9
Personal health	4.4	13.2	14.0	33.8	25.7	8.8	3.03	10
Emotions	9.6	13.2	16.9	33.8	22.8	3.7	2.85	11
Natural environment	14.0	13.2	19.1	31.6	14.7	7.4	2.81	12

Table 31.3 The extent to which being able to connect with a home's appliances through a connected smart home system will impact on the use of the home

Factor	U	Response (%)					MS	Rank
		Minor	…			Major		
		1	2	3	4	5		
Time saving	8.1	2.2	2.9	14.0	33.8	39.0	4.14	1
Safety and security	7.4	5.9	6.6	17.6	29.4	33.1	3.83	2
Ease of use	10.3	7.4	5.9	18.4	32.4	25.7	3.70	3
Living environment	12.5	6.6	8.1	23.5	33.8	15.4	3.50	4
Resource usage	14.0	7.4	8.8	25.7	27.9	16.2	3.43	5
Life satisfaction	9.6	6.6	11.0	24.3	35.3	13.2	3.41	6
Monetary expenses	14.0	8.8	8.8	22.8	30.1	15.4	3.40	7
Happiness	12.5	9.6	8.8	31.6	26.5	11.0	3.24	8
Socialisation	8.8	14.0	12.5	27.2	25.7	11.8	3.10	9
Emotions	14.0	11.0	9.6	36.8	21.3	7.4	3.05	10
Natural environment	22.8	12.5	11.8	23.5	22.8	6.6	2.99	11
Personal health	15.4	13.2	14.0	26.5	24.3	6.6	2.97	12

Respondents were then required to indicate the extent to which being able to connect with a home's appliance through a smart home system will impact on the use of the home based on a scale of 1 (minor) to 5 (major), with the results tabulated in Table 31.3.

It is notable that a similar ratio of MSs > 3.00 was achieved 10/12 (83.3%) from the respondents and that 'Time saving' is also ranked first, but with a much increased MS of 4.14. This indicates that time saving is perceived to be impacted the most by being able to connect with a home's appliances through a connected smart home system.

In terms of the impact being able to connect with a home's appliances through a smart home system will have on quality of life in general, the resultant MS is lower at 3.57 which is somewhat surprising given the previous upward tick in the MS's when looking at the factors aligned to being able to connect with a home's appliances through a connected smart home system and its impact on the use of the home.

With respect to the importance of having remote access to a home on optimising the operational efficiency of a home, the resultant MS of 3.72 is also within the same range.

Respondents were then asked to 'rate the accessibility of your current method to review consumption values of your home's equipment?', with the results tabulated in Table 31.4.

This was then followed by a question that addressed the impact of being able to better manage the consumption in a home by being able to communicate with one's home's equipment as well as between each piece of equipment through a connected smart home system, with the results tabulated in Table 31.5.

It is notable that 'Electricity' ranked first in both questions which indicates that electricity is perceived, on the ability to better manage the consumption in a home, to be impacted the most as a result of being able to communicate with a home's equipment as well as between each, through a connected smart home system.

Respondents were required to indicate their extent of current understanding of the resource consumption of a home. The resultant MS of 3.22 is in the 2.60 to ≤ 3.40 range, indicating that respondents deemed their current understanding to be between a near minor extent to some extent.

Respondents were required to indicate how frequently they monitor the consumption in their home currently (Table 31.6).

This question was followed with respondents indicating how frequently they would monitor the consumption in their home if it was readily available on a connected smart home system (Table 31.7).

Table 31.4 Accessibility of current methods' to a home's equipment consumption values

Resource	U or N/A	Response (%)					MS	Rank
		Not	…			Very		
		1	2	3	4	5		
Electricity	8.8	5.9	9.6	30.9	27.2	17.6	3.45	1
Water	10.3	10.3	12.5	27.9	19.9	19.1	3.28	2
Gas	30.9	11.0	11.0	24.3	14.0	8.8	2.98	3

Table 31.5 The impact of the ability to communicate with a home's equipment and between devices through a connected smart home system, to better manage the consumption in a home

Resource	U or N/A	Response (%)					MS	Rank
		Minor	…			Major		
		1	2	3	4	5		
Electricity	11.8	8.1	5.9	14.7	34.6	25.0	3.71	1
Water	16.2	12.5	5.1	19.1	27.2	19.9	3.44	2
Gas	33.8	8.1	5.9	21.3	17.6	13.2	3.33	3

Table 31.6 The frequency of monitoring the consumption in a home

Resource	U or N/A	Response (%)					MS	Rank
		Minor	…			Major		
		1	2	3	4	5		
Electricity	2.2	5.1	12.5	14.7	36.8	28.7	3.73	1
Water	4.4	12.5	16.9	20.6	24.3	21.3	3.26	2
Gas	27.9	13.2	14.7	16.9	14.7	12.5	2.98	3

Table 31.7 The frequency of monitoring the consumption in a home if it was readily available on a connected smart home system

Resource	U or N/A	Response (%)					MS	Rank
		Minor	…			Major		
		1	2	3	4	5		
Electricity	1.5	2.2	2.2	10.3	28.7	55.1	4.34	1
Water	2.2	3.7	2.2	9.6	30.9	51.5	4.27	2
Gas	22.8	2.9	4.4	8.8	20.6	40.4	4.18	3

It is notable that all 3 resource consumption monitoring frequencies (100%) had improved mean scores greater than 4.00.

With respect to the extent of improving understanding of resource consumption on the ability to use technology to manage a home through a connected smart home system. The resultant MS of 4.06 is also within the >3.40 to ≤ 4.20 range, which indicates that the respondents perceive it to be between some extent to a near major extent.

Finally, respondents had to indicate to what extent improving on their understanding of a connected smart home system would have on their ability to use technology to manage their home. The resultant MS of 4.07 falls within the same range, that this would between some extent to a near major extent improve on their ability to manage their home.

31.5 Conclusions and Recommendations

31.5.1 Conclusions

The research set out to understand South African users' perceptions and requirements of smart home systems, and the improvement of a homeowner's ability to manage and monitor a home more efficiently and sustainably through smart home technology. The respondent's perceptions are that smart home technology increases a homeowner's awareness of energy consumption and improves access to monitoring that consumption compared to existing methods, although knowledge of smart home technology is currently extremely limited among homeowners. Homeowners are willing to implement smart home technology if the implementation is seamless and not cumbersome for themselves and were willing to learn more about the technology. Where they had better access to resource consumption data it lead to lower consumption usage. Respondents were of the belief that smart home technology leads to an increase in quality of life for homeowners, however, in the South African market it has been concluded that cost and privacy are a barrier to implementing smart home technology in their homes.

There is a perceived negative sentiment among existing homeowners to the use of new technology within the management of a home and, in addition, that the monitoring process using smart home technology may expose too much information, seem complex to the user. However, homeowners need to be aware that if they do not implement smart home technology to improve their home management, they will in all likelihood end up paying for the inefficiencies of the current methodologies used for managing their homes.

31.5.2 Recommendations

Communicating to homeowners the total capital outlay versus monetary savings on energy conservation over lifetime of the system; Addressing privacy concerns and the security of the data captured; Focusing on time saving, life satisfaction, security and improvement in the living environment leading towards a better quality of life; increasing education and training, particularly the lack of energy consumption awareness; whilst addressing the ease of use/complexity of system challenge, are some of the areas that need to be addressed by the industry if they are to see greater uptake of these systems within the South African home building and refurbishment market.

Based upon the findings of the study and the conclusions that have been drawn, the following recommendations are thus proposed: Industry professionals need to educate homeowners on the multiple benefits of smart home technology; They need to investigate the specific needs in relation to cost that property owners are prepared to pay for when it comes to smart technology in the home; Professionals need to educate the wider population to create an awareness of smart home technology and in particular the energy consumption and monitoring type of smart home technology with inter alia safety and lifestyle support. Further education and training on resource consumption through smart home technology should be implemented in conjunction with the installation of smart home technology. Customisable smart home technology systems should be preferred over off the shelf systems to ensure the most sustainable outcome is achieved for the homeowner, with attention paid to a phased approach to installation starting with utility smart meters. This study contributed to the South African body of knowledge by understanding current perceptions within the homeowners' market towards these devices as well as overall knowledge of smart home technology, however, case study is needed to analyse whether users experience of smart home technology aligns with the perceptions of those surveyed towards the use of the technology.

References

1. South Africa. Department of Energy: a survey of energy related behaviour and perceptions in South Africa: the residential sector. Pretoria: Government Printer (2013)
2. Madakam, S., Ramaswamy, R., Tripathi, S.: Internet of things (IoT): a literature review. J. Comput. Commun. **3**(3), 164–173 (2015)
3. Froehlich, J., Larson, E., Gupta, S., Cohn, G., Reynolds, M., Patel, S.: Disaggregated end-use energy sensing for the smart grid. IEEE Pervasive Comput. **10**(1), 28–39 (2011)
4. Iwayemi, A., Wan, W. and Zhou, C.: Energy Management for Intelligent Buildings. Energy Manage. Syst. **274** (2011)
5. Abdelmohsen, S., Do, E.Y.-L.: Energy puppet: an ambient awareness interface for home energy consumption. In: Proceedings of the International Workshop on Social Intelligence Design: Designing Socially Aware Interactions (SID'08), pp. 3–9 (2008)
6. Brounen, D., Kok, N., Quigley, J.M.: Energy literacy, awareness, and conservation behavior of residential households. Energy Econ. **38**, 42–50 (2013)
7. Rihar, M., Hrovatin, N., Zoric, J.: Household valuation of smart-home functionalities in Slovenia. Utilities Policy **33**, 42–53 (2015)
8. Meyers, R.J., Williams, E.D., Matthews, H.S.: Scoping the potential of monitoring and control technologies to reduce energy use in homes. Energy Build. **42**(5), 563–569 (2010)
9. Williams, E.D., Matthews, H.S.: Scoping the potential of monitoring and control technologies to reduce energy use in homes. In: Proceedings of the 2007 IEEE International Symposium on Electronics and the Environment, Orlando, pp. 239–244 (2007)
10. Stettin, D., Sterber, F.: Heater control device and method to save energy. U.S. Patent no. 6,293,471. U.S. Patent and Trademark Office, Washington, D.C. (2001)
11. Boait, P., Rylatt, R.: A method for fully automatic operation of domestic heating. Energy Build. **42**(1), 11–16 (2010)
12. Abrahamse, W., Steg, L., Vlek, C., Rothengatter, T.: A review of intervention studies aimed at household energy consumption. J. Environ. Psychol. **25**, 273–291 (2005)
13. Scott, F.: Teaching homes to be green: smart homes and the environment. Green Alliance, London (2007)
14. Nel, P.J.C., Booysen, M.J., van der Merwe, B.: Energy perceptions in South Africa: An analysis of behaviour and understanding of electric water heaters. Energy. Sustain. Dev. **32**, 62–70 (2016)
15. Ford, R., Pritoni, M., Sanguinetti, A., Karlin, B.: Categories and functionality of smart home technology for energy management. Build. Environ. **123**, 543–554 (2017)
16. Horne, C., Darras, B., Bean, E., Srivastava, A., Frickel, S.: Privacy, technology, and norms: the case of smart meters. Soc. Sci. Res. **51**, 64–76 (2015)
17. Jacobsson, A., Boldt, M., Carlsson, B.: A risk analysis of a smart home automation system. Future Gener. Comput. Syst. **56**, 719–733 (2016)
18. Statistics South Africa, General household survey 2016. Statistical Release No P0318. Statistics South Africa, Pretoria (2017)

Seamless Integration of Multi-touch Table and Immersive VR for Collaborative Design

32

—A Real-World Case of Designing Healthcare Environments

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Abstract

During the design of a new hospital, many different stakeholders are involved. These types of complex projects require more knowledge than any single individual possesses and in this context, it is necessary for all involved stakeholders to understand, participate, communicate, and collaborate with each other to obtain a high-quality outcome. This paper presents a collaborative design system, which support these creative and shared design processes. The presented system, Virtual Collaborative Design Environment (ViCoDE), features a seamless integration of a multi-touch table and several immersive VR-systems that support interactive and collaborative design work. The system has been evaluated during two studies in a real-world context of designing new healthcare environments (e.g. operating theaters). The results show that involved stakeholders better understand, participate, communicate, and collaborate with each other and that the multi-touch table and VR-system complement each other by facilitating different design spaces—both collaborative, as well as individual.

Keywords

Virtual reality • Collaborative design • CSCW

32.1 Introduction

When designing new healthcare environments and hospitals, many different stakeholders and specialists from healthcare and construction are involved with different experiences, knowledge levels and ability to interpret information. The most common information media in these processes are documents, descriptions, 2D-drawings and pictures. However, these media can be difficult to interpret and understand and place high cognitive demands on the viewer's ability to transform the information into a self-made mental image of the project. The self-made mental image could also be misinterpreted and differ depending on the individual's background, education, experience and interest. This means that important feedback from the

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healthcare specialists (e.g. surgeons, nurses) can be lost or disappear during the planning and design process. These malfunctions are detected later when it is too late and the healthcare environment is already built [1, 2].

One potential solution to this problem is to take advantage of immersive Virtual Reality (VR) instead of traditional 2D-drawings and pictures. While the use of this technology has been naturally limited in the past due to lack of available 3D data from the design process. The recent introduction of Building Information Models (BIM) within the AEC field has opened up new possibilities to us and extracted 3D data directly from the architect's own design environment [3, 4]. Because of this, use of real-time visualizations has become more accessible in practice [4, 5]. With the use of a Head-Mounted Display (HMD) the different stakeholders can move around and experience the future planned healthcare environment in scale 1:1 and therefore share a common frame of reference. However, with HMDs being primarily a tool for the individual, it makes it less suitable for active collaborative design work, which also relies much on face-to-face communication and gestures. In this context, it is also important to allow participants to express ideas and thoughts to the other members of the team by performing actual changes to the design.

In order to address the current situation this paper presents a new collaborative design system, which uses a seamlessly connected multi-touch table and several VR-systems for interactive and collaborative design. In addition to give technical details of the system, we present and discuss the results from using the system during two design workshops held as part of an ongoing design of two new hospitals.

32.1.1 Related Work

Computer-Supported Cooperative Work (CSCW) approaches are often based on the assumption that complex problems require more knowledge than any single individual possesses and in this context it is necessary for all involved stakeholders to participate, understand, communicate and collaborate with each other to obtain a higher quality outcome [6]. The resolution of the design problem grows out of the shared understanding that emerges as different stakeholders begin to better understand each other's perspectives [6, 7]. Still, communication breakdowns are often experienced because stakeholders have different interests and agendas and belong to different cultures that use different norms, symbols, and representations. However, by creating a shared understanding through collaborative design, it is possible to provide opportunities and resources for design activities embedded in a social creative design process in which all actors can actively contribute rather than having a passive consumer roles. In this context, interactive multi-touch tables have been shown to aid such a creative collaborative design process [6, 7]. The multi-touch table has the possibility to give the participant the feeling of an active and meaningful role during the meeting. Furthermore, [6] highlighted two different spaces in their collaborative design environment—action space and reflection space. Action space provides a foundation for creative collaboration between the participants and reflection space provides a foundation for the group members to validate and form their own opinions on the design.

However, a common problem with 2D-based design environments is that the information is not presented in such a way that people can understand it. In this context, real-time visualizations and Virtual Reality (VR) have been shown to offer an efficient communication platform [5, 8, 9]. With the ability to navigate freely through 3D scenes from a first-person perspective, it is possible to present and communicate ideas regarding future buildings in a way that facilitates understanding among all involved parties, despite their background or professional expertise. To further enhance user experience, it is commonly advocated to take advantage of immersive display technologies. Furthermore, [5] showed that immersive VR gave another level of understanding and perception of space, and that this is hard to experience in other type of visualizations.

The collaborative design system presented in this paper has been implemented with the intention of creating a system that supports a better creative and shared design processes for the involved stakeholders. To support this process, we have recognized that the system has to support better understanding, participation, communication, and collaboration between the different stakeholders. The hypothesis was that the multi-touch table and VR-system complement each other by facilitating different design spaces—both collaborative (i.e. action space), as well as individual (i.e. reflection space). In comparison to other systems [6, 7, 10, 11], our system supports interactive collaboration in both spaces, e.g. changes done in the multi-touch table or in VR are updated instantly in both spaces, as illustrated in Figs. 32.1 and 32.3.

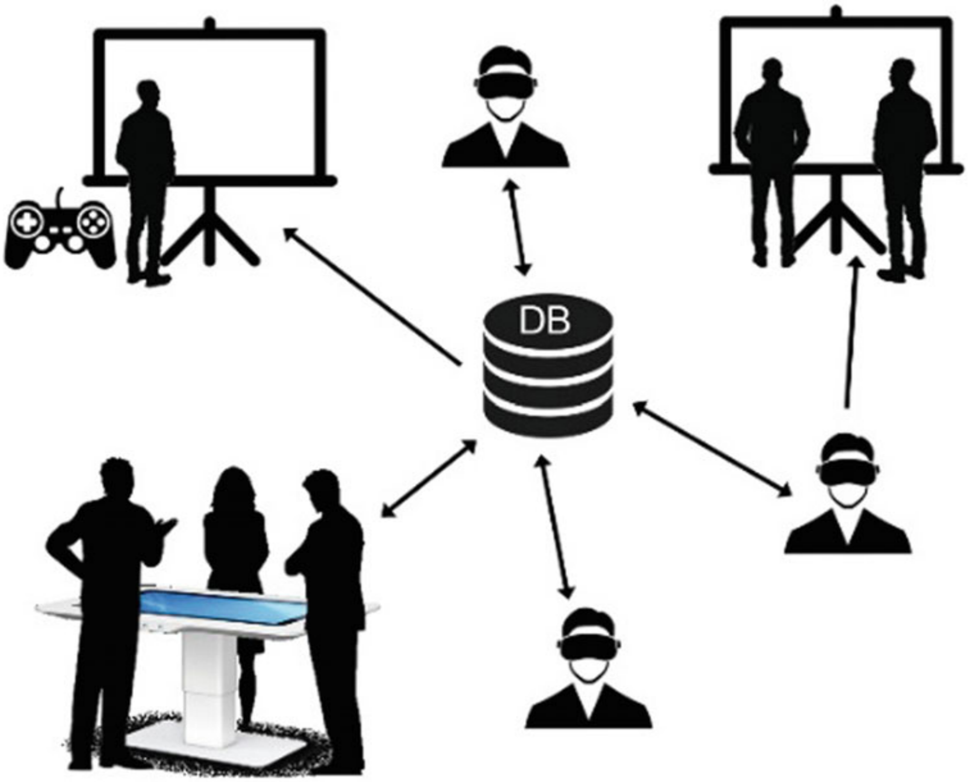

Fig. 32.1 The collaborative design system supports seamless integration of multiple viewer and interaction clients through a database/server

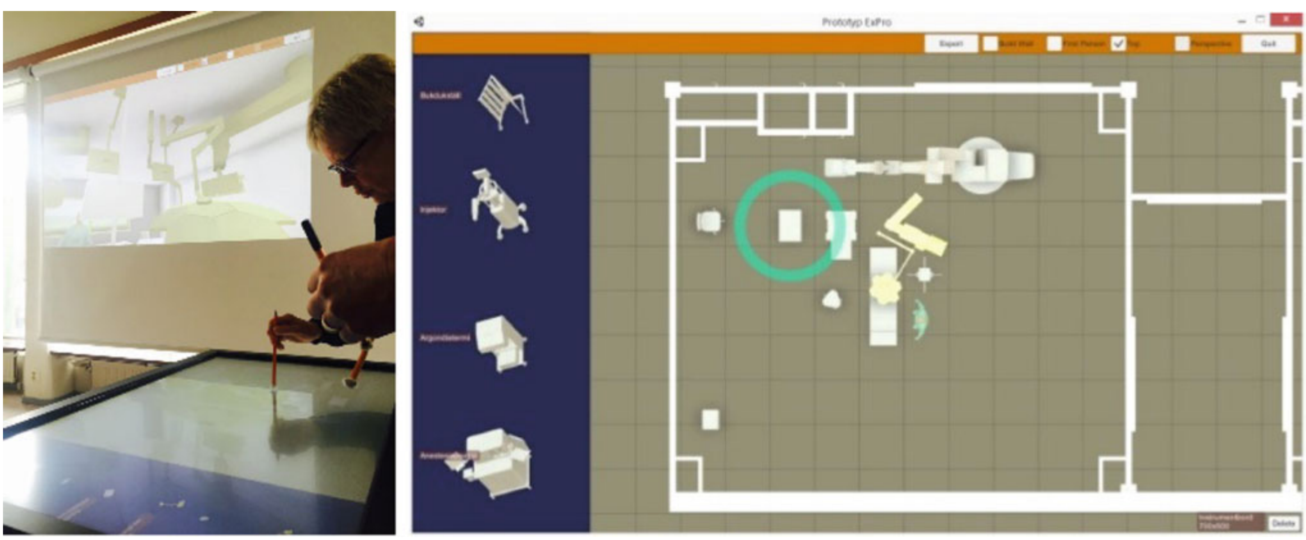

Fig. 32.2 Left: The multi-touch table used together with a non-immersive VR display, controlled by a wireless game controller (Picture from workshop 1). Right: The layout of the multi-touch table screen. Available components are accessible from a scrollable panel on the left side, and are added to the scene using drag-and-drop

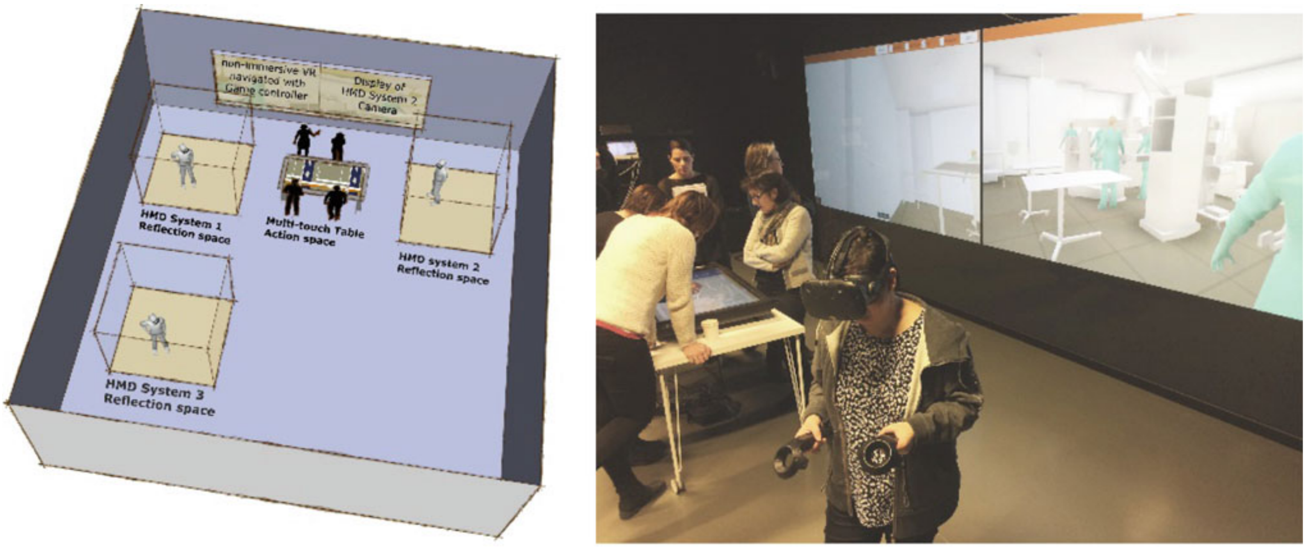

Fig. 32.3 During workshop 2, three HMD-system were seamlessly used together with the multi-touch table and non-immersive VR controlled by a game controller. This system supported both collaborative (e.g. action space), as well as individual (e.g. reflection space). The user of the HMD could interact within the VR environment by picking components and translated and rotated them using the HTC-Vive controllers

32.2 The System

The collaborative design system has been developed in the Unity Game Engine using C#. In essence, it consists of several viewer and interaction clients connected through a database/server, as illustrated in Fig. 32.1. The 3D-components in the database have unique IDs (GUID), which makes it possible to traces changes in the different connected client applications. Changes of a component's position or rotation in one client are uploaded to the server and then propagated to the other clients. However, as described below, not all clients support all degrees of interaction. The initial layout of the proposed design can be imported from the architect's design BIM-software (e.g. Autodesk Revit) and the components in the database are also BIM-objects.

32.2.1 Multi-touch Table and Big Screen Display

The layout of the multi-touch table is shown in Fig. 32.2. It represents the top view of the operating theatre and supports the typical multi-touch pan and zoom features used in most Smart-phones. To better illustrate the scale, a 1 × 1 m grid is applied on the floor as a texture. Furniture, medical equipment, walls and static avatars can be added, deleted, translated and rotated. All available components are accessible from a scrollable pane on the left side, and are added to the scene using drag-and-drop. Pressing and dragging a component will translate it whereas ticking it will show a circle for rotation and deleting. Furthermore, components that are mounted in the ceiling are given a different nuance in order to better emphasize their vertical position, see Fig. 32.2. The interface also supports simulation of how the ceiling pendant systems and its multi-movement arms can be moved around during surgery, making it possible to detect collisions with other equipment.

As seen in Figs. 32.2 and 32.3, the contents of the scene can also be displayed on a big screen from a perspective controlled by a wireless game controller, i.e. non-immersive VR.

32.2.2 VR-System

The HTC-Vive was used as the immersive display system and a teleportation locomotion mode was used for navigation [12]. Within the VR environment, components can be translated and rotated. A component will be highlighted if it intersects with any of the HTC-vive controllers and pressing/releasing the trigger allows a user to pick it up and re-place it within the scene.

To help the user with the positioning, a component is always restored to its up-right position at the correct elevation above the floor upon release (i.e. to avoid tilting). As illustrated in Figs. 32.1, 32.2 and 32.3, it is also possible to display a user´s view from VR on a big screen display.

32.3 The Study

The results in this paper are grounded on two workshops conducted in the spring of 2016 and 2017, respectively. During these workshops the collaborative design system was used in the context of designing operating theatres. The participants were different stakeholders and specialists from healthcare and construction, e.g. theatre nurses, anesthesiologists, architects and project managers, for the intended operating theatres in Skaraborg and Östra Hospital, both located in Västra Götaland, Sweden. All of the participants had previous experience of dialogue-based workshops using traditional information media, such as 2D-drawings and pictures.

The main difference between the two workshops from a technical point of view was that the first one required an export of the scene to another application to be able to view it in HMD. Also, only one HMD was available and it was not possible to move any of the components in the VR environment. The second workshop, however, used the final system as described in the previous section.

The first workshop had 8 participants and lasted for six hours. It consisted of two different design tasks; the first one being to design an operating theatre in a pre-defined space (approx. 8 × 9 meters), and the second one to design an operating theatre without any constraints on room size. The time used for each of the design tasks was equal.

The second workshop had 9 participants and lasted for four hours. It consisted of two different design tasks; the first one being to design an operating theatre in a standard sized room (approx. 8 × 9 meters), and the second one to design an operating theatre in a room of extended size (approx. 10 × 9 meters) followed by a step to shrink the extents of the room (i.e. by moving the walls closer to the equipment). The layout of the proposed operating theatre design came from the architect's BIM from the project. The time used for each of the design tasks was equal. Figure 32.3 shows the room layout and the different collaboration and visualization systems used during the second workshop.

On both occasions, the workshop started with a 10 min introduction of the system in order for the participants to familiarize themselves with the user-interfaces and the overall functionality.

32.3.1 Method

During both workshops, data was extracted by means of documented observations as well as unstructured interviews with the participants about their thoughts and experiences in relation to the collaborative design system. On both occasions three researchers were present. The workshops were facilitated mainly by the architect, with technical support from the researchers. The second workshop was also recorded with two stationary video cameras and the recorded material was transcribed and later compared to the field notes in order to reinforce the observations made. Being that the cameras were placed in elevated positions the recorded material also provided a better overview of the participants´ movement around and between the different stations in the workshop room.

32.4 Result and Discussion

The result from the two workshops showed that the participants found that the three different visualization and interaction techniques complemented each other effectively. The multi-touch table gave support for interactivity and supported creativity and collaboration to solve the task together. The 3D-view from the projector, (i.e. none-immersive VR), gave a better picture and understanding of the operating theaters. The HMD gave a further dimension to better understand the space and the size of the room. By using the HMD the different participants could actually stand at the operating table in the virtual operating theater and make sure everything felt correct.

32.4.1 Support Better Understanding and Communication

The participants at the workshops expressed that this collaborative design system gave them better understanding and communication. The observation and the video analyses from the workshops recognized that the multi-touch table created a shared understanding and that resolution and solution of the design problem emerged as different participants/stakeholders began to understand each other's perspectives. The project manager and architect had the layout and total size of the room (i.e. connected to construction cost) on their agenda, while healthcare staff focused on functionality and task-related aspect of performing surgery.

However, during the workshops it was recognized that the "2D-topview" on the multi-touch table was not enough, as it was difficult to interpret and understand. As the design progressed, the participants started to observe several design errors and clashes between equipment in the 3D-view from the projector. Although the ceiling-mounted equipment had a different nuance to indicate it´s vertical placement, it was still difficult to perceive it correctly from the top-view in the multi-touch table. In particular, it was difficult to understand how much vertical space the equipment required. After the participants' had identified this, they started working with both the multi-touch table and the 3D-view from the projector as a reference. They started to test how the ceiling pendant systems and its multi-movement arms moved around during surgery so that it would not collide with anything. During the second workshop, the participants also had the opportunity to do this validation in the HMD, which gave them an even better understanding of how the operating theater would actually function.

Furthermore, during both workshops the participants used the HMD, to do design reviews and validate and examine the operating theaters. They had the opportunity to virtually stand by the operating table and make sure that they could see and reach all the equipment and make sure everything was correct. In this setting it was also possible to make changes to design. All the participants mentioned that HMD display gave a superior level of understanding and perception of space and that you could do more detail changes in the design as it was in scale 1:1.

32.4.2 Support Better Creativity, Collaboration and Participation

The participants at the workshop expressed that the collaborative design system was user-friendly, fun to use and that the system encouraged them to solve the design task effectively. Observation from the two workshops showed that the participants became easily familiar with the user interface and started to use the system directly after the introduction. Furthermore, the participants mentioned and thought that the workshop was a socially creative design process in which all participants could actively contribute with both their knowledge and experience. The observation during the workshops was that the workshop became a very creative design process, were the different participants shared knowledge and experience. The architect highlighted that she thought the roles were changing, i.e. the architect became an administrator of the workshop and healthcare staff became designers/architects and thereby more active and involved in the process. According to the architect and project manager, this had not been the case during earlier traditional dialogue-based workshops. The architect also stated that the knowledge and experience transfer from the healthcare staff was better with the collaborative design system. Furthermore, the participants from the healthcare staff perceived that the tools gave a better understanding of the design and planning of physical spaces and that their professional skills were presented and extracted in a better way. During the first workshop, the healthcare professionals from the different hospitals exchanged knowledge and experience from their healthcare environments. Also, in this dialogue, the participants mentioned that some professions were missing during the workshop, such as facility management, operations, logistics etc., which they believed would also have benefited from using the system.

The architect and project managers argued that this collaborative design system and it´s dialogue-based workshop offered a more efficient process compared to the traditional one. The architect explained that in the traditional process, it often entails long cycles (e.g. weeks) between new proposals and feedback from the end-users. Instead, they experienced that this new type of collaborative design process provided almost immediate feedback.

32.4.3 Support for Different Design Spaces

As mentioned, the different visualization and interaction techniques gave different support to the users during the workshop, effectively supporting different design spaces. Primarily, the multi-touch table supported a social creative process between the participants, i.e. action or collaboration space, see Fig. 32.4.

Fig. 32.4 The multi-touch table supported a social creative process (Picture from workshop 1)

The setting around the multi-touch table was highlighted as the most natural in terms of inter-communication as it supports face-to-face communication and gestures. However, the observations during the workshops also showed that the participants' ability to transform the multi-touch table information into self-made mental images in 3D was demanding, difficult and gave misinterpreted understandings. This was observed and noticed during both workshops when the users started using the 3D-view from the projector and detected design errors of colliding equipment between the ceiling-mounted equipment. After recognizing the design errors and the misinterpreted understandings, the users started to include the 3D-view from the projector as a shared frame of reference in their collaboration. They used the multi-touch table interface for designing and used the 3D-view from the projector as a visualization medium for understanding 3D-space better and for validation of the design. During the workshops it also became clear that immersive VR (e.g. HMD) gave another level of understanding and perception of space, which is hard to experience in other type of visualizations. The users performed design reviews and validations by actually standing virtually next to the operating table in order to make sure that everything was correct. The immersive VR system facilitated a reflection space where the user had the opportunity to considerate, reflect, validate and confirm the design related to their future work environment and task performed in the operating theater. What was observed during the first workshop when the user used the immersive VR-system, was that they wanted to do detailed changes of the design and they communicated the proposed changes to the other participants while they were in the immersive environment. As a result of this, the second workshop had seamless integration of a multi-touch table and several immersive VR-systems that supported interactive and collaborative design work in different design spaces—both collaborative (e.g. action space), as well as individual (e.g. reflection space). Changes done in one of the spaces were updated in the other design spaces. In the second workshop featured three HMD systems and one of them shared the 3D-view on a projector, (see Fig. 32.3).

32.5 Conclusions

Revisiting the foundations for successful collaborative design work, we can identify several aspects that a systems solution needs to support:

- Create awareness of each other's work and provide mechanisms to help draw out the tacit knowledge and perspectives.
- Enable co-creation (in multiple forms: simultaneous, parallel, and serial).
- Allow participants to build on the work of others.
- Provide individual reflection and exploration.

As the results show from our study, our system provides all of these features. Multi-touch table combined with non-immersive VR, supports interactive collaboration with shared understanding and awareness, and provides mechanisms for creative collaboration and tacit knowledge transfers. By providing seamless integration, usage and collaboration between different systems it also facilitates collaboration in simultaneous, parallel, and serial. The participants could also build on the work of others, which was the case during the workshops. As the results showed, the multi-touch table and VR-system complement each other by facilitating different design spaces—both collaborative (i.e. action space), as well as individual (i.e. reflection space). In comparison to other systems, our system seamlessly supports interactive collaboration in both spaces, i.e. changes done in both multi-touch table, non- and immersive VR-systems are updated seamlessly in both spaces. However, what was noticed during the workshops was that participants primarily wanted to engage in the collaborative design around the multi-touch table and did not take the time to reflect and do design review in the HMD. Furthermore, what happened when they took the time to reflect and perform the design review in VR, they found and had a lot of input to the others. Therefore, in future workshops it is important to facilitate the collaborative design process, by a break and giving the participants time for design review and reflection in the immersive VR environment. During these design review and reflection sessions, the participants stated that the HMD gave them another level of understanding and perception of space and the design problem that they could not experience in the other mediums. Our study thus reinforces the theory that multiple design spaces are, indeed, needed in order to foster a collaborative and creative design environment.

For future work it would be interesting to evaluate some of the suggestions given by the participants, such as collision detection among components and color-coding the different equipment according to professional discipline to better illustrate different responsibilities. Furthermore, seamless integration of BIM-systems would be a natural extension of the system, e.g. trace changes and update the BIM automatically. This would then also make the system support other project types, e.g. schools, urban environments, construction sites.

References

1. Elf, M., Fröst, P., Lindahl, G., Wijk, H.: Shared decision making in designing new healthcare environments—time to begin improving quality. BMC Health Serv Res **15**(114) (2015)
2. Lindahl, G., Ryd, N.: User-clients' goals and the construction management process. Proceedings of the International CIB W70 Symposium: Changing User Demands, on Buildings—Needs for Lifecycle Planning and Management, Trondheim, Norway (2006)
3. Johansson, M., Roupé, M.: Real-Time Rendering of large Building Information Models: Current state vs. state-of-the-art, CAADRIA 2012, Beyond Codes & Pixels, Chennai, India vol. 17, pp. 647–656 (2012)
4. Johansson, M., Roupé, M., Viklund Tallgren, M.: From BIM to VR—Integrating immersive visualizations in the current design process, eCAADe 2014, pp. 261–269 (2014)
5. Roupé. M., Johansson, M., Viklund Tallgren, M., Jörnebrant, F., Tomsa Petru, A.: Immersive visualization of Building Information Models—Usage and future possibilities during design and construction. CAADRIA 2016, Living Systems and Micro-Utopias: Towards Continuous Designing, vol. 21, pp. 673–682 (2016)
6. Arias, E., Eden, H., Fischer, G., Gorman, A., Scharff, E.: Transcending the Individual Human Mind - Creating Shared Understanding through Collaborative Design. ACM Trans. Comput.-Hum. Interact. **7**(1), 84–113, ACM, New York (2000)
7. Fischer, G., Giaccardi, E., Eden, H., Sugimoto, M., Yunwen, Y.: Beyond binary choices: Integrating individual and social creativity. Int. J. Hum.-Comput. Stud. **63**(4–5), 482–512, Academic Press, Duluth (2005)
8. Bouchlaghem, D., Shang, H., Whyte, J., Ganah, A.: Visualisation in architecture, engineering and construction (AEC). Autom. Constr. **14**(3), 287–295 Elsevier (2005)
9. Roupé, M.: Development and implementations of virtual reality for decision-making in urban planning and building design, Ph.D. Dissertation. Chalmers University of Technology (2013)
10. Streitz, N.A., Tandler, P., Müller-Tomfelde, C., Konomi, S.: Roomware: towards the next generation of human-computer interaction based on an integrated design of real and virtual worlds. In: Carroll, J.A. (ed.) Human-Computer Interaction in the New Millennium, Addison Wesley, pp. 553–578 (2001)
11. Coffey, D., Malbraaten, N., Le, T., Borazjani, I., Sotiropoulos, F., Keefe, D. F.: Slice WIM: a multi-surface, multi-touch interface for overview + detail exploration of volume datasets in virtual reality. In Symposium on Interactive 3D Graphics and Games (I3D '11), pp. 191–198, ACM, New York (2011)
12. Christou, C., Aristidou, P.: Steering Versus Teleport Locomotion for Head Mounted Displays. In International Conference on Augmented Reality, Virtual Reality and Computer Graphics, pp. 431–446. Springer, Heidelberg (2017)

33

Development and Usability Testing of a Panoramic Augmented Reality Environment for Fall Hazard Safety Training

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Abstract

Construction is one of the leading industries in terms of workplace accidents. Safety training provides workers and professionals with tools to actively prevent these accidents. However, previous research has highlighted deficiencies in current safety training methods. Virtual Reality (VR) and Augmented Reality (AR) technologies have been employed to address some of the limitations associated with traditional training methods. While these technologies enable users to safely experience the complex nature of construction sites, they deliver unrealistic computer-generated simulations of the environment. Panoramic augmented reality presents a novel alternative that addresses some of the challenges present in VR and AR techniques in visualizing safety-related information in real construction sites. A pilot study was conducted to assesses the use of this technology as a safety training method for fall hazards. This study describes the development of the prototype training platform, the generation of training materials, and the findings of usability testing performed with university students. The results indicated that the technology was viewed favorably by participants, as the augmentations provided a simple and easy method to learn fall hazard-related information. Using the platform, participants an average 52% of the hazards presented. Participants also indicated that several aspects of the platform required improvement such as image quality, safety information displayed, and user interface interactions.

Keywords

Panoramic augmented reality • Fall hazards training • Usability testing

33.1 Introduction

Safety training is essential to enable workers and professionals to actively prevent accidents on the jobsite. Previous research has investigated the importance of safety training in the construction industry [1]. Despite finding that safety training has a critical influence on accident prevention, studies indicate a multitude of deficiencies in traditional safety training programs. For example, Wilkins [2] found both dissatisfaction with and ineffectiveness of OSHA's 10-h construction safety training course. Survey results revealed that less than half of respondents (49%) either "agreed" or "strongly agreed" that they

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understood the material covered. Zuluaga et al. [3] conducted interviews at 49 construction projects, and most respondents (57.1%) described the safety training they received as "low engaging."

In response to these shortcomings, academia has explored the used of virtual reality (VR) and augmented reality (AR) to train construction workers and professionals on virtual jobsites. Nevertheless, despite the immersive potential of VR and AR to generate unlimited training scenarios, these virtual environments are uncapable of simulating real working conditions. Wang and Dunston [4] argued that VR provides a limited degree of realism, potentially leading to trainees who have adequate training in virtual environments, but who cannot perform with the same proficiency in real world operations. Further, VR requires high computational costs and time-consuming modelling tasks [5]. After such an investment, the VR environment may be applicable to only one specific project or useful to only certain members of the construction industry [6]. AR presents a different set of issues that hinder its potential as a training method. It is limited to both the spatiotemporal context and geolocation of the trainee [7]. Moreover, AR also introduces the problem of "drift." A sudden movement may cause the digital object to drift away from its designated position and create a disconnect between the real world and virtual augmentation [7].

Using 360° panoramic augmented reality proposes an alternative to the traditional VR and AR limitations. Within the mixed reality continuum [8], 360° panoramas are considered in the literature to be virtual reality [9] or mixed reality [10] due the intrinsic properties of this method, in which true reality is captured with a complete view of the user's surroundings, creating a naturally immersive environment [11]. 360° panoramic augmented reality addresses the need for computationally intensive graphical renderings, which can never fully mimic true reality, while simultaneously mitigating the need for a user to be in any specific geographical location. By using this novel method, a trainee can have a true-to-life experience of a dynamic construction jobsite, without any safety or spatiotemporal constraints. This research discusses the development process and usability testing of a safety training platform for selected fall hazards based on 360° panoramic augmented reality.

33.2 Methodology

The platform developed in this study employs 360° panoramic images with augmented safety data to enable an immersive fall hazard training program (Fig. 33.1). This platform helps trainees improve their fall hazard identification skills by providing: (1) a method to explore the construction environment and obtain detailed information by interaction; and (2) instantaneous feedback on their knowledge acquisition process. The platform was tested with trainees from construction-related disciplines to better elucidate how the platform transferred safety-related knowledge to participants.

33.2.1 Panoramic Augmented Reality Platform Development

The development of the platform was divided into four distinct phases to create the panoramic augmented experience, as illustrated in Fig. 33.2: capturing, authoring, immersion, and distribution. In the capturing phase, an equirectangular projection that recreates a 360° immersive view was obtained by employing a high precision panoramic camera (NCTech iStar Fusion) with multiple fish-eye lenses. This equirectangular projection was generated by stitching the images produced by each individual fish-eye lens into a single picture using computer software (NCTech Immersive Studio). In the authoring process, the captured projection was modified to resolve distortions introduced during the capturing process and projected in a 360° spherical context, enabling immersive exploration by the user.

During the immersion process, layers of fall hazard safety-related information were introduced to augment the environment captured. Interactivity was also added to the panoramic images using the game engine Unity3D®, allowing trainees to manipulate the different augmentations contained in the platform. This safety data immersion process is explained in detail in the next section. Ultimately, in the distribution process, the augmented panoramic scenes can be exported to different devices, allowing trainees using a plethora of devices—such as PCs, laptops, handheld devices, and head-mounted displays (HMD)—to access the interactive panoramic displays. In this study, PCs were targeted as the pilot testing device, as they were easily accessible, and did not require any special setup or additional external resources (e.g. game controller, HMDs, etc.). Moreover, interactive panoramas can be accessible online using cloud technologies which may enable real-time feed and big data analysis.

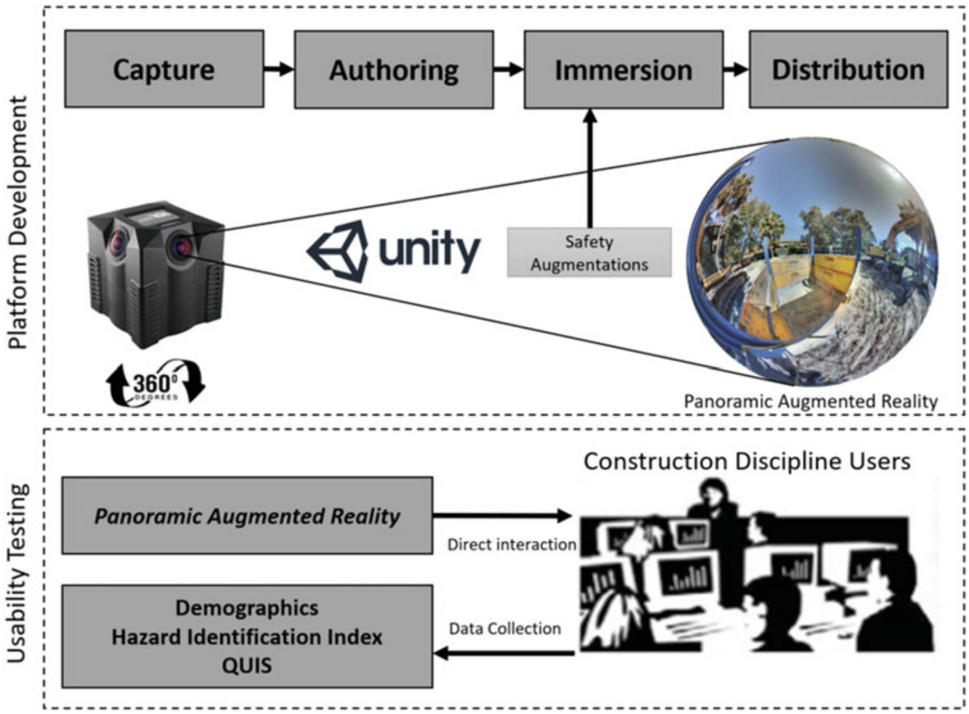

Fig. 33.1 Platform development and testing

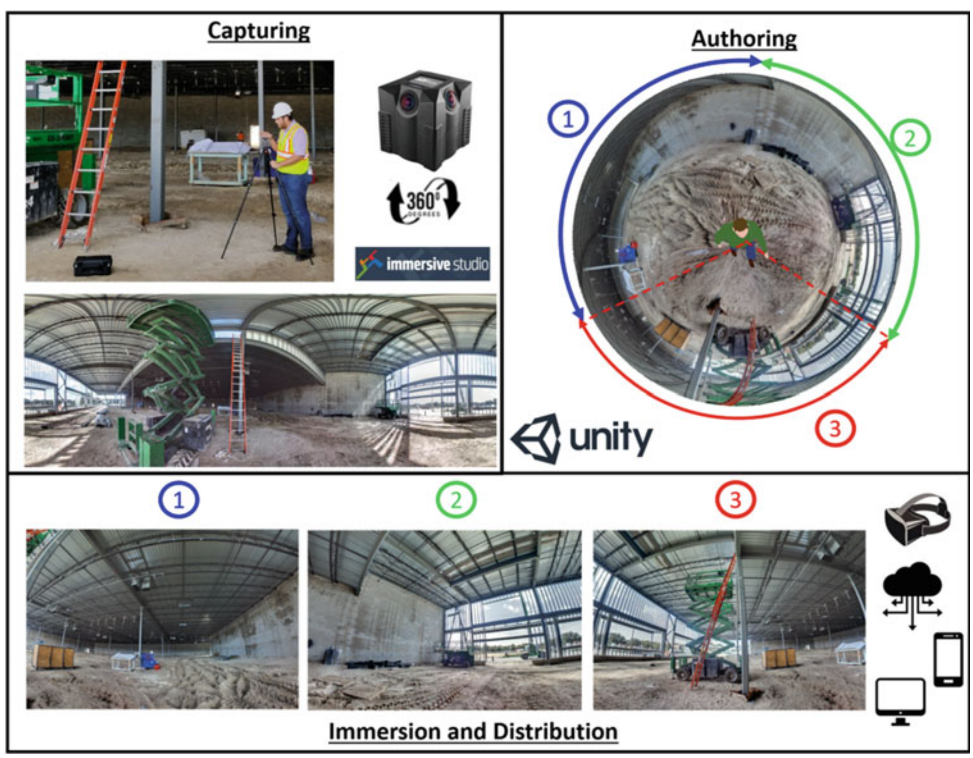

Fig. 33.2 Interactive panorama creation

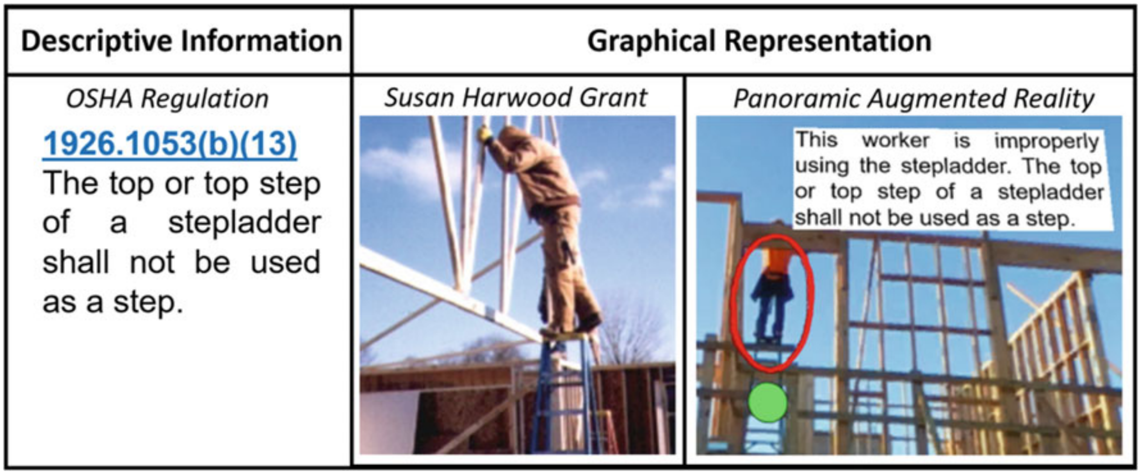

Fig. 33.3 Example of fall hazard augmentation

33.2.2 Fall Hazards Augmentations

Fall hazard-specific augmentations were developed for the platform based on OSHA regulations and the training materials provided by OSHA's Susan Harwood Grant Program (SHG). The content, descriptions, and pictures presented in the SHG training materials served as reference for the capturing, authoring, and immersion processes of the augmented reality materials. The augmentations developed for the panoramic images displayed descriptive information comparable to OSHA's regulations. Additionally, graphical representations of the hazardous conditions addressed in the platform were obtained in panoramic format, analogous to the contents in the SHG training materials. In this research, only four types of fall hazards were included in the training platform: ladders, edge protection, fall arresting, and housekeeping. The panoramic data collection for the pilot study was based on these four categories. All augmented materials developed for the platform required customized alterations of the OSHA and SHG contents, with the objective of facilitating similar learning outcomes to the trainees but in an immersive, interactive experience.

The presentation of the augmentations in the training platform was achieved using interactive hotspots that descriptively and graphically demonstrated OSHA's safety principles. Hotpots are click-based user interfaces that enable interaction with safety-data information, interconnecting the spatiotemporal location of the data and the information contained in the panoramic scenarios. For this study, these hotspots were green dots that when clicked by a trainee, showed a location marker and text with the fall hazard information. Figure 33.3. illustrates an example of content for fall hazards in the three different formats, specifically for stepladders. For this example, OSHA's regulation presents descriptive information using text to define a hazard related to stepladders. In the SHG, this information is presented by a graphical representation of the fall hazard. On the panoramic augmented reality platform, hotspot augmentations associate the descriptive information with the graphical representation using a red ellipse to denote the location of the hazard and text to describe the hazard, appearing only when the trainee interacts (mouse-click) with the interface.

33.2.3 Usability Testing

To evaluate the effectiveness of the developed platform in terms of knowledge acquisition about hazard identification and ease of use, human-computer interactions were assessed through a small-scale pilot study with real trainees. University of Florida's construction management and architecture students participated in the study. Three different instruments were used to collect data for the study: a pre-test survey, a hazard identification test, and a post-test survey.

The pre-test survey was administered to better understand the participant sample group, their previous knowledge regarding construction safety and the technology employed in the study. The survey gathered demographic information about age, gender, level of education, and educational focus. Questions were included to obtain information about each participant's construction experience, professional experience as a construction safety manager, and construction safety education. Additionally, participants self-assessed their level of understanding of augmented reality and 360° panoramic imaging.

The hazard identification test consisted of three different sessions: (1) training, (2) assessment, and (3) feedback. Sessions were consecutive and contained within the developed platform. In the training session (1), four different panoramic images, containing all the information trainees were expected to learn, were shown to the trainees as interactive augmentations. In this session, trainees were required to actively explore and interact with the panoramic locations to learn the fall hazard material presented. Immediately following, in the assessment session (2) trainees were shown sequential panoramic images without any augmentations and asked to identify all fall hazards. Data were collected within the platform, automating the data analysis process. When trainees had finished identifying the hazards in the assessment session, instantaneous feedback (3) was presented to the user on their previous hazard selections. For each image, the correct answer was displayed accompanied by Boolean "True" or "False" classifier, indicating correct (true) or incorrect (false) identification.

The evaluation of the hazard identification was performed using the hazard-identification index (adopted from Ref. [12]). The hazard-identification index (1) is defined as:

$$\mathrm{HII_j} = \mathrm{H_i}/\mathrm{H_{tot}} \tag{1}$$

The index was calculated for each trainee (j) based on the total number of identifiable hazards ($\mathrm{H_{tot}}$) in the immersive experience i. Safety professional determined the total number of hazards found the overall images. Hi indicates the number of hazards identified by the trainee j in the immersive experience i. To compute the total hazard-identification index for trainee j (*H*IIT, j), the mean of HIIj (2) was calculated across all scenarios for each hazards category:

$$H\mathrm{IIT_j} = Average(HII_\mathrm{j}) \tag{2}$$

The post-test survey centered on platform usability. Human-computer interactivity was assessed through a questionnaire with scaled numerical responses and open-ended sections for comments. The questionnaire was adapted from the Questionnaire for User Interface Satisfaction (QUIS), developed by University of Maryland researchers Chin et al. [13]. QUIS was specifically designed to test satisfaction with computer software and yield a high degree of accuracy. The newest version of QUIS (7.0) was adapted for this pilot study and included these sections: overall user reactions, screen, terminology and system information, and learning. Each section posed questions that asked respondents to rate the platform on a 1-to-9 Likert scale. The endpoint scores represented subjective adjectives (e.g., inconsistent/consistent), allowing trainees to express their thoughts regarding the platform [13]. Additionally, an open-ended question at the end of each section allowed trainees to provide supplementary comments that could not be reflected using Likert scales.

33.3 Results and Discussion

33.3.1 Participants

The sample size obtained for this pilot study was of 21 University of Florida students from Construction Management (76%) and Architecture (24%). The students were evenly distributed in Master's (57%) and PhD (43%) programs. In average, the participants had an age of 27 years, with a higher proportion of males (67%) than females (33%). The participants reported varying degrees of construction-related industry experience, ranging from less than 1 year (24%), 1 to 2 years (29%), 2 to 4 years (33%), to 4 to 10 years (14%) of experience. However, a large proportion (90%) of respondents did not report any construction industry safety-related experiences.

Many participants stated they previously taken a university-level course in construction safety (67%) and had received OSHA 30 safety certifications. No other type of safety education certification was reported by the participants. Overall, study participants reported that they had "some" to "fair" understanding of augmented reality technologies (none–5%; some–57%; fair–33%; competent–5%) and 360° panoramic technologies (none–14%; some–38%; fair–38%; competent–10%). Moreover, participants reported varying levels of understanding regarding general concepts of construction safety management (none–0%; some–38%; fair–38%; competent–24%) and OSHA regulations (none–10%; some–24%; fair–38%; competent–29%).

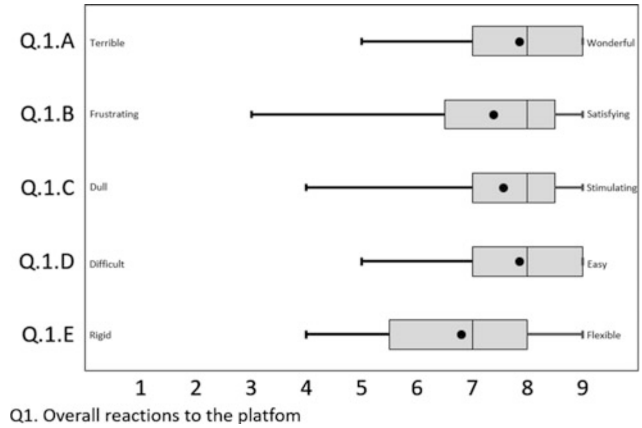

Fig. 33.4 Part 1: overall user reactions

33.3.2 Hazard Identification Index

A hazard identification index was calculated for each study participant, assessing ability to identify hazards within the developed platform. Participants identified an average 52% of the hazards presented in the assessment session. These findings are consistent with previous studies indicating that many hazards remain unrecognized on construction sites [12, 14]. This is alarming, since unrecognized hazards are the main source of incidents on construction sites.

Additionally, the proportion of participants who identified each hazard on each image was analyzed. The results obtained for each individual image were:

- Figure 33.1: ladder height-to-run ratio–86%; step-ladder improper usage–43%; improper guardrail installation, placement, or fully missing–24%; untied worker–14%
- Figure 33.2: step-ladder improper usage–71%; improper guardrail installation, placement, or fully missing–57%
- Figure 33.3: improper guardrail installation, placement, or fully missing–48%; incorrect material storage–86%
- Figure 33.4: incorrect material storage–43%; untied worker–62%; hazardous electrical cord–43%

For each individual image, most participants were able to detect the improper usage of ladders and unsafe storage material. Nevertheless, only a small number of participants were able to identify improper usage of fall protection system (i.e. untied worker) on Fig. 33.1 but were able to identify a similar condition on Fig. 33.4. It is notable that since a limited number of images were used in this study, no generalizations can be made in terms of these results.

33.3.3 Platform Usability

The overall responses of participants regarding the developed platform were favorable (Fig. 33.4). The platform was perceived as wonderful (Mean: 7.9; Median: 8.0; IQR Low: 7.0; IQR High: 9.0), satisfying (7.4; 8.0; 6.5; 8.5), and stimulating (7.6; 8.0; 7.0; 8.5) to use, with narrow distributions of responses. The platform was also rated as easy to use (7.9; 8.0; 7.0; 9.0) and flexible (6.8; 7.0; 5.5; 8.0), presenting a compact distribution. Moreover, participants provided positive comments on the platform as a method to learn about fall hazards. For example, one participant commented that "*[the platform] is a good way to learn about site hazards*," and another remarked that "*[the platform] was very easy to use*."

Participants also provided favorable feedback about the elements shown on the screen of the platform throughout the tasks assigned (Fig. 33.5). The fall hazard materials contained in the augmentations were reported as easy to read (8.1; 8.0; 7.5; 9.0). The augmentations contained sharp (7.4; 8.0; 6.5; 8.5) and very legible (8.4; 9.0; 8.0; 9.0) characters. The highlighting that the augmentations introduced on screen was very helpful (8.3; 8.0; 8.0; 9.0) in allowing participants to locate the hazards. Additionally, the amount of fall hazard information displayed (7.9; 8.0; 7.0; 9.0) on screen by the hotspots and the arrangement of that information (8.2; 8.0; 8.0; 9.0) was adequate and logical. The flow of the platform was positively perceived by the participants, as they stated that the sequence of screens (8.4; 9.0; 8.0; 9.0) and the progression of tasks (8.1;

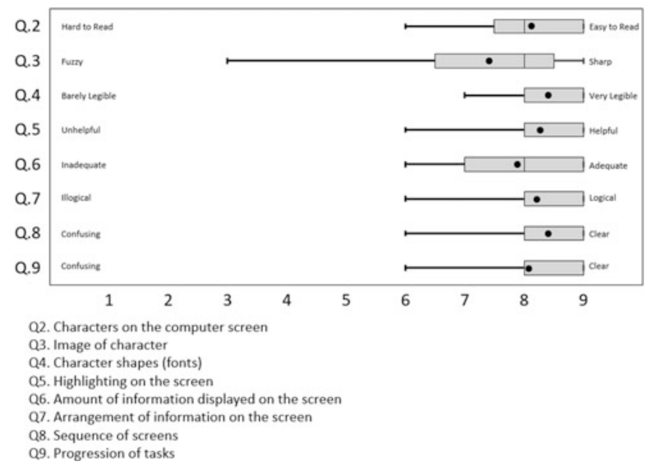

Fig. 33.5 Part 2: screen

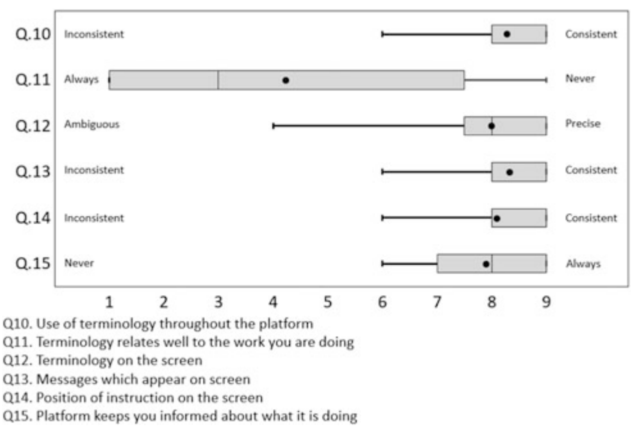

Fig. 33.6 Part 3: terminology and platform information

8.0; 8.0; 9.0) were clear and simple to follow. One participant commented that "*the hazards were shown clearly in the training [session]*," but another said that "*in the assessment [session], it was troublesome to finding some hazards*."

Feedback on the terminology and the platform information indicated generally positive results as shown in Fig. 33.6. Participants considered the fall hazard terminology employed in the platform to be consistent (8.3; 9.0; 8.0; 9.0) and precise (8.0; 8.0; 7.5; 9.0), although some terminology occasionally appeared to be disconnected with the specific tasks performed (4.3; 3.0; 1.0; 7.5). Moreover, the platform messages on screen (8.3; 8.0; 8.0; 9.0) and the position of messages (8.1; 8.0; 8.0; 9.0) that contained task instructions were considered consistent, as the platform tended to keep participants informed (7.9; 8.0; 7.0; 9.0) on what they were doing about a specific task.

Finally, the participants expressed the tasks that required to learn how to identify hazards in the platform were simple to learn as shown in Fig. 33.7. The platform operations were easy (8.3; 9.0; 8.0; 9.0), as the task could be often performed in a straight-forward manner (8.3; 9.0; 8.0; 9.0). There was adequate number of steps to complete the tasks (8.2; 8.0; 8.0; 9.0) and these followed a logical order (8.2; 8.0; 8.0; 9.0). Additionally, the feedback provided to the participants was reported to be clear (7.4; 8.0; 7.0; 9.0), allowing an understanding of what the hazards presented in each of the images shown in the assessment session.

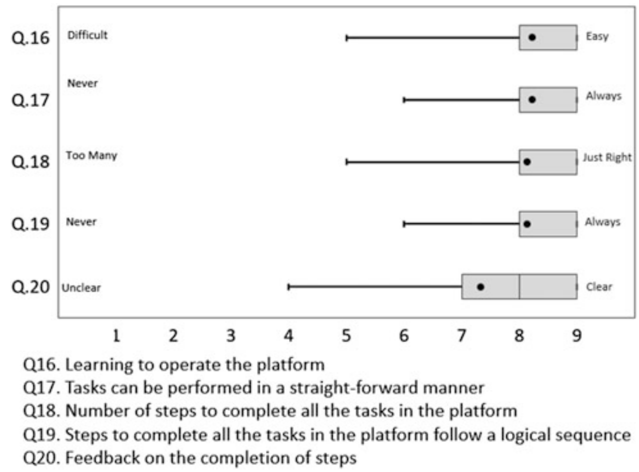

Fig. 33.7 Part 4: learning

33.3.4 Lessons Learned

Qualitative comments obtained from the participants provided valuable insight into major issues with the platform that must be addressed in the future. The responses collected were classified in five categories: (1) image quality; (2) safety information displayed; (3) interface visual and interactions; (4) hazard navigation; and (5) general recommendations.

Several participants noted that image quality (1) was an issue for hazard identification as "the resolution of specific points [in the images] are not high enough". This comment reflected current limitations of the 360° panoramic technology, as other participants noted that "*the quality of the images could improve" as there are some parts of the images where it was difficult to see or identify the hazards*." Because fall hazard identification relies on intrinsic detail found in the images, some participants expressed that "*a higher resolution on imaging would produce a better experience*". In the platform, several issues were raised by the participants regarding the safety information displayed (2) on screen. Some participants stated that in the training session the "*[hazard] identification descriptions were not clear*" and "*some of the hazards explanations on the screen were not clear when it moved in certain directions or faced a certain way*." Additionally, one person commented that "*[fall hazard] information was only shown in one image but was present in multiple images*" producing confusion because it was not clear if those were the same type of hazard or different independent hazards.

The interface (3) used by the participants also had design problems both in the visual aesthetics and the interactions. Some participants reported that in the feedback section "*fonts were too small and not as appealing as the rest of the platform*" The hotspots also caused some problems because in some of the locations "*the green highlights and the circles overlapped*." Moreover, the participants conveyed that in the training session they had difficulties assessing "*how many hazards are present in an image and were to look for them*", suggesting that "*it could be easier for the trainee to see the number of hazards on the screen to be aware and not miss any hotspots*." Other participants described interaction problems that included "*scrolling and panning direction*" and "*buttons did not easily switch between hazard types*." The platform hazard navigation (4) also was concerning for several participants who stated that "*it is only possible to see what is going on directly near you. For example, it was unclear if the people in one of the images were on an area that needed harness*." In general, participants recommended (5) that the platform could be improved by integrating audio as "*some people might understand or learn better when they are doing both listening and visualizing things*" or video to "*show the user the right way of doing things*."

33.4 Conclusion and Further Work

Panoramic augmented reality has the potential of providing an immersive safety training experience for construction workers and professionals. This paper described the process of creating a platform using 360° panoramic images augmented with fall-related hazard information based on OSHA and SHG training materials. The development required four steps: capture, authoring, immersion, and distribution. A pilot study was performed to assess the platform's ability to enhance learning about fall hazards identification and the overall usability of the interface. The results indicated that an average 52% of fall hazards were recognized by study participants. Positive feedback was obtained regarding participant usability of the platform. The participants expressed that the platform was overall easy to use and flexible, especially highlighting that the augmentations introduced on screen were very helpful in locating the fall hazards. Nevertheless, the participants indicated that several improvements needed to be addressed to provide a better overall experience.

Future research should investigate the ability of panoramic augmented reality to provide trainees with hazard identification knowledge about other types of hazards (e.g., caught-in, struck-by, electrical). Further, a larger sample size is required to perform a statistical analysis of participants' hazard-identification skills that would yield significant results. Finally, the incorporation of video, audio, and Building Information Models (BIM) in the platform should be explored to determine their impact on trainees' hazard identification skills

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References

1. Bahn, S., Barratt-Pugh, L.: Safety training evaluation: the case of construction induction training and the impact on work-related injuries in the Western Australian construction sector. Int. J. Training Res. **12**(2), 148–157 (2014)
2. Wilkins, J.R.: Construction workers' perceptions of health and safety training programmes. Constr. Manage. Econ. **29**(10), 1017–1026 (2011)
3. Zuluaga, C.M., Mostafa, N., Alex, A.: Impact of training methods on hazard recognition and risk perception in construction. Construction Research Congress, pp. 2861–2871 (2016)
4. Wang, X., Dunston, P.S.: Design, strategies, and issues towards an augmented reality-based construction training platform. ITcon **12**, 363–380 (2007)
5. Lin, K.Y., Son, J.W., Rojas, E.M.: A pilot study of a 3D game environment for construction safety education. ITcon **16**, 69–84 (2011)
6. Goulding, J., Nadim, W., Petridis, P., Alshawi, M.: Construction industry offsite production: a virtual reality interactive training environment prototype. Adv. Eng. Inform. **26**(1), 103–116 (2012)
7. Gheisari, M., Foroughi Sabzevar, M., Chen, P., Irizary, J.: Integrating BIM and panorama to create a semi-augmented-reality experience of a construction site. Int. J. Constr. Educ. Res. **12**(4), 303–316 (2016)
8. Milgram, P., Takemura, H., Utsumi, A., Kishino, F.: Augmented reality: a class of displays on the reality-virtuality continuum. In: Conference on Telemanipulator and Telepresence Technologies, SPIE, vol. 2351, Boston, MA, USA, pp. 282–292 (1994)
9. Gomes, D.L., Jansen, P.R., Paiva, A.C., Silva, A.C., Braz, G., Araujo, A.S., Gattass, M.: Semi-automatic methodology for augmented panorama development in industrial outdoor environments. Adv. Eng. Softw. **114**, 282–294 (2017)
10. Ryskeldiev, B., Cohen, M., Herder, J.: Stream space: pervasive mixed reality telepresence for remote collaboration on mobile devices. J. Inf. Process. **26**, 177–185 (2017)
11. Eiris Pereira, R., Moud, H.I., Gheisari, M.: Using 360-degree interactive panoramas to develop virtual representation of construction sites. In: Proceedings JC3 (2017)
12. Carter, G., Smith, S.D.: Safety hazard identification on construction projects. J. Constr. Eng. Manage. **132**(2), 197–205 (2006)
13. Chin, J.P., Diehl, V.A., Norman, K.L.: Development of an instrument measuring user satisfaction of the human-computer interface. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 213–218, Washington D.C., USA (1988)
14. Perlman, A., Sacks, R., Barak, R.: Hazard recognition and risk perception in construction. Saf. Sci. **64**, 22–31 (2014)

34

The Negative Effects of Mobile ICT on Productivity in Indian Construction Projects

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Abstract

Due to increased affordability of mobile devices, better network coverage, and availability of a wide range of mobile applications, the use of mobile information and communication technologies (mobile ICT) has increased significantly in construction projects. While considerable research on both positive and negative implications of using mobile ICT has been conducted in different industries and social contexts, relatively few studies have examined the perception of construction management (CM) professionals. A questionnaire survey conducted across the Indian construction industry revealed that the use of mobile ICT could impede construction productivity due to factors such as: (1) pressure to remain accessible outside the work hours, (2) temptation to check it frequently, (3) adverse effects on work-life balance, (4) compulsion to work outside the normal work hours, (5) massive amount of information, (6) distraction, (7) less time to respond to changes, (8) loss of productive time due to personal internet usage, (9) adverse effects on health of the users, and (10) frequent drawing changes. Since potential applications of mobile ICT in construction projects present enormous opportunities for CM professionals, these issues need to be addressed through user awareness, training, and organizational policies.

Keywords

Information and communication technology (ICT) • Mobile ICT • Construction productivity

34.1 Introduction

Unplanned changes to work and design, temporary critical problems, and unanticipated events are inevitable on construction sites [1]. Therefore, the information should be easily available to construction management (CM) professionals to make informed decisions while working on sites. However, due to the outdoor and harsh nature of construction sites, CM professionals often face difficulty in using conventional computers while working in the field [2]. In addition, the temporary nature of project organizations makes communication a very complex process [3]. As a result, poor communication is often identified as one of the major factors that impede productivity in construction projects [4]. Moreover, frequent travels between the site office and work front to gather the information could affect progress, cost, and quality of various construction activities.

The use of mobile devices such as smartphones and tablets by CM professionals could facilitate instant communication and access to information with the help of wireless network and mobile applications [5, 6]. In the last few years, mobile information

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and communication technologies (mobile ICT) have changed the ways in which communication and information transfer take place across different industries [7]. These technologies provide greater flexibility in communication, collaboration, and information transfer [8]. People carry their mobile devices everywhere and use them for various purposes [9]. These technologies enable their users to easily and quickly connect to other people and information sources from almost anywhere [10]. Therefore, mobile ICT have potential to significantly improve the field work, on-site information management, and productivity in construction projects [11–13]. These technologies can make CM professionals more accessible regardless of their location on site [6, 14]. In addition, the use of mobile ICT can also reduce communication costs in projects [15].

Currently, with the remarkable advancements in both hardware and software, the use of mobile ICT in the construction industry has increased enormously [16]. Although their use usually aims for increased productivity, the impacts may be perceived as both positive and negative depending upon user experience and overall evaluative judgments [17]. Therefore, more studies to inquire into the perception of CM professionals about negative implications of the use of mobile ICT could help the industry to take advantage of their full capabilities by addressing those concerns.

34.2 Literature Review

The information-intensive and knowledge-based nature of the construction industry needs it to embrace ICT to remain competitive. Previous studies have shown that the industry has significantly benefited from successive improvements in ICT and successful adoption over a period [18, 19]. The use of mobile information system to improve work efficiency, reduce costs, and generate both social and economic benefits has remained a significant area of research [20].

Previous studies have found that the users sometimes point out more cons than pros of using mobile ICT at the workplace. These include distraction, safety issues, privacy concerns, software bugs, reluctance of older workers, and issues with data synchronization [16]. Due to proliferation of cloud-based applications and mobile devices, workers now use personal mobile devices for enterprise work [21]. Accidental or purposeful disclosure or dissemination of proprietary, confidential, or material information online by the employees is another major cause of concern for the companies [22, 23]. Moreover, failure to integrate mobile devices into their overall security strategy can put organization's enterprise network and database into risk due to the whole range of devices being used across the organization [24].

While mobile ICT increases the access of workers to one another and to work both within and outside of the workplace [25, 26], it becomes difficult for users to 'escape' work into their non-work lives due to continuous access to information [26]. The greater access to individuals can be problematic due to work–family spillover [27, 28]. Therefore, while implementing modern ICT tools, it is important to remember that the use of any technology does not necessarily ensure better performance [29].

The benefits that mobile ICT have to offer the construction industry are quite evident, however, such benefits cannot be realized until these technologies are adopted and used by CM professionals in productive ways [30]. However, the research investigating the perceptions of CM professionals on the use of mobile ICT has been limited. The present study examines the negative implications of the use of mobile ICT for productivity in construction projects. This knowledge can further enhance understanding of the future deployment of mobile ICT in the construction industry.

34.3 Research Methodology

An initial questionnaire was developed based on literature review. The questions were divided into five parts and covered different areas of mobile ICT usage in construction projects. The first and fourth sections have been reported in the current paper. The link to the relevant sections of the questionnaire is https://www.dropbox.com/s/9f93s7eg1i9nkk3/Questionnaire.pdf?dl=0. The first part of the questionnaire consisted of questions on personal and professional attributes of the respondents. The fourth part had questions on negative implications of the use of mobile ICT use for productivity in construction projects. The initial questionnaire was administered to six CM professionals who had an average eight years of experience of using mobile ICT in construction projects. The feedback received from the participants brought attention to few mistakes committed in the self-administered questionnaire. As a result, some changes in the layout and language were performed to make sure that the members of the population interpret the questions correctly. The questionnaire was tested again after corrections in the initial questionnaire by a different group of four experienced CM professionals [31].

The final questionnaire was administered online. The organizations or respondents accounted for the sample survey comprised of the members of the Construction Industry Development Council (CIDC). The CIDC was set up in 1996 by the Planning Commission, Government of India, jointly with the Indian construction industry to take up activities for the development of the Indian construction industry [32]. It is a consortium of construction companies, construction equipment manufacturers, technology providers, and research institutions. Since most of the key organisations in the Indian construction industry are also the members of CIDC, the authors considered CIDC as a credible source for collecting data. In addition, due to the wider presence of these organisations in construction projects across India, the construction professionals working in these companies were found suitable for examining the use of mobile ICT and its implications for construction productivity. The CIDC had 117 members at the time of data collection. Of these, 62 organisations who directly undertake construction projects of different nature were chosen as the sample for this study. Moreover, nine other construction companies who were not in the CIDC list were also found suitable for collecting data and thereby, included in the sample. The anonymous questionnaire was finally sent to CIDC member organisations and other companies and after a continuous follow-up for 6 months through monthly email reminders, a total of 119 questionnaires were received. However, 14 responses were discarded due to incomplete information provided by the respondents. Finally, 105 completed survey responses received from 54 construction organisations were used for further analysis. Table 34.1 shows the details of participants.

Table 34.1 demonstrates that the respondents came from different educational and professional backgrounds. The average experience of the participants was 7 years. These CM professionals were working at various positions in construction projects. Moreover, the turnover of the organizations show participation of small, medium, and large-sized companies. Therefore, the collected data represented a good mix of respondents and organizations with distinct characteristics.

The responses were obtained in terms of a five-point Likert scale in which 1 represented 'strong disagreement' and 5 represented 'strong agreement'. Each of the factors associated with the use of mobile ICT affecting construction productivity was ranked based on mean values. The highest mean value indicates the most critical factor with rank 1, the next most critical factor with rank 2 and so on. If the mean values are equal, the factor with lower standard deviation received the higher ranking.

Table 34.1 Respondents' profile

Characteristics	Categories	Number of respondents	% of total
Experience (in years)	Less than 5 years	59	56.19
	6–10	26	24.76
	11–15	9	8.57
	Over 15 years	11	10.47
Sector	Residential projects	19	18.10
	Commercial projects	21	20.00
	Industrial projects	26	24.76
	Infrastructure projects	39	37.14
Job title	Site Engineer	29	27.62
	Planner	33	31.43
	Construction Manager	10	9.52
	Project Manager	19	18.10
	Executive	14	13.33
Years of mobile ICT usage in construction projects	Less than 1 year	9	8.57
	Between 1 and 3 years	27	25.71
	Between 3 and 5 years	22	20.95
	Between 5 and 10 years	34	32.38
	More than 10 years	13	12.38
Respondent's company turnover, 2016–17 (in million INR)	Less than 100,000	44	41.90
	100,001–500,000	29	27.62
	Above 500,000	32	30.48

34.4 Results and Discussions

Table 34.2 shows the ranking of different factors based on their mean and standard deviation values. The top ten factors have been discussed briefly in the subsequent sections.

34.4.1 Pressure to Remain Accessible Outside the Work Hours

In developing countries such as India, work on construction sites continues in multiple shifts and even during weekends and holidays due to tight project schedules. Consequently, CM professionals are often contacted by their project team members outside the normal work schedule for various reasons such as seeking clarifications or advice on important issues. This work culture puts pressure on CM professionals to remain in constant touch with their colleagues. This confirms the findings of previous studies that the users of mobile ICT experience huge pressure to be accessible and responsive even during non-work hours [10, 33].

34.4.2 Temptation to Check It Frequently

Since mobile ICT facilitate instant access to information, CM professionals are expected to update themselves on various developments that occur on a construction site. The temptation that they might miss something important forces CM professionals to check their mobile devices on short intervals. This tendency of engaging with mobile devices after every few minutes affects productivity in construction projects. Previous studies have found that the smartphone usage varies from a couple of hours to 14 h per day and the average number of interactions varies from 10 to 200 times per day [34, 35].

34.4.3 Adverse Effects on Work-Life Balance

The construction industry is known for long work hours and harsh working conditions. The increased use of mobile ICT further aggravates these issues. More demands on CM professionals' time and attention could create conflicts in their personal lives. Employees who work outside of the confines of the traditional office space or work time may incur negative impacts on their work–life balance due to excessive burdens of being connected all the time [36]. Due to proliferation of cloud-based applications, workers often use personal devices at home for doing enterprise work [21].

Table 34.2 Ranking of factors

Rank	Factors	Mean	Standard deviation
1	Pressure to remain accessible outside the work hours	4.04	0.865
2	Temptation to check it frequently	4.01	0.882
3	Adverse effects on work-life balance	3.84	0.921
4	Compulsion to work outside the normal work hours	3.82	0.896
5	Massive amount of Information	3.70	0.831
6	Distraction	3.50	0.942
7	Less time to respond to changes	3.44	0.898
8	Loss of productive time due to personal internet usage	3.42	0.959
9	Adverse effects on health of the users	3.30	0.932
10	Frequent drawing changes	3.28	0.995
11	Unsafe acts/behaviour	3.26	0.971
12	Increased workload	3.08	1.026
13	Frustration	2.98	0.961
14	Increase in project cost	2.67	0.816
15	More complex job requirements	2.55	0.796
16	Poor quality of construction work	2.55	0.820

34.4.4 Compulsion to Work Outside the Normal Work Hours

The respondents perceived that the use of mobile ICT results in increased work hours. Although professional use of mobile devices offers flexibility due to ability to work from anywhere, it has reduced personal autonomy of the users and their ability to disconnect from work [37]. Consequently, CM professionals spend considerable amount of time working on queries or emails beyond their normal work hours. The fatigue due to extended work hours could have a negative impact on productivity.

34.4.5 Massive Amount of Information

The large amount of information produced due to continuous use of mobile ICT could be counterproductive. The reduced cost of communications has increased the number of interactions and time required to process the large amount of information exponentially, thus sometimes resulting in unproductive use of time [38].

34.4.6 Distraction

The respondents believed that the use of mobile ICT causes distractions which could be detrimental for both productivity and safety considering the hazardous work environment on construction sites. Often, the users get too immersed into these technologies which leads to the more incidents of slips, trips, collisions on construction sites [39]. Moreover, irrelevant emails and unnecessary information waste the productive time of CM professionals.

34.4.7 Less Time to Respond to Changes

Due to continuous exchange of data and information, CM professionals often have less time to process the information and respond to various changes that are happening continuously on a construction site. This situation may result in overlooking few important details that could lead to construction errors or rework. The continuous flow of information at an incredible pace can be problematic sometimes [39].

34.4.8 Loss of Productive Time due to Personal Internet Usage

The personal use of the internet negatively affects the productivity rates in construction projects. Previous studies have found that the employees spend at least one hour on non-work-related activities using internet [40]. Non-work-related use constitutes approximately 30–50% of internet usage at the workplace [41]. However, many CM professionals use same devices for both personal and professional purposes. Therefore, it could be difficult to eliminate the personal use of internet on construction sites.

34.4.9 Adverse Effects on Health of the Users

The side-effects of mobile ICT usage on CM professionals' health and well-being could lead to more absenteeism and turnover in construction projects and thereby, low productivity. While these technologies provide greater temporal and spatial flexibility, they also constitute adverse consequences on users' health and well-being due to various work-related stressors of ICT use as discussed in previous sections. Moreover, many studies report that the radiations from mobile devices and network can also affect health of the user [42].

34.4.10 Frequent Drawing Changes

Respondents believed that the number of changes in drawings has increased with the uptake of mobile ICT in construction projects. The architects can now change the drawings on the cloud and it is a challenging task for the contractors to communicate those changes across the supply chain. A negative aspect of mobile ICT is the architect's tendency to change drawings at quick intervals [39]. The updates and changes to plans occur more frequently due to the use of mobile ICT [27].

34.5 Conclusion

The full potential of mobile ICT in construction projects can be realised only when various aspects related to the use of these technologies are properly understood. Therefore, research into examining both positive and negative implications of these technologies on productivity is highly warranted. While the previous studies have focused mainly on the extent of usage of different types of mobile ICT and benefits of adoption of these technologies in construction projects, the aim of this research was to examine the negative implications of the use of mobile ICT for construction productivity from users' perspective.

The study uncovered few important issues that require further investigation and thereby, may inform future research in this domain. For instance, CM professionals expressed concerns over their health, safety, work-life balance, and well-being that emerge directly from the use of these technologies for extended periods both within and outside the normal work hours. They also feel pressure to stay connected with work and a regular urge to check their mobile devices for new information. In addition, the personal use of internet, time to process massive information, and distractions due to the use of these technologies negatively affect productivity in construction projects. However, the respondents do not seem to agree that the use of mobile ICT results in frustration, complex job requirements, and increase in project cost. Also, the factor to evaluate adverse effects of mobile ICT usage on the quality of construction work received the lowest ranking. Therefore, it can be concluded that most of the negative aspects of mobile ICT usage are related to the health, safety, and wellbeing of CM professionals rather than construction processes or project outcomes.

It is put forth that construction organizations develop a deeper and wider understanding of the negative implications of the use of mobile ICT to strategize its usage with the help of proper policy framework and training. More research efforts are required to devise innovative measures to address various issues identified in this research. However, the findings of this study must be considered within the context of its limitations. The data for this study was gathered only from CM professionals working in the Indian construction industry and therefore, cannot be necessarily generalized to other contexts due to different work cultures and organizational practices. Nonetheless, the present study highlights some of the major issues associated with the use of mobile ICT in the context of the construction industry. Since most of the research on negative implications of using mobile ICT has been conducted in different contexts, the findings of this research make significant contribution to the construction literature on mobile ICT.

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References

1. De la Garza, J.M., Howitt, I.: Wireless communication and computing at the construction jobsite. Autom. Constr. **7**(4), 327–347 (1998)
2. Williams, T.P.: Applying handheld computers in the construction industry. Pract. Periodical Struct. Des. Constr. **8**(4), 226–231 (2003)
3. Kaplan, A.M., Haenlein, M.: Users of the world, unite! The challenges and opportunities of social media. Bus. Horiz. **53**(1), 59–68 (2010)
4. Hasan, A., Baroudi, B., Elmualim, A., Rameezdeen, R.: Factors affecting construction productivity: a 30 year systematic review. Eng. Constr. Architectural Manage. **25**(7), 916–937 (2018)
5. Mathiassen, L., Sørensen, C.: Towards a theory of organizational information services. J. Inf. Technol. **23**(4), 313–329 (2008)
6. Disterer, G., Kleiner, C.: BYOD bring your own device. Procedia Technol. **9**, 43–53 (2013)
7. Bresnahan, T., Yin, P.: Adoption of new information and communications technologies in the workplace today. Innov. Policy Econ. **40**, 95–124 (2017)
8. Nah, F., Siau, K., Sheng, H.: The value of mobile applications: a study on a public utility company. Commun. ACM **48**(2), 85–90 (2005)
9. Finnie, S.: Mobile is immediate. Computerworld, ProQuest Technol. Collect. **46**(2), 32 (2012)

10. Matusik, S.F., Mickel, A.E.: Embracing or embattled by converged mobile devices? Users' experiences with a contemporary connectivity technology. Hum. Relat. **64**(8), 1001–1030 (2011)
11. Anumba, C.J., Aziz, Z., Ruikar, D.: Mobile and semantic web-based delivery of context-aware information and services in construction. In: Anumba, C.J., Wang, X. (eds.) Mobile and pervasive computing in construction, 1st edn. Wiley, UK (2012)
12. Chen, Y., Kamara, J.M.: Using mobile computing for construction site information management. Eng. Constr. Architectural Manage. **15**(1), 7–20 (2008)
13. Son, H., Park, Y., Kim, C., Chou, J.S.: Toward an understanding of construction professionals' acceptance of mobile computing devices in South Korea: an extension of the technology acceptance model. Autom. Constr. **28**, 82–90 (2012)
14. Kim, C., Park, T., Lim, H., Kim, H.: On-site construction management using mobile computing technology. Autom. Constr. **35**, 415–423 (2013)
15. Bertschek, I., Niebel, T.: Mobile and more productive? Firm-level evidence on the productivity effects of mobile internet use. Telecommun. Policy **40**, 888–898 (2016)
16. Sattineni, A., Schmidt, T.: Implementation of mobile devices on jobsites in the construction industry. Procedia Eng. **123**, 488–495 (2015)
17. Väätäjä, H.: Perceived impacts as user experience components in mobile news making with smartphones. In: J Lumsden (ed.) Emerging perspectives on the design, use, and evaluation of mobile and handheld devices. IGI Global, PA, USA, pp. 218–238 (2015)
18. Samuelson, O.: IT-Barometer 2000-the use of IT in the Nordic construction industry. ITcon **7**, 1–26 (2002)
19. Underwood, J., Khosrowshahi, F.: ICT expenditure and trends in the UK construction industry in facing the challenges of the global economic crisis. J. Inf. Technol. Constr. **17**, 26–41 (2012)
20. Chen, X.: Web service based mobile worker supporting system for construction industry applications. Telecommun. Syst. **54**(3), 277–286 (2013)
21. Olalere, M., Abdullah, M.T., Mahmod, R., Abdullah, A.: A review of bring your own device on security issues. SAGE Open **5**(2), 1–11 (2015)
22. Al Harthy, K., Shawkat, W.: Implement network security control solution in BYOD environment. In: IEEE International Conference on Control System, Computing and Engineering, Penang, Malaysia (2013)
23. Jennings, S.E., Blount, J.R., Weatherly, M.G.: Social media—a virtual Pandora's box prevalence, possible legal liabilities, and policies. Bus. Prof. Commun. Quart. **77**(1), 96–113 (2014)
24. Hale, J.: Integrate mobile. SC Mag. **26**(9), 30–33 (2015)
25. DiMaggio, P., Hargittai, E., Neuman, W.R., Robinson, J.P.: Social implications of the Internet. Ann. Rev. Sociol. **27**, 307–336 (2001)
26. Madden, M., Jones, S.: Networked workers', Pew Research Center (2008), http://www.pewinternet.org. Last accessed 21 Mar. 2018
27. Southerton, D.: Time pressure, technology and gender: the conditioning of temporal experiences in the UK. Equal Opportunities Int. **26**(2), 113–128 (2007)
28. Chesley, N.: Blurring boundaries? Linking technology use, spillover, individual distress, and family satisfaction. J. Marriage Fam. **67**, 1237–1248 (2005)
29. Emmitt, S., Gorse, C.: Communication in Construction Teams. Taylor & Francis, Oxon (2007)
30. Basaglia, S., Caporarello, L., Magni, M., Pennarola, F.: Individual adoption of convergent mobile phone in Italy. RMS **3**(1), 1–18 (2009)
31. Saris, W.E., Gallhofer, I.N.: Design, evaluation, and analysis of questionnaires for survey research, 2nd edn. Wiley, NJ (2014)
32. CIDC.: http://www.cidc.in/new/aboutus.html. Last accessed 21 Mar. 2018
33. Orlikowski, W.J.: Sociomaterial practices: exploring technology at work. Organ. Sci. **28**(9), 1435–1448 (2007)
34. Verkasalo, H.: Contextual patterns in mobile service usage. Pers. Ubiquit. Comput. **13**(5), 331–342 (2009)
35. Falaki, H., Mahajan, R., Kandula, S., Lymberopoulos, D., Govindan, R., Estrin, D.: Diversity in smartphone usage. In: Proceedings of the 8th International Conference on Mobile Systems, Applications, and Services, ACM, pp. 179–194 (2010)
36. Diaz, I., Chiaburu, D.S., Zimmerman, R.D., Boswell, W.R.: Communication technology: pros and cons of constant connection to work. J. Vocat. Behav. **80**(2), 500–508 (2012)
37. Mazmanian, M., Orlikowski, W.J., Yates, J.: The autonomy paradox: the implications of mobile email devices for knowledge professionals. Organ. Sci. **24**(5), 1337–1357 (2013)
38. Mankins, M.C.: Is technology really helping us get more done? Harvard Bus. Rev. (2016), https://hbr.org/2016/02/is-technology-really-helping-us-get-more-done?utm_campaign=HBR&utm_source=facebook&utm_medium=social. Last accessed 21 Mar. 2018
39. Hasan, A., Elmualim, A., Rameezdeen, R., Baroudi, B., Marshall, A.: An exploratory study on the impact of mobile ICT on productivity in construction projects. Built Environ. Project Asset Manage. **8**(3), 320–332 (2018)
40. Vitak, J., Crouse, J., LaRose, R.: Personal internet use at work: understanding cyberslacking. Comput. Hum. Behav. **27**(5), 1751–1759 (2011)
41. Restubog, S.L.D., Garcia, P.R.J.M., Toledano, L.S., Amarnani, R.K., Tolentino, L.R., Tang, R.L.: Yielding to (cyber)-temptation: exploring the buffering role of self-control in the relationship between organizational justice and cyberloafing behavior in the workplace. J. Res. Pers. **45** (2), 247–251 (2011)
42. Attalla, S.M.: Health hazards of mobile information communication technologies. In: Abdel-Wahab, A.G., El-Masry, A.A.A. (eds.) Mobile Information Communication Technologies Adoption in Developing Countries: Effects and Implications, pp. 237–251. IGI Global, PA, USA (2011)

35 Augmented Reality Combined with Location-Based Management System to Improve the Construction Process, Quality Control and Information Flow

Julia Ratajczak, Alice Schweigkofler, Michael Riedl, and Dominik T. Matt

Abstract

Efficient construction management is highly depending on respective persons in charge and their ability to steer the inherently complex flow of information. Communication among stakeholders is crucial to improve construction process management, which is usually managed by means of paper-based documents in most of construction sites. To improve on-time delivery of projects and automate construction management, the mobile application—AR4Construction was developed. It integrates technologies such as BIM and AR with Location-based Management System. This application aims to improve productivity, collaboration between project participants as well to provide tailored information to the user. This paper describes concept, framework and functionalities of the AR4C application as well as testing and validation phase.

Keywords

BIM • BIM metadata • Augmented reality • Location-based management system • Digital construction

35.1 Introduction

The construction industry (CI) is a project-based industry characterized by heterogeneity, extreme complexity, fragmented supply chain and variability of trade performance. It is widely recognized that the CI is one of the less efficient sectors, if compared to other industries like manufacturing. It was found that only 16% of construction projects are brought to the conclusion on time, within the budget, meeting all required quality standards [1]. In UK, 60% of construction project organizations struggle with time and cost overruns on more than 10% of their projects [2] This is due to inefficient and inaccurate monitoring and control processes [3]. According to [4], in the US, 10% of project cost is spent in one rework. The waste in construction is between 25 and 50% of construction cost and it is due to inefficient interaction between trades and control of labor and materials. Cost and time losses are caused by omitted errors in the design phase, which are detected afterwards on the construction site.

The CI is struggling with difficulties in sharing information between project participants, which is one of the most common causes of poor performance [5]. Since efficiency and productivity of construction processes depend mostly on the accurate and timely information availability on site [6], an efficient management of the information flow as well as improved communication are crucial to enhance construction processes. Along with the development of technology like Building Information Modeling (BIM), Augmented Reality (AR), Virtual Reality (VR) and Internet of Things (e.g. RFID, NFC), new

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hardware and software tools have been introduced to the construction industry. These tools allow the automation of construction processes and have potential for improving monitoring of construction works and management of information flow as well as for reducing construction errors.

35.2 Background

Information on construction sites is mostly exchanged by means of traditional methods such as phone, email and fax. However, these solutions have not solved communication problems so far, because information systems are still not integrated and characterized by a lack of interoperability [7]. In major construction sites, information is still managed by means of paper-based processes, which create some difficulties in keeping track of information and up to date [8]. Construction managers use also inadequate tools to visualize and represent the information [9]. This leads often to misunderstanding between stakeholders, construction errors and low ability to make rapid and right decisions. Construction managers are not able to focus on important task, because they spend 30–50% of their time to collect and analyze site data due to the manual methods for monitoring and controlling of construction works [10]. If successful progress monitoring is applied, it is possible to reduce execution schedule deviations up to 15% [11], project cost up to 10% [12] as well as cost of reworks, claims and disputes [13].

Recently, the adoption of computing and communication technologies in the CI has had a significant impact on both productivity and economic growth of construction companies. BIM is one of these technologies, which allows the automation of several processes during the construction phase and has shown the potential to control construction project effectively. On the market, there are available commercial software based on BIM technology like Autodesk BIM 360 Field, Dalux, BIManywhere, etc., which can be deployed on mobile devices like tablet, smartphone.

Another promising technology is AR, which has undergone an important transformation towards more use-friendly solutions for mobile devices. This technology has potential to improve scheduling process. It is possible to show as-planned and as-built project and visualize the construction progress [14]. Ref. [15] found out that AR can facilitate the understanding of project documentation, construction progress through 3D visualization of models on site. AR is also useful to improve communication between experts and investors [15]. Ref. [16] proposed a solution for markerless mobile-based AR using HoloLens to assist inspection and progress monitoring for interior activities by displaying 3D as-planned BIM model and detecting differences with actual construction. Ref. [17] developed the ACCEPT system for construction management, which uses smart glasses and smartphone to display digital model and information in AR, which are overlaid onto real construction environment. Also commercial software for construction management are integrating AR technology. Autodesk Field 360 is working with DAQRI to display tailor content and documents using smart helmet. In last year Dalux released TwinBIM application, which allows user to see and interact with 3D model in AR using a smartphone. Sublime provides a prototype of AR solution using HoloLens or DAQRI to monitor and visualize construction process and to guide workers through the installation process. BIM and AR technology increase automation of controlling processes on site as well as improve decision-making process and provide real-time access to information. Nevertheless, to achieve more efficient construction process, BIM-based tools combined with AR and Lean Construction (LC) methods are required. The application of LC methods such as Location-Based Management System (LBMS) with BIM technology can improve construction processes. LC methods are promising to reduce, if not completely eliminate, non-value-adding works. LBMS was able to achieve a duration compression of 10% using schedule optimization [18]. Ref. [19] evaluated that LBMS is able to increase production rate on average 37% and prevent production problems by 50%. Several researchers have attempted to integrate LBMS into construction management systems such as VisiLean [20] and KanBIM [21] to improve construction processes and scheduling reliability. Nevertheless, most of software for LC management are not available on mobile devices and are not compatible with AR technology.

35.3 Proposed Solution

The main goal of the AR4C project is to investigate how AR combined with BIM and LBSM can enhance the management of information flow, monitoring of the construction process as well as communication among project participants on the construction site. Research activities on the AR4C application are based on the European project—ACCEPT (www.accept-project.com) and they are currently carried out by Fraunhofer Italia and Free University of Bozen-Bolzano within the Ph.D. Programme “SET”.

This paper describes concept and functionalities of the AR application for the construction site. It is still under development and the preliminary testing within a group of experts was conducted and described. Further testing in real conditions (construction sites) and calculation of impacts on the construction process, quality and information flow are planned and they are shortly mentioned in this paper.

35.3.1 Concept of the AR4Construction Application

The AR4C application is addressed mainly to site managers and workers and it is envisioned to provide them with context-aware information at anytime and anywhere on the construction site. Information delivered to the user is as follows: (a) 3D BIM model overlaid onto real world objects; (b) component/material technical data; (c) assigned construction tasks in a specific location; (d) assembly instructions; (e) quality checklist to verify performed work; (f) construction process KPIs for each location on site. The AR4C is developed for the Android smartphone Lenovo Phab 2 Pro. Initially, different devices were considered like smart glasses (e.g. HoloLens), but finally smartphone was chosen, since it is low cost device, it does not disturb the user mobility and safety on site and the interaction with the device is more familiar, if compared to other head-mounted devices. Another advantage of the Lenovo smartphone is the integration of the Google Project Tango technology like motion tracking, area learning, and depth perception. These technologies give the ability to understand the device position relative to the world around it with high precision and accuracy.

35.3.2 AR4Construction: System Architecture

To create the AR4C prototype, Unity was chosen as the main development environment. The application is composed of several components (Fig. 35.1) like: (a) **3D model Management**; (b) **Data Management**; and (c) **GUI Management**. It is necessary to import external assets to component (a) and (b) like 3D BIM model (.fbx file) and its metadata via .xml file, respectively. Component (c) allows the visualization of 3D model in AR and related information within the Graphical User Interface (GUI). External APIs are integrated with Unity: (a) **Tango SDK**, which provides different features to gather information on the device position and orientation and to interact with it; (b) **Firebase SDK**, which stores digital assets like images, video, checklist, drawings, messages and allows the AR4C application to access them whenever needed. It acts as digital data repository of the application.

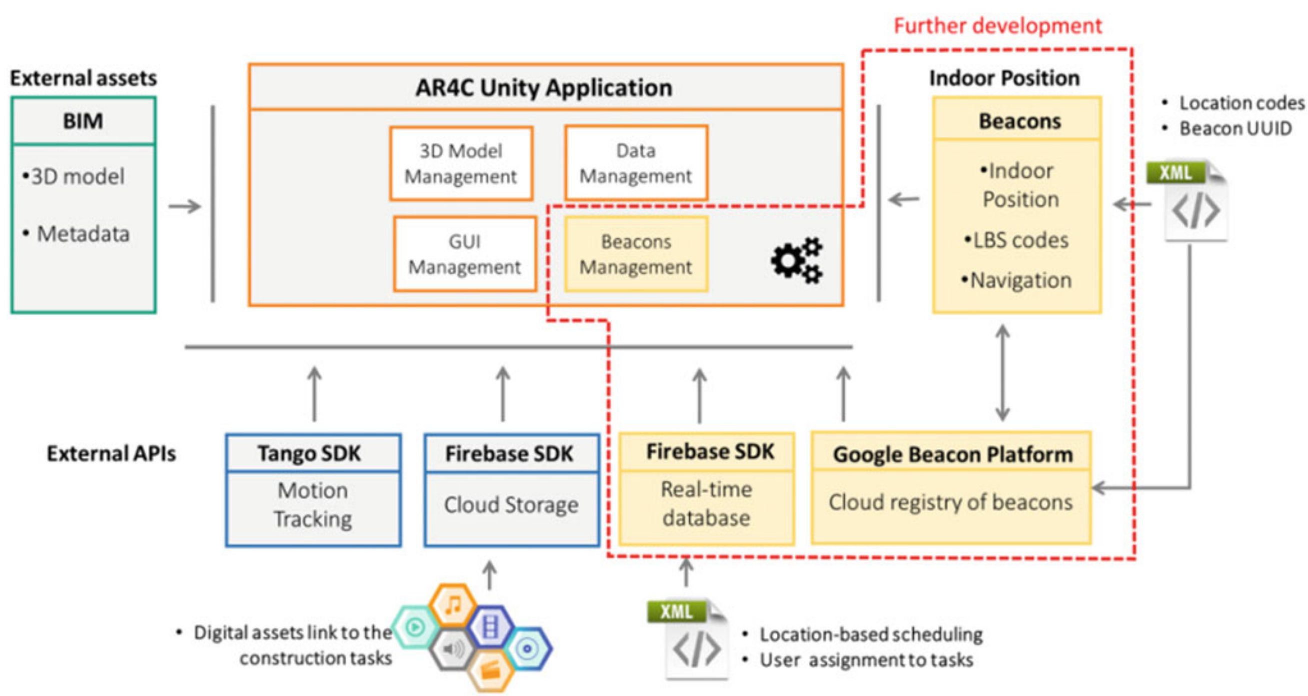

Fig. 35.1 AR4C system architecture

Components related to locations of the construction project and to task assignment according to LBMS will be implemented in further developments of the AR4C. The identification of construction locations will be done by means of beacons. It will be done by placing them in predefined construction locations with correlated location codes. In addition, a scheduling database linked to location codes will be required.

35.3.3 Integration of BIM and Scheduling Data in AR4C

To enable the integration of LBMS in AR4C application, it is necessary to link construction tasks to building components and materials in a BIM model in a specific location defined in the construction project. Such connection allows a graphical representation of where construction works should be executed and how they are progressing. While a worker is walking though the construction site with the AR4C application, he should see in AR assigned tasks to him on the 3D model aligned with the surroundings. When he clicks on a task, related components/materials are highlighted on the model and information on installation process is displayed (Fig. 35.2). Digital assets linked to construction tasks are stored in Firebase service.

To link BIM components with respective tasks in the specific location, the system of WBS code (WBS – Work breakdown Structure) and LBS code (Location Breakdown Structure) was developed. It assumes that the master schedule of the construction project is prepared considering these codes. The same codes are also inserted in related components/materials in the BIM model. The combination of both codes provides a unique nomenclature for each task, so-called WBS/LBS code, which is used to identify the specific task in the specific location. In BIM software, 3D geometry data and respective metadata with codes are exported via .xml file and imported to Unity. Afterwards, data can be managed by the AR4C application. Since Google Project Tango technology can recognize only physical location defined by position and orientation, it will be necessary to make AR4C application identify locations defined by LBS codes. It will be done be means of beacons placed at the construction site. This part is currently under development. It is planned that the AR4C application will allow site manager to monitor construction process KPIs (progress, productivity and performance) in different locations. KPIs will be visualized by means of widgets, graphs displayed within the location on the 3D BIM model. The measured KPIs related to assigned tasks will be as follows: (a) current activity progress [%]; (b) PPC [%], (c) Performance Ability

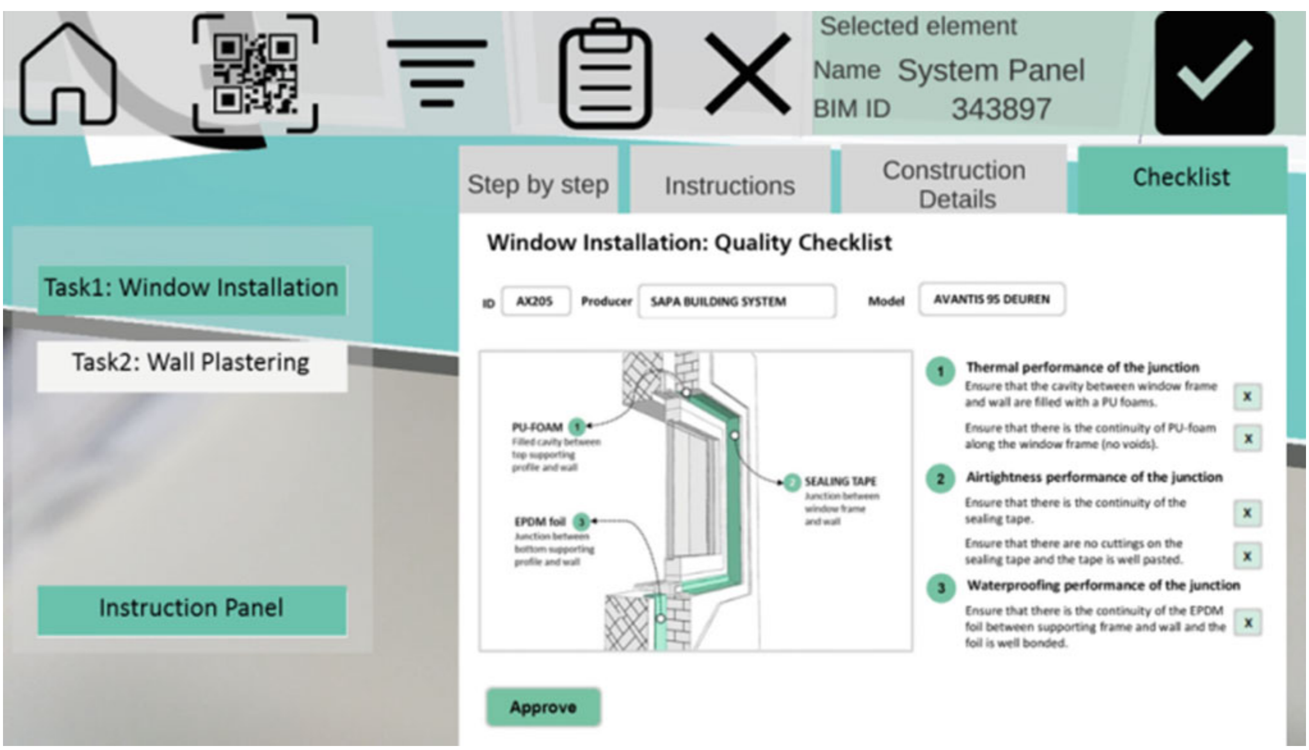

Fig. 35.2 Visualization of tasks and related information

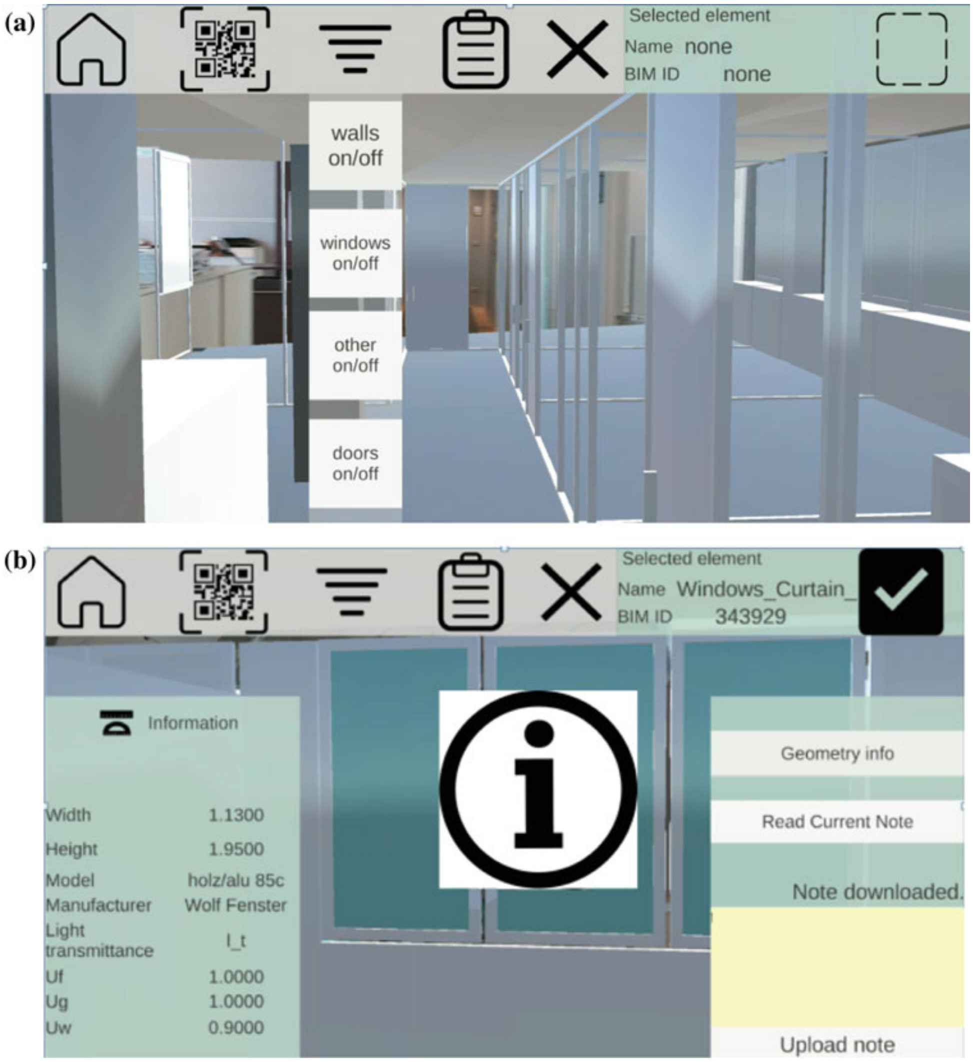

Fig. 35.3 AR4C: **a** 3D model in AR; **b** Information displayed for selected components

Ratio—PAR [-]; (d) Reason for non-completion—RNC; (e) cumulative delay [days]. Values of these KPIs are calculated based on input data collected by the Construction progress checklist (Sect. 3.4, point 3).

35.3.4 AR4C Functionalities

The AR4C application is under continues development. So far, the following functionalities have been implemented:

1. **Display and explore 3D model based on the user position**. The user can start displaying 3D model in AR by launching the application in the same physical position as it was defined in the virtual model. Afterwards, the user can move around. The model remains aligned with the surroundings, since the application is using motion tracking technology. The user can interact with the 3D model by clicking on objects and switching on/off group of components, therefore see only objects of interest (Fig. 35.3a).
2. **Touch objects to access quickly information on building components.** When the user touches an object on the 3D model, it is highlighted in green. By doing so, the user can access general information about the geometry as well as physical and technical data of the selected component. This information is displayed only if it has been embedded in the BIM model beforehand (Fig. 35.3b).

3. **Display the scheduled tasks and related information**. Based on the user position on the construction site, the worker can see a list of tasks that have been scheduled for him on a weekly basis. By clicking on the task, the information panel appears. It provides the following types of information: (Fig. 35.2): (a) **Step by step** tab, which shows steps that should be followed by a worker in order to perform a work according to the rule of the trades; (b) **Instructions** tab, which shows a document with installation procedures that can be scrolled down; (c) **Construction Details** tab, which contains construction drawings and details; (d) **Checklist** tab, which contains a quality checklist that should be filled out by a worker at the end of the task.
   In further development, there will be integrated also Construction progress checklist tab, which will be used to report the construction progress at the end of the day. The worker will provide input data regarding the percentage of completed work with respect to the established daily goal of assigned tasks. This input data will be used for calculations of construction process KPIs displayed for the specific locations to enhance the project controlling and inspections done by site manager directly on site.
4. **Create and read virtual notes attached to building components**. The user can use this functionality to attached comments, report issues related to the specific building component. Firstly, the component has to be selected on the 3D model and afterwards the massage window appears. The user can write down a massage and upload it to Firebase. It remains available and can be displayed any time, once the component is selected.

35.3.5 Testing and Validation

The AR4C application was tested in two buildings in the area of approximately 200 m^2, focusing mainly on the calibration of the 3D model alignment with the real building. The motion tracking technology used by the application allows the tracking of the user position without using GPS signal. However, its precision was not always accurate. The testing consisted in the definition of the starting point (x, y, z) for the application in the real world (Fig. 35.4a). The same position was applied to Tango camera in Unity. Theoretically, it allows the perfect alignment of both real and virtual worlds. However, some differences were noticed between real position of the user and the position computed by the device. Such difference was variable and approximately varied between 0,4 and 1 meters. After testing the following assumption were stated. The lack of perfect alignment is caused by: (a) incorrect setting of the Field of View (FOV) of the device's camera and the FOV of the Tango camera; (b) problems with the perfect positioning of the device at the starting point. The initial error related to the starting point propagates further computation errors of the device position. Another alignment error was occurring, when the

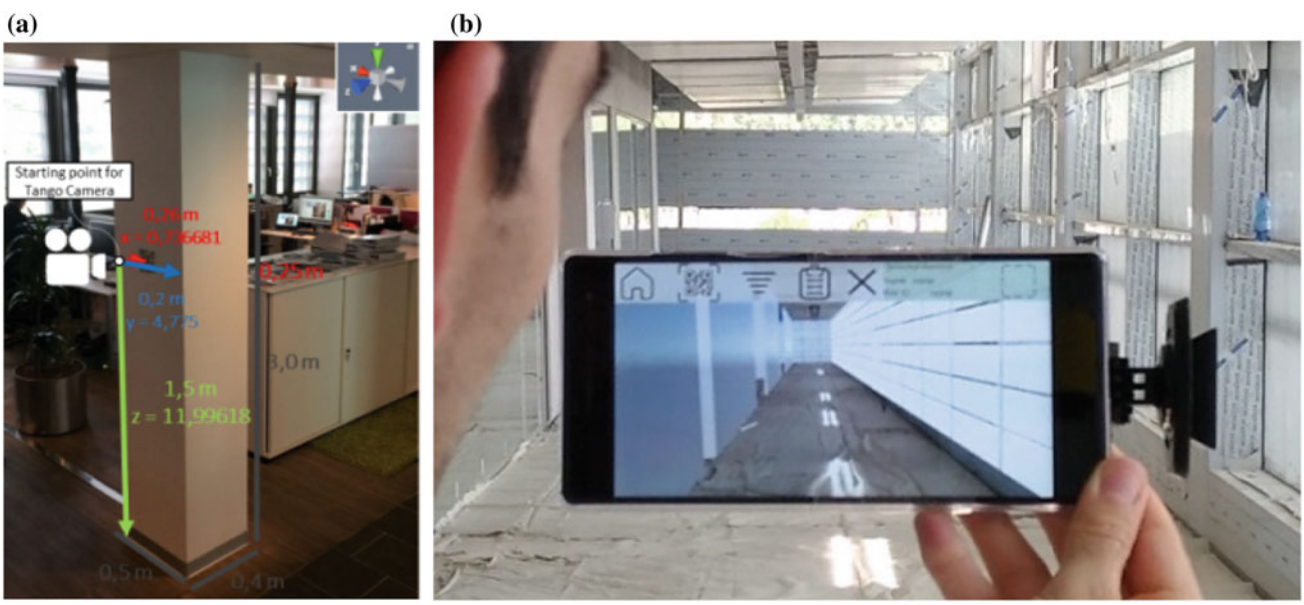

Fig. 35.4 Application testing: **a** definition of the starting point for AR4C; **b** alignment of the virtual model with the real building in the construction environment

user was reaching the surface of virtual objects. In this situation, the model visualization was blocked and the computation of the device position was affected, resulting in model misalignment. In further application development, all these issues will be investigated and adjusted.

The second part of testing was focused on the user acceptance. The application was tested within a group of 14 experts form the construction sector, who were asked to use the AR4C and fulfill afterwards a questionnaire. The questionnaire contained 25 questions related to functionalities, usability, utility of the information on the construction site that AR4C provides and graphical user interface. According to respondents, all functionalities met defined functional and non-functional requirements. All respondents ranked their interaction with the system as clear and intuitive. Organization of displayed information was considered good, nevertheless several feedback on the GUI improvement were reported. Almost all respondents considered that it is very likely that the information provided by the AR4C prototype will allow a faster access to relevant information on site and will improve the productivity of the construction process, if the monitoring of construction works will be implemented. Half respondents answered that it is likely that through the use of AR4C, an improvement in the overall communication between stakeholders involved in a construction project and error reduction can be achieved. As further development, it is planned to conduct testing in construction site to evaluate the qualitative and quantitative impact of this application on the construction process and building quality. Beyond the user acceptance the further tasting will focus on measuring: (a) KPIs related to the construction progress and performance calculated from input data provided by workers using AR4C; (b) number of avoided errors due to installation instruction and visualization of the 3D model overlaid onto the real world. All these data will be used to estimate cost savings generated by improved processes, quality and information flow. To provide realistic data and estimations, the application and its functionalities will be tested on the construction site of the polish general contractor—Budimex S.A. A specific use case will be selected (e.g. office building) and several construction tasks will be monitored in different locations. Workers and site managers will be also asked to test the application to evaluate its usability. The special focus will be put on the construction process monitoring according to LBMS and the integration of KPIs that can support effectively the management of construction works.

35.4 Conclusion

This paper describes concept and functionalities of the mobile AR application for the construction site, so-called AR4C, which runs on the Android smartphone—Lenovo Phab 2 Pro. It provides users with context-aware information related to the construction project like 3D model, technical features of building components and materials, list of construction tasks, installation procedures as well as quality and construction progress checklists. The application integrates Lean Construction methods like Location-based Management System (LBMS) in order to support the efficient management of construction works on site. Tasks displayed in AR are linked to the specific location of the construction project, to BIM elements. To link BIM components with respective tasks in a specific location, the system of WBS code (WBS—Work breakdown Structure) and LBS code (Location Breakdown Structure) was developed. Moreover, the AR4C application allows users to create virtual post 'its, which can be attached to the virtual model and read any time by different users. The preliminary functional testing and validation were carried out in two buildings. It was found that even though Lenovo smartphone uses the computer vision technology, some important differences were found in alignment of the virtual model with the real building. The application was tested also by a group of specialists, who provided a good feedback regarding the usability and utility of the application. They agreed that the AR4C application should improve communication by providing a faster access to relevant information on site. It is also likely that it will improve building quality by avoiding construction error and the productivity of the construction process, when the monitoring of construction works will be implemented. The qualitative and quantitative impact of this application on the construction process, quality and information flow will be tested on real construction site carried out by the general contractor—Budimex S.A. in Poland.

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References

1. Frame, J.D.: Establishing project risk assessment teams. In: Kahkonen, K., Artto, K.A. (eds.) Managing Risks in Projects. E & FN Spon, London (1997)
2. Olawale, Y., Sun, M.: Cost and time control of construction projects: inhibiting factors and mitigating measures in practice. Constr. Manage. Econ. **28**(5), 509–526 (2010)
3. Memon, A.H., Rahman, I.A., Aziz, A.A.A.: The cause factors of large project's cost overrun: a survey in the southern part of peninsular Malaysia. Int. J. Real Estate Stud. **7**(2) (2012)
4. Forbes, L.H., Ahmed, S.M.: Modern Construction: Lean Project Delivery and Integrated Practices. CRC Press Taylor & Francis Group, Boca Raton (2011)
5. Dainty, A., Moore, D., Murray, M.: Communication in Construction. Taylor & Francis, New York (2006)
6. Dave, B., Boddy, S.C., Koskela, L.J.: Improving information flow within the production management system with web services. In: Proceedings of the 18th Annual Conference of the International Group for Lean Construction, Haifa, Israel, pp. 445–455, 14–16 July 2010
7. Dave, B., Kubler, S., Främling K., Koskela, L.: Addressing information flow in lean production management and control in construction. In: Proceedings of the 22nd Annual Conference of the International Group for Lean Construction. IGLC, 2 International Group for Lean Construction, Oslo, Norway, pp. 581–592 (2014)
8. Hyunjoo, K., Kyle, A., Sanghyun, L., Hildreth, J.: Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. Autom. Constr. **35**, 285–295 (2013)
9. Lee, S., Pena-Mora, F.: Visualization of Construction Progress Monitoring. In: Joint International Conference on Computing and Decision Making in Civil and Building Engineering, pp. 2527–2533 (2006)
10. McCulloch, B.: Automating field data collection in construction organizations. In: Construction Congress V: Managing Engineered Construction in Expanding Global Markets, pp. 957–963 (1997)
11. IBC: Industry Benchmarking Consortium: Project Control Best Practice Study by IPA—Independent Project Analysis (2000)
12. IBC: Industry Benchmarking Consortium: Cost Engineering Committee (CEC) (1999)
13. Yates, J.K., Epstein, A.: Avoiding and minimizing construction delay claim disputes in relational contracting. Yeomans S (2005). "ICT enabled collaborative working methodologies in construction", EngD thesis, Loughborough University, UK (2006)
14. Zollmann, S., Hoppe, C., Kluckner, S., Poglitsch, C., Bischof, H., Reitmayr, G.: Augmented reality for construction site monitoring and documentation. Proc. IEEE **102**(2), 137–154 (2014)
15. Meža, S., Turk, Ž., Dolenc, M.: Measuring the potential of augmented reality in civil engineering. Adv. Eng. Softw. **90**, 1–10 (2015)
16. Kopsida, M., Brilakis, I.: BIM Registration Methods for Mobile Augmented Reality-Based Inspection. In: Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016), Limassol, Cyprus, 7–9 Sept. 2016
17. Ratajczak, J. et al.: Digital Tools for the construction site. A case study: ACCEPT project. In: LC32017: Volume I—Proceedings of the Joint Conference on Computing in Construction (JC3), Heraklion, Greece, pp. 981–988 (2017)
18. Seppänen, O.: Empirical research on the success of production control in building construction projects. (Doctoral thesis), Department of Structural Engineering and Building Technology, Faculty of Engineering and Architecture, Helsinki University of Technology, Espoo, Finland (2009)
19. Seppänen, O., Evinger, J., Mouflard, C.: Effects of the location-based management system on production rates and productivity. Constr. Manage. Econ. **32**(6), 608–624 (2014)
20. Dave, B.A.: Developing a construction management system based on lean construction and building information modelling (Doctoral dissertation, University of Salford) (2013)
21. Sacks, R., Radosavljevic, M., Barak, R.: Requirements for building information modeling based lean production management systems for construction. Autom. Constr. **19**, 641–655 (2010)

36 Workflow in Virtual Reality Tool Development for AEC Industry

Lucky Agung Pratama and Carrie Sturts Dossick

Abstract

The relatively low cost and intuitive user interface of modern virtual reality devices offer many possibilities for it to be adopted in various industry. One characteristic that is offered by virtual reality is its ability to enhance user's perception by making the user immersed in the virtual world. As such, the system has a potential to be used in the Architecture, Engineering, and Construction (AEC) industry, especially during the design and pre-construction phase. Some AEC firms, including architects and general contractors, had implemented this technology into their projects. However, there is little known on how the firms integrated the technology. Previous researches have been studying the impact of this technology but did not analyze the workflow of its implementation. Therefore, the novelty of this study is in the analysis of the workflow. Semi-structured interviews were conducted on AEC firm to develop the workflow and identify several challenges in VR integration into project. The study found that most AEC firms utilize VR technology mostly for building walkthrough. There are several software solutions that were used to build the walkthrough. Depending on the complexity and time constraints, the AEC firms utilize either a one-click solution or develop the walk-through in-house. The study found that latest software solutions allow for quick deployment of VR for visualization purpose. However, AEC firms still must develop their own solution for some other purposes such as model annotation and multi-user environment.

Keywords

Virtual reality • Workflow • Organization

36.1 Introduction

The relatively lower cost and intuitive user interface of virtual reality offers many possibilities for it to be adopted in various industry. One characteristic that makes virtual reality promising is its ability to immerse the user in the virtual environment. As such, the system has a potential to be used in the AEC industry, especially during the design phase.

Several AEC firms, not limited to just architects but also general contractors, have begun incorporating virtual reality system in their projects. The firms use the technology as an alternative to physical mockups that takes time to build. Some benefits offered by the use of virtual reality are the "environment fidelity" and the "interface fidelity" that closely resemble those that are encountered in real-life [4]. With the help of the technology, architects are able to visualize and immerse themselves in their designs and achieve much clearer understanding of both qualitative and quantitative nature of the space they are designing [2].

The creation of virtual reality content has been made easier with the releases of tools that offer one-click solution. Despite offering the benefit of accelerating the project, these tools are specialized and has little customizability. Therefore, certain companies develop their own workflow of developing their own VR environment with interactions that are required to support the project.

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Different studies had outlined a workflow of VR assets conversion for AEC firms and presented challenges associated with the conversion based on a case study. However, the organizational structure of the development team was not outlined. By investigating the organizational structure, it is expected the general practice of VR development by AEC firms could be identified.

36.2 Background

36.2.1 Organizational Structure in Developing Virtual Reality Content

Since virtual reality is some form of interactive content, it would be best to draw its similarities to interactive entertainment industry before going further into VR development for AEC industry. Interactive content development requires a multitude of specialties. The number of individuals involved in a project varies depending on the scope of the project they are working, aside from the size of the company. In a typical development, there are several roles involved in a project [6]. The first role is the designer who decides which direction the application is going to take. This responsibility also covers the decision on what software to use and what interaction is required to achieve the desired result.

The second role which takes a large work responsibility during the development. To the programmers, the product is seen as line of codes which they have to create. They develop many aspects such as graphics, interaction, network, or physics through coding language. The coding language used by the programmer would be determined by their own language specialties and the language the software primary uses. The programmer could build the product from the ground up, which would take a significant amount of development time, or use a specific software which could significantly reduce the workload of the programmer.

The third role is the artist which designs the visual aspects of the application. This role is assigned to design objects, environment, interface, and visual presentation. In designing these aspects, the artist can use several approaches such as hand drawing, sculpting, or digital drawing. Artists also model the assets to be used in the interaction.

36.2.2 Asset Creation and Optimization in Virtual Reality

Unlike pre-rendered 3D design practice commonly found in design firm practices, virtual reality is identical with real-time representation of model in 3D. Real-time representation in 3D means that the viewer is given a certain degree of freedom to interact with the 3D environment, usually in the form of movement. This requires the computer to rapidly update the displayed image to give a sense that the user is moving. The rapidly updated images are measured in frame per second. Interactive 3D simulation would require between 30-60 fps to be an enjoyable experience.

This standard applies to virtual reality, whereas most virtual reality headsets available on the market today could render a maximum of 90 fps, with each display on each eye rendering the image sequence in 45fps.

Because of the higher resource demand for rendering in virtual reality, developers must develop their own optimization methods. Some of these methods are already implemented for real-time rendering application, especially in the development of videogames. The process of optimization allows artists or modeler to create a good 3D model without impacting much of the performance.

The 3D artists, the people who work in the game industry, must have both a good sense of aesthetics and understanding of how the tool used to develop the real-time simulation works. These knowledges are mandatory because they allow the artists to make a good use of the limitation of the hardware.

Polycount used to be the main driver that determines the graphical load of a real-time 3D rendering. It is the number of polygon that defines an object in 3D and often associated with the amount detail on the object. Developers used to keep the numbers as low as possible to maintain the real-time rendering's performance. The low detail was hidden by applying details on the model's textures. However, as the rendering technology advances, additional factors are beginning to surface such as post-processing effects and shaders. Nowadays, it has grown the point where developers think it is faster to add more polygon instead of applying additional texture maps.

Polycount optimization is about reducing the amount of polygon of an object. Because the amount of polygon determines how the shape would look like. Therefore, when it comes to the polycount optimization it is important to maintain the shape and general looks of the geometries while reducing the polycount. Applying additional details to texture maps can also be considered because it reduces the polycount. However, this process would require additional development time.

Graphical Processing Units, from herein referenced as GPUs, are capable of rendering polygons at a fast rate. However, it needs to receive a data that instruct it to draw those polygons from the relatively slower CPU. The data that contains those instructions is called draw calls. Whenever a new mesh or material needs to be rendered, the CPU will issue a draw call.

Optimization of the draw call for real-time rendering is very important, especially when the rendering will be used to represent a virtual reality environment. The optimization can be done by geometry instancing or combining meshes into a single mesh.

In optimization, model or mesh reusability is important because it can be created multiple times with minimum impact on the resources' memory. This method is also known instancing. The key here is to maintain the balance between reused meshes and non-reused meshes. When designing an environment, it is not preferable to build it from a big, combined meshes because it reduces the reusability. Likewise, having too many small meshes to be placed individually on the scene is not preferable either because it would inflate the development time [7].

A research conducted at Sodertorn University attempted to observe the performance difference between a scene that implemented optimization strategies and another scene that did not implement any optimization. In the study, the researchers created two scenes in Unreal Development Kit.

The first scene in the study didn't use models with reduced polygons. Instead of using texture mapping technique, the researchers modeled the detail using polygons. This resulted in many of the models in the scene to be high-poly models. Meanwhile, most of the models used different instanced materials instead of reusing the materials.

On the other hand, the second scene was an optimized version of the first scene. The models used in this scene were low-poly models and used more normal mapping technique to give the impression of high detail. The low-poly models were the result of polycount optimization based on the high-poly models in the first scene. Geometries that were obscured from player's view were deleted, this process is called culling. Additionally, materials on the scene were instanced from two master materials and had lower resolutions than the materials in the first scene.

From the results, the study found that the optimization strategies used in the second scene were able to increase the performance from 6.1 fps to 10.21 fps. The researchers were also managed to reduce the memory usage by 42.9%. These results indicated that optimization of 3D models could positively impact the performance, especially in improving the framerates and reducing the memory usage.

In general, the performance aspect of real-time 3D simulation is important. Developers of real-time visualization experience would take different approach by limiting the amount polygon displayed on-screen. Other optimization approaches are also taken such as simplifying the textures and lighting. In virtual reality development, the performance aspect is more important because a person's perception is more sensitive in virtual reality environment. A variability in performance would cause discomfort for the user.

36.2.3 Assets Optimization for Virtual Reality

Unlike the videogame industry, architectural and structural models used in construction projects are designed using CAD tools specifically developed for the AEC industry. Pre-rendered models are more preferred because the design will be printed on paper. However, with the adoption of BIM, the industry is seeing more applications of real-time rendering in tools such as Revit.

Realtime visualization in Revit is relatively different than realtime visualization in VR. In Revit, the users are not concerned with framerate because the tool is used for design and the model's photorealism is not the focus. Meanwhile, in VR environment, the performance becomes important the users because low performance would have side effects on the users themselves. For instance, a virtual reality environment with low performance would induce motion sickness.

Therefore, when creating a visualization of a building design in virtual reality the optimization process becomes important again. With the amount of works that the optimization take, there should be a solution to automate the process. Researchers at Chalmers University of Technology from Sweden developed a Revit plugin for viewing the geometries through virtual reality headsets [5]. The developers utilized effective culling methods in which the software only renders object that are within visibility range. The plug-ins were capable of extracting 3D geometry data through Revit C# API into Oculus Rift HMD.

The developers optimized memory usage through geometry instancing. Basically, it is an optimization method where identical components share the same geometrical representation. Through this method, the memory usage for duplicate instances of an identical object can be minimized. The challenge that developers faced during the development of this plug-in was the difference of language used by Revit API and the Oculus API. Revit uses C# language while Oculus uses C++ language. The developers had to connect the different software components through a C++/CLI bridge. The developers also faced difficulties of displaying Revit's material in the plug-in's visualization prior to the 2014 update of the Revit's API. Fortunately, subsequent update addressed that, and the developers could extract material and texture's data directly from Revit.

Based on the practice done by previous studies, conversion process from BIM/IFC model to videogame engine follows the following pattern

1. Assuring the compatibility of the BIM model with videogame engine.
2. Generating meshes based on the information received from the original model.
3. Realigning the UV mapping.

Additional parameter associated with the original model are usually ignored. But it is possible to implement the information retrieved from parameters into the programming logic in the videogame engine. Two most popular videogame engine (Unity3D and Unreal) are capable with injecting the information through each engine's programming language. In Unity 3D, this can be achieved through the scripting component attached to the geometry. Meanwhile, in Unreal Engine, the information can be embedded in its visual scripting tool.

Optimization is important for maintaining the comfort level of the virtual reality environment. As discussed in the previous segment, there are several ways to optimize a model. Some of these optimization strategies can also be implemented for BIM model conversion:

1. Mesh Decimation
   This strategy can be done in external 3D modeling tool such as 3Ds Max or Blender as both tools have scripting capabilities that allows for polygon optimization. This method reduces the number of polygon on the mesh without significantly altering the appearance of the object. Further optimization can be done manually by the user.
2. Texture baking
   Baking the texture could have several benefits. For one, it could help reducing the number of model's polygons. Aside from reducing the polygon, it also reduces the requirement for dynamic lighting which requires heavy computational power. Baking the lighting into the texture will give the impression that the texture is "lit" by the lighting while it is just the color of the texture that was made lighter.
3. Culling
   For heavily-detailed BIM models, it is possible to gain significant performance improvement through culling. Culling is essentially an automated process that hides any meshes within a certain distance from the viewer. For BIM, there are several ways we can implement this strategy: (1) Hiding interior geometries while the viewer is outside the building model and (2) Preserving the geometry of the room the viewer is currently located at while hiding the rest of the geometry.

Based on prior studies, asset optimization is an important aspect when developing a virtual reality asset. Geometries that were extracted from BIM models often contain details that would significantly impact the real-time performance. Compared to other Virtual Reality experience development workflow, developing a VR product for AEC presents more challenges because the available assets might not be appropriate for VR visualization. Therefore, additional steps might be required to deliver a VR-ready asset. This study investigated how AEC firms minimize performance impact when using the BIM models as the virtual reality assets.

36.2.4 Related Studies

Adams et al. [1] addressed the general workflow of VR implementation for general contractors [1]. However, this research only covered one specific project within a general contractor at a time when there was a limited selection in VR systems. With the current state of VR technology, the authors felt the need to improve update a review of VR implementation by gathering more data from several firms that also implemented VR technology into their project workflow with the current array of hardware and software.

In prior research the first author documented difficulties in bringing CAD design files into virtual environment. He found that:

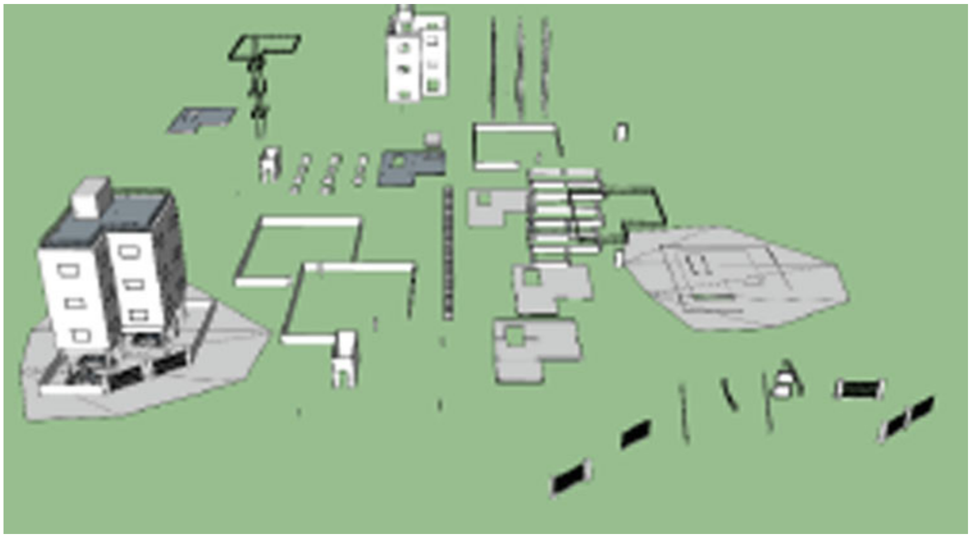

Fig. 36.1 Revit model broken down into smaller parts [9]

1. Directly converting the whole CAD model resulted in the creation of only one single building geometry in the software. For the 4D model simulation, the building model must consist of smaller geometries.
2. Materials/textures from CAD models were not converted properly. As a result, the geometries were either missing textures or displaying incomplete textures. The software used to develop the virtual reality model only recognize certain texture format.
3. Typical materials imported from CAD models were flat textures. Displaying the texture without any modification resulted in the model incorrectly showing its lighting properties.

The study attempted to convert a 3D model created in Revit to simulate a construction schedule similar to 4D models in Navisworks. Conversion of the Revit model required additional process in other modeling software such as 3DSMax, especially because the purpose of the model was not simply to represent the completed building in virtual reality. The model had to be manually subdivided into individual building components and the materials had to be remade due to the loss of information during the conversion process. In addition to modifying the models, important information that was embedded in the model such as information on Revit family of each component did not carry over into the program used to create the virtual reality model [9] (Fig. 36.1).

Rather than focusing on the impact of VR in the construction project, this study would break down how AEC firms implement and organize the team to utilize the technology.

This study aims to achieve several goals:

1. Identify how AEC firms organize a team when incorporating virtual reality technology to their projects.
2. Identify the technical aspects of optimization approach done by AEC firms to provide a good virtual reality user experience.

36.3 Research Methodology

To identify the workflow, the author decided to approach the study using qualitative method using semi-structured interview as its primary tool for obtaining data. The interviews were conducted concurrently with literature reviews. The semi-structured interview that used open questions allowed the researcher to gather as much information as possible with a limited time. From the interviewee’s standpoint, semi-structured interviews allowed the respondents to express their own answers in their own way. However, this can be a challenge for the researcher because the response need to be analyzed thoroughly.

During this study, interviews were recorded through audio and field notes. Both approach had to be made because of the open questions. Relying solely on the field notes for open questions could be difficult and time-consuming. In this qualitative approach, records of the interviews were transcribed and coded to help with the data analysis. From these record, observations about the VR development workflow were identified. This methodology is deemed to be useful when there is little knowledge of an area, especially when the area is relatively new. All related aspects and observation would be thoroughly explored to build a new theoretical explanation of the area [3].

36.3.1 Study Population

Respondents from four AEC firms were invited to participate in this study. All participants have experience working on projects that utilizes the virtual reality technology. Participants, ranging from architects to general contractors, were interviewed either in person or through phone interview.

36.3.2 Interview Questions

The interview questions were formulated to identify elements of the virtual reality workflow: (1) organizational, (2) technical, and (3) execution.

Purpose	Interview questions
Background information and team structures	• How have you been involved in VR development? • Tell me about your background regarding VR development • When showcasing the Virtual Reality, does the company provide a dedicated infrastructure for it? If yes, could you elaborate on what kind of facility does the company provide? • For what purpose does your company use VR? • How VR has helped your company's business? • In a typical development, how many people are involved in the team? • How is the VR team structured? • Is there anyone outside of your team that provides feedback on the quality of the VR experience?
Identifying the conversion process	• In developing the VR, how do you develop the assets? Do you use an existing BIM/3D model? • What software do you usually use for model optimization? • What kind of optimization strategies do you usually incorporate when putting the assets into the tool used to develop VR? • What are your goals in doing the optimization process? • What elements from the original model do you usually keep during the optimization process? • What kind of lighting method do you use? Do you bake the lighting into the texture?
Other questions: desired output from VR, interaction, involvement of third party software or plugins	• In the final product what kind of output/feedback do you typically receive? • What kind of interaction do you typically add to the model? • What kind of external plugin or script do you typically use? • Are there other issues that you would like to discuss that we have not covered yet?

36.4 Interview Results

36.4.1 Organizational Structures in Content Development

Team Structures in AEC Firms

Based on the interview conducted with several AEC firms, it was found that AEC firms typically designate only a handful of people specifically for VR content development. All three AEC firms use models that are already built instead of developing the model from zero.

AEC firm #1, which identified itself as a general contractor, formed its own division called Immersive Technology team. This team is consisted of 2 staffs, would develop virtual reality tool for a project the company is working on. The team consists of a person with construction management background and another member with architectural background. In the team, one member would do the programming while the other would mainly be working on the assets creation and optimization.

In AEC Firm #1, The decision to use the technology is made after the team proposed it to the client. Insofar, the company has yet to receive a new request to use virtual reality because the client asked for it. If there is any, it is usually a request from the repeat client.

AEC firm #2, an architectural firm, also designates an employee to handle virtual reality projects. The employee, who has a two years' experience in VR development, would lead the VR project and collaborate with other division. The model used for the VR development is a model that is already developed and used in the design document. The employee would then proceed to add details not present in the existing model. Feedbacks would be received at the end of the development when the VR environment is demonstrated in front of the client. The feedback would be used mainly for altering the designs.

Similar to AEC firm #1, the virtual reality is only incorporated after the firm pitched the idea of using this technology the client. The firm also designate a specific space for demonstrating the technology to the client.

AEC firm #3, also an architectural firm, does not have a specific division for VR content creation. When asked about how the team is usually structured, the source said, "We have individual with VR capability that we can deploy to the team to provide whatever resources they required".

AEC firm #4, a general contractor, stated that the firm allocated funds for research and development for XR. In terms of organizational approach, the team size and structures vary by needs. Usually, the team is formed from a collaboration between integrated design engineer and project team. In certain circumstances, the team enlisted help from a VR company that specializes in AEC content creation. The firm also stressed that they do not develop apps, but instead utilizing existing resources that the company has. This company has incorporated VR/AR in various purposes, including constructability review, clash detection, estimating, and quality control.

It can be inferred from AEC firm #1 and AEC firm #2 that the VR core team consists of roles similar to the designer and programmer. Artist roles are usually taken by the people with architecture background who designed the building model and they are not part of the core team. Firm #4 is slightly different with the incorporation of design engineer in the team, but their roles are mostly similar to those in firm #1 and #2.

36.4.2 Technical Aspects

AEC Firm #1 mentioned that the team usually develop their virtual reality tool in-house using videogame engine such as Unity. The team would first determine what kind of application the virtual reality environment will be used for. After the goal has been set, the team then decides what level of interactivity needs to be incorporated:

1. Model walk-through that allows the user to navigate through the model.
2. Interface that allows user to swap between several design alternatives.
3. Networked environment that support several users in one session.

In developing the virtual model, the division would take a completed model, usually a BIM model, and begin their development by adding details to the model. The VR division of this firm is open to using third-party plugins or script because of the time-saving factor.

AEC Firm #2 has similar workflow in general, except the person working on the VR initially used Unreal Engine because of its visual scripting system. The VR division of this firm develop the script in-house and seems reluctant to use third-party plugins. When asked on the reason, the respondent replied that by developing their own script, it gave them opportunity to improve their understanding on the engine. An example of script that the team developed is a spline tool system that can be used to place fences or railings.

Unlike the others, AEC firm #3 would rather use already available VR plugin or application. The respondent also addressed the VR contents as outputs rather than tools. According to the firm, it would save the company a lot of development time compared to using videogame engine such as Unity because there are already software and plugins that fulfill what the company needs for a VR application. The firm argued that even if the company would develop a specific tool in-house, they prefer to collaborate with a video game developer rather than spending development time on in-house tools.

The company also prefers using mobile/phone-based VR because it is more practical to use, especially during meeting with clients.

Since AEC firm #4 have their own research and development budget allocated for VR and AR development, they prefer the product that they developed in-house. The company also did not limit their approach to one kind of software suite, although for in-house developed content they prefer to use video game engine as their primary VR development tool. The firm also used custom-made scripts and plugins to work on features that are not available yet.

From the interview this far, it can be concluded that there are two general models of workflow based on the tool used:

1. Develop the virtual reality content in-house.
2. Use existing software to produce a ready-to-use virtual reality content.

36.4.3 Optimization Approach Taken by AEC Firms

AEC Firm #1 mentioned that the team would take 3D models from the architectural rendering to be optimized. At the beginning of the workflow, the team would decimate the mesh by reducing the number of polygons in Rhino. Interestingly, the team would add more details to the model because they perceive 3D models, especially those extracted from BIM, do not contain enough details or even missing details. The extracted model usually looks like primitive objects and does not look good when put in a virtual environment. Optimization was also done through grouping the geometries into categories. The categorization allows the team to rapidly modify the model should any design changes occur during the review.

AEC Firm #2 uses similar approach, including mesh decimation, lighting and shadow baking. The respondent also mentioned a type of geometry instancing method developed by their own team. Additionally, additional technique such as culling was used in some projects.

AEC Firm #3 does not do much optimization because the process had already been taken care of by the third-party plugins or tools they are using.

AEC Firm #4 does optimization to achieve smooth VR/AR integration and gamification of certain tasks, which are primarily focused for illustrating how the completed construction would feel and operate once it is completed. In achieving the goals, the team relies on displaying the highly detailed objects and visual effects within the operator's field of view. Whenever the object is out of range of view, the system would show either a low-detailed model or completely hide it to save system resources.

AEC firms #1, 2, and 4 all approached the optimization process similarly. They also mentioned a specific commercial software that could automate the optimization. Using the tool, the project team can generate several models of a same object but with different Levels of Detail (LOD). It should be noted that the term LOD used in the optimization process is the term that is used in real-time graphics application, in which the model's detail is determined by how much polygon is used to build the model. Despite being able to cut the majority of the optimization process, it could increase the cost of the project since the model that is generated by the tool can only be accessed as long as the user is subscribed to the service.

36.4.4 Challenges in Assets Conversion

In a study conducted by NYU researchers to identify challenges in Building Information models into virtual worlds, it is found that geometry models tend to lose all of its attributes during the process. At the end of the conversion, all data that is left is the geometry [8].

AEC Firm #1 and AEC Firm #2 stated that they find difficulties particularly in texture conversion for the process. BIM models extracted from Revit do not contain enough texture detail to be presented in VR environment. As a result, the team must develop new textures before assigning those textures as material for the geometries.

Additionally, none of the firms retrieves semantic data from the BIM. Semantic data could contain attributes for the geometries such as weight, material, room information, and cost. Should the project need any attributes from the semantic data be included, the team had to inject the information manually by referencing the original BIM.

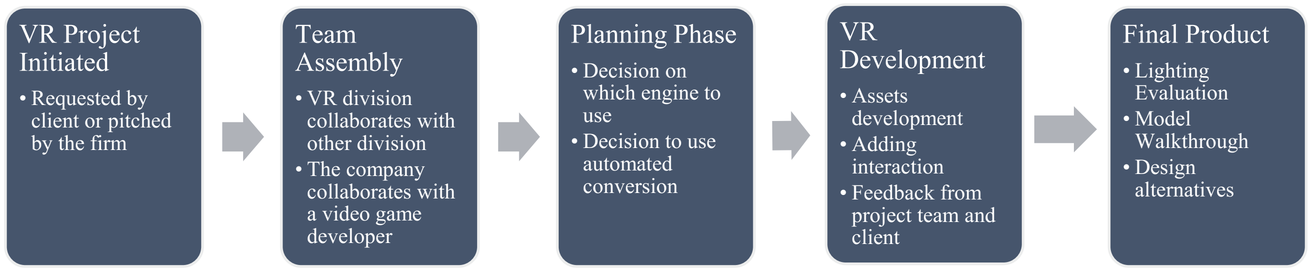

Fig. 36.2 VR development workflow

36.5 The Workflow

From the interviews, it can be summarized that the general VR development workflow is initiated when the project receives a request to use virtual reality technology. Afterwards, the VR development team/individual will be assigned to the project. The virtual reality environment would be developed either in-house or using a commercial software. At then the product is showcased to the client. During this process, the client would generally provide feedback on the design, not the virtual reality experience itself (Fig. 36.2).

From the assets creation and optimization, there are two types of workflow based on the current practices identified from the AEC firms:

1. Manual Conversion of 3D Models into Virtual Reality Environment (Fig. 36.3)
2. Automated Conversion using Plugin and Software (Fig. 36.4).

The second workflow skipped the format conversion and model optimization in the previous workflow using a 3rd party software or plugin. This workflow also skips the optimization because they are already created during the conversion process. Because most of the conversion process lie in the optimization, this workflow type could greatly save the amount of development time. The downsides of this workflow are:

1. The tools used for conversion are not free and require the user to pay subscription fees.
2. The tools are specialized for certain development software packages. One tool even requires the user to be connected to the authorization server in order to display the optimized model.
3. Most tools can not do subdivision of the models. This type would not be efficient if the user would like to use the model for something other than model walkthrough.

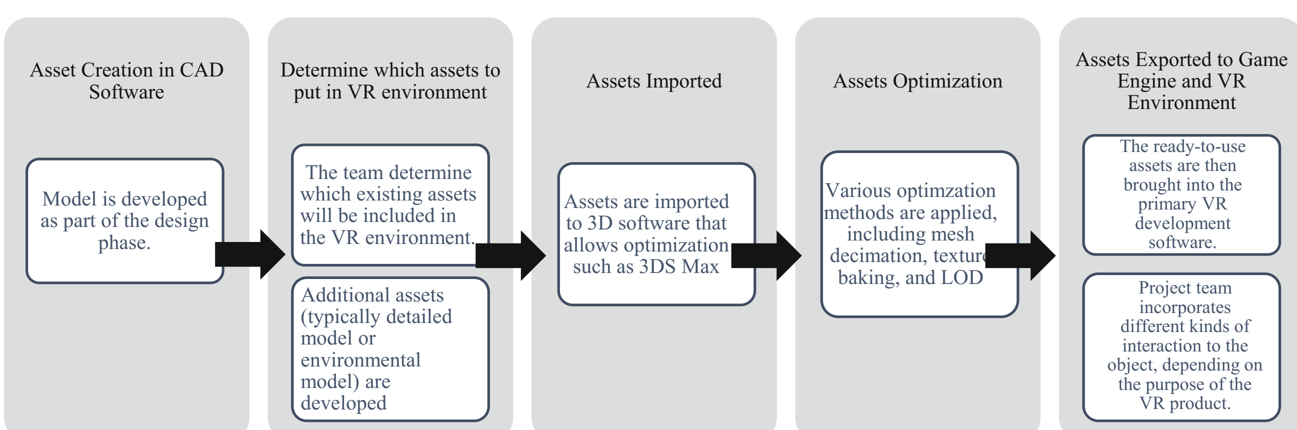

Fig. 36.3 Manual assets creation

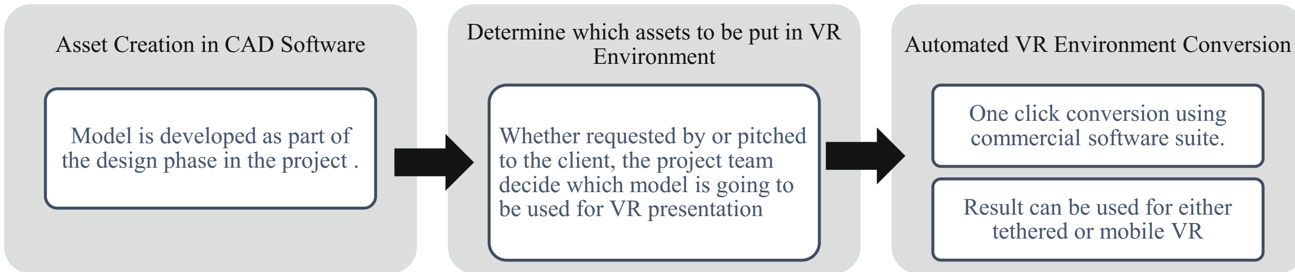

Fig. 36.4 Automated conversion

36.6 Conclusion and Suggestions

From the study, it can be concluded that:

1. Virtual reality division, if any, in AEC firms plays a relatively minor role in the whole project. The core team would consist of only one or two members who, depending on the scope of the project, would collaborate with other division.
2. The minor role and the very specific skillset required for this field which are removed from the skillset desired by many AEC firms can be a barrier to implementing VR in AEC firms. Therefore, it would be logical for the company to use a commercial software for the VR environment creation.
3. For a very specific need, the firms would rather develop the tool using video game engine. Aside from natively supporting off the shelf headsets such as HTC Vive and Oculus Rift, the development team would have more freedom in programming the interaction.
4. Mesh decimation, shadow and light baking are the most prominent approach to optimization in VR development. These approaches are common because the process can be automated in 3D modeling software.
5. In order to improve the workflow, VR should not be considered as a "novelty" but rather an integral part of the project.
6. There are commercial software suites that could greatly streamline the optimization process. However, further study about the cost/benefit ratio of the software needs to be conducted.
7. There are more potential uses of VR than simply a design visualization tool. Since currently VR software suite tailored for AEC industry is quite limited, AEC firms could use this opportunity to develop their own VR tool to leverage their company.

References

1. Adams, W. et al.: Investigating The Potential of Immersive Virtual Reality Technologies in The Operation of Mortenson Construction (2014)
2. Bouchlaghem, D., et al.: Visualisation in architecture, engineering and construction (AEC). Autom. Constr. **14**(3), 287–295 (2005)
3. Grbich, C.: Qualitative Data Analysis: An Introduction, Metzler, K. (ed.), 1st ed., SAGE Publications Ltd., London (2013)
4. Hunt, E., Waller, D., Knapp, D.: The Transfer of Spatial Knowledge in Virtual Environment Training The Transfer of Spatial Knowledge. Presence Teleoperators & Virtual Environments, (April) (1998)
5. Johansson, M., Roupe, M., Tallgren, M.V.: From BIM to VR—Integrating Immersive Visualizations in the Current Design Process. *Fusion—Proceedings of the 32nd eCAADe Conference—Volume 2 (eCAADe 2014)*, 195, pp. 261–269 (2014)
6. Liming, D., Vilorio, D.: Work for play: Careers in Video Game Development. Occup. Outlook Quart. Available at: https://www.bls.gov/careeroutlook/2011/fall/art01.pdf (2011)
7. Lohikoski, L., Ruden, E.: Optimization of 3D Game Models: A qualitative research study in Unreal Development Kit. Sodertorn University (2013)
8. Nopachinda, S., Ergan, S.: Challenges in Converting Building Information Models into Virtual Worlds for FM Operations and User Studies in the Built Environment (n.d.)
9. Pratama, L.A.: Immersive Virtual Reality Prototype for Evaluating 4D CAD Model. University of Washington (2015)

37 Implementation of Augmented Reality Throughout the Lifecycle of Construction Projects

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Abstract

Over the years, information and communication technologies (ICT) have advanced significantly to where their applications in the construction industry have improved the efficiency of projects to a large extent. To continuously thrive in the information and technology-driven industry, it is imperative for construction companies to modify their mode of operations to embrace new technology, methods, and processes to influence the performance and efficiency of construction projects positively. Augmented Reality (AR) as a new and emerging technology generates several opportunities for enhancing traditional methods through the integration of AR technologies in the architecture, engineering, construction, and operations (AECO) industry. However, AR technologies are yet to become prevalent in the AECO industry. While AR has a great potential of impacting the construction process, there has been insufficient research on the identification of specific areas for the integration of AR in all phases of construction projects. The purpose of this paper is to offer construction professionals and researchers an account of the possible implementation of AR technologies in each stage of construction projects. The study provides construction professionals the latest research trends and developments in the application of AR, thus helping in the advancement towards significant implementation in the industry for the improvement of construction processes. The paper describes work performed in different construction stages and presents the potential benefits of AR implementation. Finally, recommendations for future research are discussed.

Keywords

Augmented reality (AR) • Construction • Project lifecycle • Productivity

37.1 Introduction

Over the years, information and communication technologies (ICT) have advanced significantly to where their applications in the construction industry have improved the efficiency of projects to a large extent. The advancement of technology has sparked a revolution in the construction industry regarding the way construction and engineering related tasks are being carried out [1]. To continuously thrive in the information and technology-driven industry, it is imperative for construction companies to modify their mode of operations to embrace new technology, methods, and processes to influence the performance and efficiency of construction projects positively. Augmented Reality (AR) is an evolving technology, and over time it has attained substantial significance in research and development in the AECO industry.

The paper begins by introducing AR as a concept, its definition, as well as its different systems and enabling technologies. In totality, this study aims to discuss the reality of AR, and its objective is to offer a review of the present applications of AR technologies in all the phases of construction projects and the associated potential benefits to implementing this technology.

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The paper contributes to the level of understanding of AR, by highlighting its potentials and provides future recommendations regarding AR applications and the adoption of the technology.

37.2 Augmented Reality

37.2.1 Defining Augmented Reality

Over the years AR has been defined in different terms by several researchers. One of the most universally accepted definitions by Azuma [2] states that AR is technology that has three fundamental features:

(1) It combines both the real and the virtual contents in the real world
(2) It runs interactively in real time
(3) It is registered in three dimensions.

Primarily, AR is perceived as a medium between virtual reality and telepresence as it amplifies reality instead of substituting it [3, 4]. However, perhaps the most uncomplicated definition is that AR is the augmentation of the real world (reality) with information from the virtual world (virtuality) [1].

37.2.2 AR Systems and Enabling Technologies

AR systems combine the virtual and the real world, they are interactive in real time and synchronize three-dimensional items in the mixed reality. To combine virtual objects and real images, three central systems can be implemented to overlay virtual components on the real world environment [5–7].

1. GPS and Compass Based AR systems which use the built-in GPS and compass to determine the current position of the user and aligns the virtual objects accordingly. This system is mostly applicable for use on mobile phones and hand-held devices.
2. Marker Based AR systems utilize tracking methods for detecting fiducial markers that act as a fixed point of reference for the position or scale of the virtual object to be recognized in augmented view.
3. Marker-Less AR systems depend on the physical features of the real world to accomplish object tracking, which eliminates the need for fiducial markers.

The main hardware components required for performing AR applications and their functions include processing devices, displays, tracking and calibration systems [7, 8].

1. The processing device which is primarily a computer is used for creating virtual objects and accurately aligning them and the position of the user with the real environment. It is also used to run all other devices in the AR system.
2. Displays for observing the merged virtual and real environments can be classified into three categories; (a) head-mounted displays (HMD), which are mounted on the head of users, (b) hand-held displays (HHD), which acts as a window that shows the real objects with an AR overlay, such as a tablet or cell phone, and (c) spatial displays (SD), which project the desired virtual information directly on the physical objects to be augmented.
3. Tracking systems are required to log and verify the position and orientation of the user in the real environment, to ensure accurate alignment and registration of the virtual image to the physical object.

37.3 Review Methodology

To effectively present the applications of AR technologies in all the phases of construction projects and the associated potential benefits, as well as the challenges to implementing this technology, a content analysis-based review method was completed. Through this method, several publications were reviewed, from which outcomes were rationalized and integrated into this paper.

The content analysis-based review method was conducted in two phases to accomplish a focused and organized review in literature from the period 2008 to 2018. Phase 1 involved a comprehensive search of literature using the Google Scholar search engine. Numerous keywords such as AR, mixed reality, construction, lifecycle, and so on were included in the search with the aim of including a wide range of related disciplines. After completing phase 1, 215 related articles were identified from the journals listed below:

- Advances in Computer Science
- Advances in Engineering Software
- Automation in Construction
- IEEE Computer Graphics and Applications
- International Journal of Advanced Research in Computer Science
- International Journal of Architectural Computing
- International Journal of Virtual Reality
- Journal of Computing in Civil Engineering
- Journal of Construction Engineering and Management
- Journal of Information Technology in Construction
- Presence: Teleoperators and Virtual Environments
- Visualization in Engineering.

Phase 2 involved the process of screening out publications that were not relevant to this research through a brief review of the content of the articles. After the screening process, a total of 79 publications were selected for additional examination. Although this two-phase search does not provide a full representation of the publications deserving evaluation, it sufficiently provides a substantial amount of significant research, from which this study could infer conclusions and recommend areas for future research.

37.4 Augmented Reality Applications in the Project Lifecycle

Research on the applications for AR ranges across several fields of study, including the construction industry. Applications of this technology in the (AECO) industry spans over the entire lifecycle of construction projects, and they include as-planned to as-built progress monitoring, training, dynamic site visualization, construction defect detection and integrating with various building information modeling (BIM) workflows [9]. For the purposes of this paper, the lifecycle of a construction project is comprised of the conceptual planning, design and preconstruction, construction, operation and maintenance, and demolition phases [10–12].

37.4.1 AR and Conceptual Planning

A construction project usually begins with a conceptual idea visualized by the owner and its possibility of fruition is determined by the success of the conceptual planning phase. During this phase, a feasibility study is conducted to determine the projects needs and objectives. To conduct such a study as accurately as possible within an all-encompassing scope, all project stakeholders need to thoroughly understand the inherent limitations that affect the scope of the project. By overlaying a three-dimensional space with the conceptual model developed using Building Information Modeling (BIM) technology at full-scale, the project team can easily understand the parameters of the space so that they can speedily decide how to proceed with the project [13].

The application of AR technology in the conceptual planning phase can be applied to all sizes and complexities of projects, but most especially large-scale complex projects which require that the project need and objectives be communicated to a large number of people [14, 15]. Also, by integrating AR with other technologies like laser scanning and GIS technology, the project team can obtain more accurate and detailed information about the project, such as volume and location [13]. The accuracy of information in conceptual planning is essential as the detailed design drawings, cost estimating, scheduling, and cost control will emanate from the scope defined in this phase.

37.4.2 AR and Design and Preconstruction

During the design and preconstruction phase, project owners, important stakeholders and project team members need to be continually apprised on the status of the project, per the rate of recurrence and means of communication agreed on in the contract. One of the key factors to be considered when communicating ideas at the design stage is the ability of the project team to visualize the different components of the project as shown in the architects and engineers design. AR allows users to have the ability to view a proposed three-dimensional model in the actual environment [13]. Using data from BIM, the system can combine the three-dimensional architectural layout of a building with the GPS data of a specified location on the site. With the aid of enabling technologies, such as head-mounted displays (HMD) and mobile devices, an individual can visualize a three-dimensional concept of where components need to go relative to their current location on the site [15].

One of the emergent trends of AR technologies are platforms that enable a walkthrough of virtual buildings, as early on as the design phase through to construction completion [14]. With mobile augmented reality (MAR), the actual scale of the three-dimensional model can be conveyed in its proposed final location, which gives all project stakeholders an adequate interpretation of the scale of objects. This information can help support decision-making processes that enable costs savings on fabrication and materials of the building components in reality. Also, MAR applications that scale components to size are useful in clash detection and coordination, to discover any conflicts between the proposed design models and real-world elements [14].

37.4.3 AR and Construction

The construction phase is the implementation phase, where the plan for the construction project is set into motion, and the project tasks are performed practically on site. With construction sites being very dynamic, it requires mobility of the users, and technologies that provide access to information at any time and any place needed to be implemented, thereby warranting the use of mobile devices [5]. AR is a wide-ranging technology that provides mobile computing solutions that provide constant access to information and situate it in time, place and context to accommodate the constant change that occurs on construction sites [16].

One of the notable applications of AR during the construction phase is that it provides a visual aid to supervise the construction process and also to inspect the finished product [17, 18]. Also, coordination is one of the keys to a successful project. AR can be used for facilitating construction discussion through multiscreen environment [3] and for producing construction simulations that provide a visual representation of the current conditions of the project [17, 19]. AR offers visual aids for interpreting drawings and specifications and for communication on construction projects [17]. AR can be used for visualizing BIM on site, conceiving conflict detection during coordination and visualizing the construction sequence on site to improve the efficiency of site logistics [20, 21].

Other applications of AR during the construction phase include geo-locating BIM data on the construction site, task support for construction processes [20, 21], real-time field reporting [14], way-finding and site navigation [14], on-site building information retrieval by using projection-based augmented reality [22], construction safety [23], and construction site monitoring and documentation [24].

37.4.4 AR and Operation and Maintenance

During the operation and maintenance phase, the maintenance professionals need to grasp a significant amount of relevant information to promptly locate a maintenance point in a building. AR systems can enable maintenance workers to evade concealed features such as hidden infrastructure, electrical wiring, and structural elements as they complete maintenance tasks on buildings and outdoor environments [25].

AR can be used for locating and replacing building elements for maintenance purposes [20]. A combination of BIM and MAR devices can be used to provide virtual data and information about actual building components and systems to facility managers on their mobile devices [26]. AR can also be used to train professionals to complete complex repair and maintenance tasks on building systems [14].

37.5 Benefits of AR Implementation

The use of AR with a combination of other supporting technology, computer software, and hardware offers several intangible, qualitative and quantitative benefits that improve construction, engineering, and other related tasks. One of the factors that result in a successful construction project is completion on-time and within or even under budget. To effectively measure the benefits of AR implementation throughout the lifecycle of construction projects, it is important to categorize the potential benefits of AR under quantitative units such as schedule and cost savings [27]. Table 37.1 shows the potential benefits of AR and their quantitative units.

37.6 Challenges to AR Implementation

Regardless of the appeal of AR to researchers and industry professionals, AR technology is advancing, and it is not flawless. Some drawbacks need to be overcome before AR can be fully integrated into daily construction activities, as it gains widespread acceptance in the industry. A few of the challenges that need to be addressed include portability and suitability for outdoor use [32, 33], tracking and auto-calibration in an unprepared environment [1, 32, 33], accurate depth perception [33], overload of information [33], lack of support staff and available resources that aid ease of use [32], absence of integration standards that support integration [34], and social acceptance [32, 33].

37.7 Conclusions

Owing to the significant advancement of information and communication technologies, the application of AR technologies in construction to improve the efficiency of projects to a large extent is feasible. AR technologies have shown the potential to enhance productivity, improve coordination and collaboration, as well as the quality of work and safety of workers in every phase of the construction lifecycle. The paper reviews the present applications of AR in the all the phases of construction projects. However, despite the relevance of the technology described by researchers, it has not attained its maximum abilities in the construction industry.

This study aims to contribute to the level of understanding of AR by highlighting the application of areas of the technology throughout the construction lifecycle and illustrating that AR is a valuable investment for industry professionals. Nevertheless, the potential of every AR technology needs to be carefully considered before they can be efficiently integrated into the construction industry. The issue is not a question of whether AR is useful in enhancing construction-related tasks. Instead, the challenge is understanding how to implement this technology to exploit its full potentials competently.

Table 37.1 Benefits of AR implementation

Reduced complexity [5]	Time savings
Improved efficiency [5, 19, 28, 29]	
Improved decision-making [5, 28, 29]	
Reduction in the quantity of paper [21, 28, 29]	Cost savings
Improved quality by reducing rework and defects [30]	
Delivery of project on-time and on-budget [31]	
Reduced physical and mental workload for employees [19]	
Enhanced safety [5, 29]	

37.8 Recommendations for Future Study

This study reviews literature to document present applications of AR in the all the phases of construction projects. However, there were insufficient studies showing applications of AR during the deconstruction phase of the project lifecycle. Further study in this area could explore possible applications of AR in building deconstruction and material disposal. Possible future directions in this study could involve the development of an AR technology integration plan tailored to the construction industry.

Finally, there is a need to verify the quantitative and qualitative benefits and value of implementing AR technology in the construction industry, throughout the lifecycle of construction projects, through a controlled and structured evaluation process. With the data collected from closely monitoring the use of AR through-out the lifecycle of these projects, an accurate monetary value of the investment and operation costs of AR, as well as the dollar value of time and money savings amassed from implementing AR can be projected. The cost of capital and savings can then be used to establish the return of investment on AR.

References

1. Cleveland Jr., A.B.: Emerging tools to enable construction engineering. J. Constr. Eng. Manage. **137**(10), 836–842 (2010)
2. Azuma, R.T.: A survey of augmented reality. Presence: Teleoperators Virtual Environ. **6**(4), 355–385 (1997)
3. Lin, T.H., Liu, C.H., Tsai, M.H., Kang, S.C.: Using augmented reality in a multiscreen environment for construction discussion. J. Comput. Civil Eng. **29**(6), 04014088 (2014)
4. Milgram, P., Takemura, H., Utsumi, A., Kishino, F.: Augmented reality: a class of displays on the reality-virtuality continuum. In: Photonics for Industrial Applications. International Society for Optics and Photonics, pp. 282–292 (1995)
5. Izkara, J.L., Pérez, J., Basogain, X., Borro, D.: Mobile augmented reality, an advanced tool for the construction sector. In Proceedings of the 24th W78 Conference, Maribor, Slovenia, pp. 190–202 (2007)
6. Vyas, D.A., Bhatt, D.N.: Augmented reality (AR) applications: a survey on current trends, challenges, & future scope. Int. J. Adv. Res. Comput. Sci. **8**(5), 2724–2730 (2017)
7. Dini, G., Dalle Mura, M.: Application of augmented reality techniques in through-life engineering services. Procedia CIRP **38**, 14–23 (2015)
8. Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B.: Recent advances in augmented reality. Comput. Graph. Appl. IEEE **21**(6), 34–47 (2001)
9. Rankohi, S., Waugh, L.: Review and analysis of augmented reality literature for construction industry. Vis. Eng. **1**(1), 9 (2013)
10. Azhar, S.: Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. Leadersh. Manage. Eng. **11**(3), 241–252 (2011)
11. Azhar, S., Khalfan, M., Maqsood, T.: Building information modelling (BIM): now and beyond. Constr. Econ. Build. **12**(4), 15–28 (2015)
12. Eadie, R., Browne, M., Odeyinka, H., McKeown, C., McNiff, S.: BIM implementation throughout the UK construction project lifecycle: an analysis. Autom. Constr. **36**, 145–151 (2013)
13. Ren, J., Liu, Y., Ruan, Z.: Architecture in an Age of Augmented Reality: Applications and Practices for Mobile Intelligence BIM-based AR in the Entire Lifecycle. DEStech Transactions on Computer Science and Engineering, (ICEITI) (2016)
14. Abboud, R.: Architecture in an Age of Augmented Reality: Opportunities and Obstacles for Mobile AR in Design, Construction, and Post-Completion (2014)
15. Broschart, D., Zeile, P., Streich, B.: Augmented reality as a communication tool in urban design processes. Proceedings REAL CORP, pp. 119–126 (2013)
16. Meža, S., Turk, Ž., Dolenc, M.: Measuring the potential of augmented reality in civil engineering. Adv. Eng. Softw. **90**, 1–10 (2015)
17. Dunston, P.S.: Evaluation of augmented reality in steel column inspection. Autom. Constr. **18**(2), 118–129 (2009)
18. Feiner, S.K., Webster, A.C., Krueger III, T.E., MacIntyre, B., Keller, E.J.: Architectural anatomy. Presence: Teleoperators Virtual Environ. **4** (3), 318–325 (1995)
19. Wang, X., Dunston, P.S.: User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. Autom. Constr. **17**(4), 399–412 (2008)
20. Danker, F., Jones, O.: Combining augmented reality and building information modelling—an industry perspective on applications and future directions. Educ. Res. Comput. Aided Architectural Des. Eur. **32**, 525–536 (2014)
21. Golparvar-Fard, M., Savarese, S., Peña-Mora, F.: Interactive Visual Construction Progress Monitoring with D4 AR—4D Augmented Reality—Models. In: Construction Research Congress 2009: Building a Sustainable Future, pp. 41–50 (2009)
22. Yeh, K.C., Tsai, M.H., Kang, S.C.: On-site building information retrieval by using projection-based augmented reality. J. Comput. Civil Eng. **26**(3), 342–355 (2012)
23. Li, X., Yi, W., Chi, H.L., Wang, X., Chan, A.P.: A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom. Constr. **86**, 150–162 (2018)
24. Zollmann, S., Hoppe, C., Kluckner, S., Poglitsch, C., Bischof, H., Reitmayr, G.: Augmented reality for construction site monitoring and documentation. Proc. IEEE **102**(2), 137–154 (2014)
25. Gheisari M., Irizarry J.: Investigating human and technological requirements for successful implementation of a BIM-based mobile augmented reality environment in facility management practices. Facilities **34**(1/2) (2016)

26. Gheisari, M., Goodman, S., Schmidt, J., Williams, G., Irizarry, J.: Exploring BIM and mobile augmented reality use in facilities management. In: Proceedings of the Construction Research Congress, pp. 1941–1950 (2014)
27. Oesterreich, T., Teuteberg, F.: Evaluating augmented reality applications in construction–a cost-benefit assessment framework based on VoFI. In: Proceedings of the Twenty-Fifth European Conference on Information Systems (ECIS), Guimarães, Portugal, pp. 342–358 (2017)
28. Kamat, V.R., Martinez, J.C., Fischer, M., Golparvar-Fard, M., Peña-Mora, F., Savarese, S.: Research in visualization techniques for field construction. J. Constr. Eng. Manage. **137**(10), 853–862 (2010)
29. Wang, X., Love, P.E., Kim, M.J., Park, C.S., Sing, C.P., Hou, L.: A conceptual framework for integrating building information modeling with augmented reality. Autom. Constr. **34**, 37–44 (2013)
30. Forcada, N., Gangolells, M., Casals, M., Macarulla, M.: Factors affecting rework costs in construction. J. Constr. Eng. Manage. **143**(8), 04017032 (2017)
31. Wang, X.: Augmented reality in architecture and design: potentials and challenges for application. Int. J. Architectural Comput. **7**(2), 309–326 (2009)
32. Mekni, M., Lemieux, A.: Augmented reality: applications, challenges and future trends. In: Applied Computational Science—Proceedings of the 13th International Conference on Applied Computer and Applied Computational Science (ACACOS '14) Kuala Lumpur, Malaysia, pp. 23–25 (2014)
33. Van Krevelen, D.W.F., Poelman, R.: A survey of augmented reality technologies, applications and limitations. Int. J. Virtual Reality **9**(2), 1 (2010)
34. Sanna, A., Manuri, F.: A survey on applications of augmented reality. Adv. Comput. Sci.: Int. J. **5**(1), 18–27 (2016)

38 Challenges Around Integrating Collaborative Immersive Technologies into a Large Infrastructure Engineering Project

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Abstract

Collaborative virtual reality (VR), such as room-based or CAVE-type systems, has demonstrated benefits in engaging teams in the shared design exploration. Though much research explores how virtual reality may be affecting and contributing to the quality of the team discussion for making design decisions, evidence of how this technology becomes used and adopted in practical settings remains limited. Studies from other engineering and manufacture domains consistently report on practical, behavioral and organizational challenges and more often, resistance to introducing innovative technologies and processes. This study examines how technology adopters experience virtual reality, and explores the factors determining the extent of its implementation as an innovative practice. Drawing on the concept of technological frames, we examine how collaborative VR may introduce a non-trivial process change in an organization before it can potentially become an everyday practice. A large portable VR display system was set up in the central office of a large infrastructure project over a period of one year. During the latter half of a second study we did not observe the extensive uptake and use that we and the technology sponsors within the project anticipated. To understand the reasons, we use three technological frames that allows us to examine the technology adoption and organizational change: (i) nature of technology, to understand users' view of the technology; (ii) technology strategy, to understand users' role-based views of the motivations and incentives for technology adoption within an organization, and (iii) technology in use, to understand how intended users view the technology use on a daily basis.

Keywords

Virtual reality • Technology frames • Project-based organization

38.1 Introduction

Virtual reality (VR) has been around for several decades, but recently has gained traction as a technology for visualizing building and infrastructure design bringing the possibility of improved communication through shared visualization [1]. This renewed interest coincides with the noticeable rise in offer of low-cost consumer market virtual and augmented reality technologies. While single-user wearable technologies may easily find their use on construction sites, the use of large projection-based collaborative VR systems in practical settings still lags despite their benefits for collaborative decision-making [2–4]. The potential of such technologies to act as communication catalysts parallels a strand of research

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that points that communication methods, collaboration sessions, and contractors' involvement in design reviews, are critical for achieving high performance outcomes [5]. Gathering project stakeholders alone is insufficient, but engaged and informed collaborative decision-making will greatly depend on the stakeholders' ability to visualize and understand the project information. Virtual mock-ups using immersive projection displays have been shown to help project teams better understand the design and promote conversations that are valuable for problem solving [6–8].

In this paper, we look into the literature on organizational context of construction technology-related innovation practices and the relevance of the technological frames to study technology adoption. To examine how adopters experience virtual reality, we draw on a two-phase study in which we set up a large-screen portable VR display system in the central office of a large infrastructure company over a period of one year. The initial phase observations and participant surveys indicated the value of the technology to engage teams in the design discussion, further confirming that room-like VR acts as highly sociable environment conducive to collaborative design review tasks. This resulted in the company innovation team's commitment and interest to incorporate the technology on a project in a more structured manner in the subsequent 6-month research phase. However, in the second phase the technology was not utilized in the way we anticipated. To understand the contextual factors and possible reasons, we use the concept of technological frames to examine how collaborative VR as a novel technology may introduce a non-trivial process change on a megaproject before it can potentially become an everyday practice. The discussion and the presented findings directly contribute to the knowledge of how collaborative virtual reality as an example of innovative practice becomes adopted in practical settings through resolution of tension between stability and change in a specific context. More broadly, the goal is to expand an understanding on the changing practices and the technology adoption process in a project-based organizational setting.

38.1.1 Organizational Context for Innovation

Innovation in construction has been discussed through a broad range of sociological and economics approaches [9, 10] and also through application of diffusion of innovation perspectives [11, 12]. Rogers [11], outlines that innovations gradually become diffused by starting with initiation, which involves recognizing a need and identifying fitting innovation before proposing it for adoption. Decision to use a selected innovation typically comes from higher organizational members and is subsequently imposed onto lower level team members [13]. Implementation takes place when a decision-making unit (individual or an organization) puts an innovation to use and often involves overt behavioral change [11]. However, as Rogers also points out, problems in how to exactly use the innovation may surface at the implementation phase. When organizations, rather than individuals are adopters, these problems are likely to be more serious and diminish the benefits from innovations. Innovative aspects brought by technological changes are further reflected in procedural, managerial and business model changes that gave rise to the need for "change management" [14] that extends beyond simply installing the equipment and having trained people to use it [15].

To understand how such changes unfold, it is important to account for the recognized distinctiveness of the organizational context of the construction sector. Namely, the project-based nature of construction tends to result in instances of innovation taking place primarily within projects [16]. At the same time, the challenge to transcend the success of a project-based innovation perhaps resides in a stark contrast between the limited duration of a construction project and a continuing technology-mediated change processes [17].

38.1.2 Collaborative Virtual Reality in Construction Practice

Collaborative practices increasingly focus around 3D models at a realistic scale, though the scale at which the models are viewed resides within the size of the display media. This is particularly relevant for tasks that rely on adequate spatial understanding, where a viewing perspective (e.g. object-centered vs. viewer-centered) and the viewing scale (e.g. monitor vs. large screen), can affect the way users extrapolate information. Therefore, both the choice of a medium and a representation play an important role in how the information is perceived and evaluated [18, 19].

In addition to potentially simulating built environment in a visually more compelling manner, virtual reality often contains features that allow the user to dynamically navigate the virtual environment, switch between different viewpoints and viewing perspectives, access maps, markers or otherwise more meaningfully interact with the displayed information. Comparing how immersive VR, non-immersive VR or paper as a design medium supports various steps in the architectural process, experimental studies [20] suggest that large display immersive VR enable a more intuitive design review in terms of presentation and perception of space. Experiments and user tests have similarly confirmed the value of using large display collaborative VR systems in: design review and construction planning [21–23], on-site safety training [24], computational fluid dynamics [25], as well as overall effects of immersion on explorative analysis of 3D data [26]. The value of using large-display collaborative VR for design has been primarily associated with its ability to support the communication and understand users' reactions to design and their experience in virtual spaces [6, 27, 28]. Furthermore, the use of large display immersive VR for design review has been indicated to affect collaborative aspects through enabling distinct interactions among project stakeholders and enhancing the client engagement [29]. While collaborative VR presents opportunities to effectively engage a broad range of users in a shared conversation with the digital prototype, it is the adoption of single-user wearable VR that has had most uptake within the industry.

38.1.3 Technology Frames as a Theoretical Lens

Based on the previous studies, we can consider collaborative virtual reality to carry transformative potential for the design and construction practice, especially in instances such as interdisciplinary design reviews. Nevertheless, despite the initial enthusiasm around the perceived benefits and continually decreasing costs, there is relatively little uptake of such systems in the every-day practices of delivery in the sector. Studies on technology adoption that may prompt process change provide some clues to the potential reasons, such as organizational roles, their involvement in the decision making process, incentives and value misalignment among other [11, 30]. Other studies point to the interpretive nature of technologies where subjective goals result in different user groups using the same technology in different ways [4, 15].

Technology frames offer a helpful lens to understand how such technologies are interpreted among different users in the contexts specific to the introduction, adoption and subsequent implementation of technology [31] and is specifically useful for (change) managers and organization development specialists [14]. When developing their contribution to social-cognitive theory, Orlikowski and Gash [32] argued that the differences in social groups' knowledge, views and expectations of a technology (i.e. frames) can often hinder its effective implementation. To understand why different organizational groups (e.g. based on job roles or experience) may react differently to a technology-enabled change initiative, they defined three main domain frames that look into: (1) individual views of the nature of technology; (2) technology strategy and the reasons for its implementation; and (3) technology-in-use in terms of changes in work processes, incentives and culture [14]. Technology frames thus seem to be particularly relevant in the context of change management where knowing how people think and perform when using specific technologies can enable change managers to implement technology-based changes that also account for changes in organizational culture and employee skills. The point of departure in this study is to understand how collaborative VR becomes used and adopted in a project-based context, and what may be the contextual factors shaping actors' frames of reference for interacting with the VR system in a particular way.

38.2 Methods

Taking a qualitative approach, the study draws on the concept of technological frames to understand the contextual aspects around how project teams mobilize collaborative VR on a megaproject. In the first of a two-phase study, a large portable three-screen VR display system [33] (Fig. 38.1, left) was set up in the central office of a large infrastructure company in the UK over a period of three months starting October 2015. The initial set up and user testing resulted in an interest to incorporate the technology in a more structured manner in the subsequent research phase of six-month duration, starting August 2016. To address the participants' views on how the technology might better support their infrastructure engineering practice, in the second study, the three-screen, rear-projected VR has been replaced with the four-screen front-projected VR system (Fig. 38.1, right). The main adjustments to the VR technology included the provision of a projected ceiling; reduced footprint by changing the projection system from rear to front; streamlined workflows for converting the project teams' native files for VR simulation, and the relocation of the VR into a larger room which included a meeting table.

Data was collected through field notes and both formal and informal conversations with approximately 30 project engineers and managers who used the technology in both phases. Three formal interviews lasting between twenty and sixty minutes were conducted at the end of the second phase of research. The primary goal was to understand the context specific aspects and users groups' experience and interpretations of a collaborative VR in the infrastructure engineering firm distinctively based on a unique megaproject.

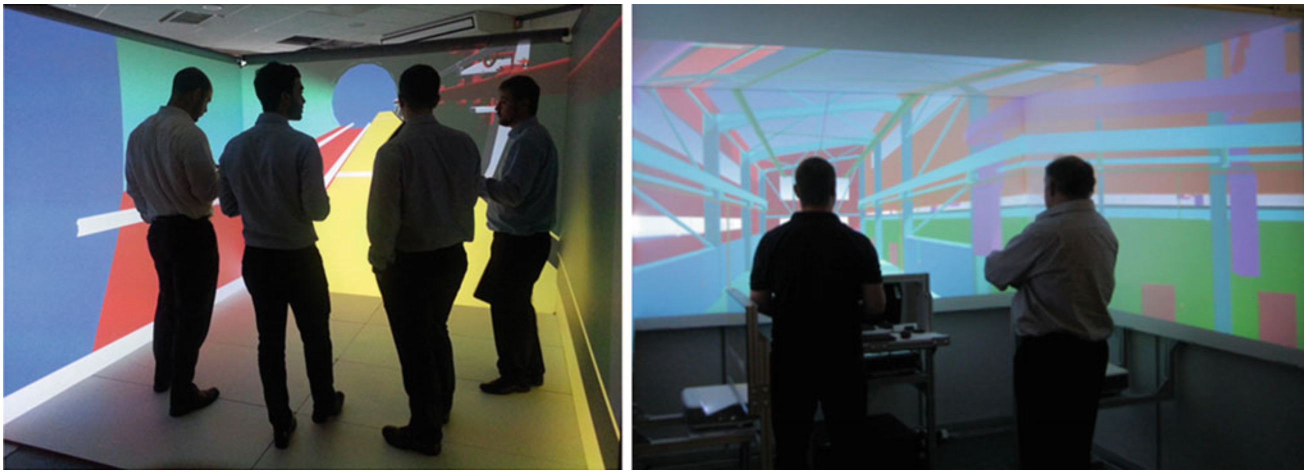

Fig. 38.1 The VR system at the company offices: phase 1 (left) and 2 (right)

38.3 Findings

The findings presented below are organized around how two dominant user groups (project team members and project managers) view the room-like VR in terms of its: (i) nature, features and capabilities; (ii) use strategy, motivations and incentives for technology adoption, and (iii) envisioned use on a daily basis.

38.3.1 Nature of Technology

Project team members and project managers shared similar views on the technology characteristics in terms of their experience with room-like VR and the potential benefits. The immersive aspect of the large screens and enhanced model experience both VR configurations offered were perceived to specifically benefit design communication and collaboration within and across project teams. At the same time, both groups of users raised specific technology-related challenges, mainly around the workflows and learning curve for preparing larger and complex models for displaying in VR (Table 38.1).

These findings point out the need for allocating appropriate resources, in the form of training, support as well as time needed for these technology-related challenges to be addressed. These challenges emphasize broader considerations that can be incorporated into an implementation strategy for novel technologies and processes.

38.3.2 Technology Strategy

Defining the value of collaborative VR resides in knowing who the target users are and what specific tasks they are envisioned to do. Room-like VR is seen as considerably-sized technology to introduce a change in daily work processes. As seen by project team members, part of the strategy is to ensure *communication* to inform, familiarize, and generate interest among potential users in a project team to gradually build knowledge around what works well for continued deployment. In

Table 38.1 Perceived benefits and challenges around the room-like VR technology

Benefits	Challenges
Projected ceiling for viewing overhead system	Handling large size models
High resolution (1080p@60 Hz)	Conversion issues—geometry and textures
Immersive experience	Revising the model on the spot, mark-up
More streamlined model development workflow	Navigation sickness
Stakeholders and client engagement	Location-access and time to travel

terms of communication, the project managers indicated that the company's process for rolling the technology out involves the Innovation team, which produces briefing notes on each innovation that are shared. As a way to increase the chances of successful deployment, additional methods for familiarizing the teams include newsletter and simple communication pieces to encourage interest. The innovation group, though acting as a driver for procuring novel technologies and practices, was however seen as insufficient to alone secure a successful diffusion and adoption of the procured technology. In practice, knowledge around how these technologies work and can be used is built within smaller teams of self-motivated individuals who end up appropriating and championing the use of this technology. The tension between what is seen as the predominantly top-down approach to implementing VR technology and the lack of bottom-up authority for its adoption is reflected in differing motivations for its use: "*[The company] wants to be seen as innovative, that's why we have the equipment here [VR], […], but they only came along from a directive, from the board, not because we needed it, not because management said we need it*."

Overall, both user groups emphasized their positive attitude towards collaborative VR as innovative technology, but framed their views around their distinct role expectations. While for some of the members "*Technology is what I have to keep up with, cause if I don't, I get fired*"; and "*I embrace technology in a way I have to do what I'm supposed to be doing. I don't like technology for technology's sake*"; the project managers' framing of the value of room-like VR highlighted a stronger emphasis on the potential benefit of the technology for the entire project: "*Why use VR? I am accountable to the project stakeholders- as PM my goal is that we don't have problems in the future. […] Design review we do anyways and look at a 3D model—only the way the model is presented [in VR] is different*."

As both user groups pointed out, the difficulty in using collaborative VR appears at the team-level due to individuals' perceived priorities of other daily tasks and hence, insufficient time or guidance on integrating the technology without much disruption: "*Ultimately, if the person on the ground just did not have time and there are no additional resources to implement, it is a struggle*". For project members and engineers, beyond those who are personally motivated, the question "*What's in it for me*?" reflects a broader attitude that the time and effort required to use VR still outweigh the positive views and appreciation of the immersive experience it offers, claiming that: "*We are here to build a railway, not to test technology*." This view appears to be grounded in the assumption that the use of (novel) technology is an appendage to the daily responsibilities for which there is no allocated time. Even when the individual members assume the role of a technology-champion on a project, once the project teams disband and the team members relocate to different projects or roles, the experience and knowledge built during the project is lost.

38.3.3 Technology in Use

For collaborative VR to become more used in interdisciplinary design reviews on a megaproject, both the project team members and managers indicated an array of logistical, resource and strategy considerations including access and location of the technology, timeframe for its implementation that would allow for necessary training, and raising awareness of the value and goals of the technology more systematically.

Both groups pointed that the location tends to be an issue for geographically dispersed teams which is typical in this case. Project managers further explained that the central offices where the collaborative VR was located are mainly populated by chief personnel and mostly used for final stage design reviews when no further iterations are expected. Subcontracted design offices also tend to hold design reviews at their locations: "*Getting all the sites that were not centrally based to come and have design reviews, getting CEG's buy-in was a struggle*."

Access to the room revealed the need to specifically address the protocols around using the space. While the room that housed VR was publicly available, access to the technology still required signing-in day ahead of the intended use and passing through security in addition to common and non-trivial time-consuming travelling logistics. Hence, finding the most appropriate location for engaging other site teams should balance the requirements and availability of such spaces with a fairly open, but monitored access, and with an adequate and dedicated technical support.

Framing of the VR use as part of daily practices highlighted the need for consistency in information requirements for conducting design reviews, as project managers noted that currently 3D models may not always be required: "*This mostly depends on the type of design reviews—single discipline design reviews are done probably with 2D drawings only, but interdisciplinary design reviews require a 3D model*." Furthermore, reviewing the model on the screen follows a different narrative from that viewed in the large scale VR, where the former tends to be more structured to look for specific problems in the model, whereas the latter allows less constrained exploration of the model and potential discovery of unanticipated issues. This revealed a seemingly persistent challenge of the reluctance around using large scale VR resulting from concerns of incomplete, inaccurate or not up to date 3D models that in turn would be perceived as increased scope or liability. However, this infers coordination challenges for maintaining an up to date and accurate model that has been checked ahead of the design review.

38.4 Discussion and Conclusions

This work contributes to research on the uptake of VR technology in practical settings using a megaproject case study context. Despite the interest and positive experience using the technology, we did not observe the extensive uptake for interdisciplinary design reviews that we and the technology sponsors within the megaproject anticipated. The three technological frames [14, 32] used to examine the technology adoption revealed a number of strategic, logistical and organizational considerations to ensure successful implementation of technologies such as collaborative VR.

The project team members' and project managers' framing of the *nature of technology* indicated shared enjoyment of the immersiveness and enhanced model experience, seen to benefit design collaboration within and across project teams. Addition of the projected ceiling in the second VR configuration was specifically perceived as useful for the ability to review overhead engineering systems. At the same time, the perceptions of added scope of work in terms of using, or learning how to use the technology need to be addressed through a conversation with the target users in defining values for introducing process-changing technologies, such as collaborative VR and adequate resources to support their deployment.

Considering the *technology strategy*, the value and motivations for using collaborative VR are framed around particular roles expectations where project managers consider the value for the project performance, while members may view it as part of their individual performance. This brings about the importance of carefully considering communication about the technology and its potential, whilst also ensuring time and training needed to use it at team levels.

The user groups' framing of the *use of technology* highlighted practicalities of accessing the facility and the incentives for finding time to use novel visualization technology. Specific concerns were raised by users around the need for sufficient contact time with the technology to enable team members to learn how to use, test and adapt the technology over time to enable combining the use of collaborative VR alongside their current practices.

This study extends current understanding on the changing practices and the collaborative VR technology adoption project-based organizational settings. The study has broader implications and recommendations for practice by revealing context specific organizational challenges in technology adoption. Despite the excitement about the collaborative VR, the contextual complexity of a megaproject, role distribution and the logistics brought about notable managerial challenges for its adoption in everyday practice. The study also suggests the potential of mobilizing the concept of technological frames through action research for revealing and monitoring change in technological frames within organizational adoption of technology innovation.

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References

1. Whyte, J., Nikolić, D.: Virtual Reality and the Built Environment. Routledge, Abingdon; New York (2018)
2. Castronovo, F., Nikolic, D., Liu, Y., Messner, J.: An evaluation of immersive virtual reality systems for design reviews. In: CONVR 2013, London (2013)
3. Pelken, P.M., Zhang, J., Chen, Y., Rice, D.J., Meng, Z., Semahegn, S., Gu, L., Henderson, H., Feng, W., Ling, F.: "Virtual Design Studio"—Part 1: interdisciplinary design processes. Build. Simul. **6**, 235–251 (2013)
4. Whyte, J.: Innovation and users: virtual reality in the construction sector. Constr. Manage. Econ. **21**, 565–572 (2003)
5. Gultekin, P., Mollaoglu-Korkmaz, S., Riley, D.R., Leicht, R.M.: Process indicators to track effectiveness of high-performance green building projects. J. Constr. Eng. Manage. **139**, A4013005 (2013)
6. Dunston, P.S., Arns, L.L., McGlothin, J.D.: Virtual reality mock-ups for healthcare facility design and a model for technology hub collaboration. J. Building Perform. Simul. **1** (2010)
7. Messner, J.: Evaluating the use of immersive display media for construction planning. In: Smith, I. (ed.) Intelligent Computing in Engineering and Architecture, pp. 484–491. Springer, Berlin (2006)
8. Whisker, V.E., Baratta, A.J., Yerrapathruni, S., Messner, J.I., Shaw, T.S., Warren, M.E., Rotthoff, E.S., Winters, J.W., Clelland, J.A., Johnson, F.T.: Using immersive virtual environments to develop and visualize construction schedules for advanced nuclear power plants. In: 2003 International Congress on Advances in Nuclear Power Plants (ICAPP)., Córdoba, Spain (2003)
9. Schweber, L.: Putting theory to work: the use of theory in construction research. Constr. Manage. Econ. **33**, 840–860 (2015)

10. Reichstein, T., Salter, A.J., Gann, D.M.: Last among equals: a comparison of innovation in construction, services and manufacturing in the UK. Constr. Manage. Econ. **23**, 631–644 (2005)
11. Rogers, E.M.: Diffusion of innovations. Simon and Schuster (2010)
12. Shibeika, A., Harty, C.: Diffusion of digital innovation in construction: a case study of a UK engineering firm. Constr. Manage. Econ. **33**, 453–466 (2015)
13. Klein, K.J., Sorra, J.S.: The challenge of innovation implementation. Acad. Manag. Rev. **21**, 1055–1080 (1996)
14. Gallivan, M.J.: Meaning to change: how diverse stakeholders interpret organizational communication about change initiatives. IEEE Trans. Prof. Commun. **44**, 243–266 (2001)
15. Orlikowski, W.J.: CASE tools as organizational change: investigating incremental and radical changes in systems development. MIS Q. **17**, 309–340 (1993)
16. Tatum, C.B.: Process of innovation in construction firms. J. Constr. Eng. Manage. **113**, 648–663 (1987)
17. Jacobsson, M., Linderoth, H.C.J.: The influence of contextual elements, actors' frames of reference, and technology on the adoption and use of ICT in construction projects: a Swedish case study. Constr. Manage. Econ. **28**, 13–23 (2010)
18. Brown, A.G.P.: Visualization as a common design language: connecting art and science. Autom. Constr. **12**, 703–713 (2003)
19. Nikolic, D.: Evaluating relative impact of virtual reality components detail and realism on spatial comprehension and presence (2007)
20. Campbell, D., Wells, A.: A critique of virtual reality in the architectural design process. HITLab, Seattle (1997)
21. Castronovo, F., Nikolic, D., Liu, Y., Messner, J.: An evaluation of immersive virtual reality systems for design reviews. In: 13th International Conference on Construction Applications of Virtual Reality, London, UK (2013)
22. Shiratuddin, M.F., Thabet, W., Bowman, D.: Evaluating the effectiveness of virtual environment displays for reviewing construction 3D models. In: CONVR 2004, Lisbon, Portugal, pp. 87–98 (2004)
23. Whisker, V.E., Baratta, A.J., Yerrapathruni, S., Messner, J.I., Shaw, T.S., Warren, M.E., Rotthoff, E.S., Winters, J.W., Clelland, J.A., Johnson, F.T.: Using immersive virtual environments to develop and visualize construction schedules for advanced nuclear power plants. In: Proceedings of ICAPP. pp. 4–7 (2003)
24. Sacks, R., Perlman, A., Barak, R.: Construction safety training using immersive virtual reality. Constr. Manage. Econ. **31**, 1005–1017 (2013)
25. Kuhlen, T.W., Hentschel, B.: Quo Vadis CAVE: does immersive visualization still matter? IEEE Comput. Graphics Appl. **34**, 14–21 (2014)
26. Laha, B., Sensharma, K., Schiffbauer, J.D., Bowman, D.A.: Effects of immersion on visual analysis of volume data. IEEE Trans. Visual Comput. Graphics **18**, 597–606 (2012)
27. Christiansson, P., Svidt, K., Sørensen, K.B., Dybro, U.: User participation in the building process. J. Inf. Technol. Constr. **16**, 309–334 (2011)
28. Nykänen, E., Porkka, J., Kotilainen, H.: Spaces meet users in virtual reality. In: Proceedings of ECPPM 2008 Conference on eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2008. pp. 363–368. CRC Press, Sophia Antipolis, France, 10–12 Sept. 2008
29. Tutt, D., Harty, C.: Journeys through the CAVE: the use of 3D immersive environments for client engagement practices in hospital design. In: Association of Researchers in Construction Management (ARCOM), Reading, UK (2013)
30. Gambatese, J.A., Hallowell, M.: Enabling and measuring innovation in the construction industry. Constr. Manage. Econ. **29**, 553–567 (2011)
31. Cornelissen, J.P., Werner, M.D.: Putting framing in perspective: a review of framing and frame analysis across the management and organizational literature. Acad. Manage. Ann. **8**, 181–235 (2014). https://doi.org/10.1080/19416520.2014.875669
32. Orlikowski, W.J., Gash, D.C.: Technological frames: making sense of information technology in organizations. ACM Trans. Inf. Syst. **12**, 174–207 (1994)
33. Parfitt, M., Whyte, J.: Developing a mobile visualization environment for construction applications. In: Proceedings of the 2014 International conference on Computing in Civil and Building Engineering. Orlando, Florida, pp. 825–832. 23–25 June 2014

Part III

Computer Support in Design and Construction

39 Cybersecurity Management Framework for a Cloud-Based BIM Model

Ivan Mutis and Anitha Paramashivam

Abstract

Today, building information models (BIM) are developed independently among participating project stakeholders, often using independent technology platforms. Integrating the information these models convey into one standalone system results in substantial challenges. It hinders the stakeholders' use of a shared and common platform, thereby restricting access to a common data environment (CDE). These problems lead to inefficiencies in managing the information exchange process among the actors throughout a project's lifecycle. Cloud computing has emerged as a new model for hosting and delivering services over the internet. This model has rapidly altered the methods by which information technology is used to meet today's demand for economically efficient, powerful, and ubiquitously available computer resources. The model promises a technology transformation across the highly interconnected business environments of the architecture, engineering, and construction (AEC) industry. Integrating Cloud computing and BIM technologies is the next generation of BIM development and will further pervade the adoption of BIM in the AEC industry, thereby incorporating new forms of collaboration amongst project stakeholders. Cloud-BIM implementation overcomes the natural limitations of standalone models in multiple ways. Benefits include reducing up-front investments in computer resources, lowering operating and maintenance costs through on-demand service allocation, enabling rapid scalability of computing, and enhancing and facilitating rapid access, to name several benefits. Cloud-BIM models enable distributed and highly intensive data transactions among project actors; however, a new way of operating and transacting, they bring with them challenges related to security management. For instance, data redundancy occurs when multiple instances of the same data exist, and it leads to problems of inconsistency (i.e., identical fields having different or multiple values) where an update is not reflected in all fields. A Cloud-BIM model provides a central access point to the project actors, safeguards data and promotes data consistency by helping to avoid redundant data and promote positive types of data redundancy. Another major challenge is the data breach that involves leaks of information not intended for public release. Data breach is the result of application vulnerabilities, human error, and/or poor security practices. The most common types of security challenges in cloud computing are addressed by this research.

Keywords

BIM • Cloud computing • Cloud-based BIM • Cloud security • BIM Cloud integration

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39.1 Introduction

Adoption of Cloud-based Building Information Modelling (BIM) in the architecture, engineering, and construction (AEC) industry results in the development of efficient collaborative workflows among the different disciplines involved in the lifecycle of a construction project. Cloud computing directly benefits BIM and is emerging in the IT sector for its efficient web-based data exchange and storage. The effective integration of cloud computing and BIM is the focus of recent research. BIM provides automation capabilities for more integrated communication, data exchange and sharing between project actors within a virtual 3D environment ([11] #118). Large amounts of data are generated during the life cycle of a construction project and are stored in the centralized, accessible repository for usage. The concept of a centralized repository is important as it forms a framework to manage the process of data generation and exchange between all project members and stakeholders ([23] #2). It is highly challenging to handle data in collaborative work environments while ensuring security, privacy, and protection against other IT risks. Privacy, risk, and Cybersecurity concerns, however, continue to impede the widespread adoption of Cloud-based BIM technology in the AEC industry. This leads to the information management implications and the need to develop appropriate governance and security policies to maintain data quality and integrity ([18] #3).

Cybersecurity encompasses people, processes and governance issues, as well as their inter-relationships ([24] #4). It is critical for all actors operating and transacting within a Cloud-BIM implementation to understand the implications of cybersecurity ([19] #8). Under Cloud-BIM, the BIM development results in a broadening view that incorporates operating and transacting between people, governance, technology, and processes. Security policies are required to facilitate efficient BIM management in a Cloud platform throughout the construction project lifecycle, where vast amounts of data must be coordinated, exchanged, and protected in real time ([17] #4). Cloud-BIM requires the use of a secured framework that comprises confidentiality to access sensitive information, integrity for data assurance, validity, authenticity, and availability of data reliance and resilience. The study presents a Cybersecurity Management Framework for a Cloud-BIM computing model based on fundamental concepts, architectural principles, and challenges for implementation. The aim is to provide to the AEC research community a framework to incorporate a Cloud-BIM model into a project and to identify critical research directions in this new computing model paradigm ([21] #7). This contribution offers valuable insights to BIM practitioners involved in the development of Cloud-BIM integration, including the identification of cybersecurity threats and the management of distributed BIM data.

This study analyzes the implications of real and perceived threats that arise in a collaborative work environment. This study will aid the appropriate selection of Cloud technologies to benefit BIM integration.

The key questions addressed by this analysis are:

- What are the possible cyber-attacks on Cloud Computing?
- How can security risks, data loss, and other data related issues in BIM and Cloud integration be prevented?

An overview of Cloud Computing, the study of BIM, security threats, data breaches, data protection and the analysis of preventive measures are discussed in the following sections.

39.2 Related Studies

39.2.1 Building Information Modelling (BIM) Outline

Building Information Modeling (BIM) is a digital visualization of the functional and physical characteristics of a facility ([2] #44). BIM transforms the way in which we design buildings and manages the information about a facility forming a reliable basis for decisions during its life-cycle. BIM facilitates the interoperability exchange of data in digital format ([10] #8). It allows any aspect of a design's performance to be simulated and assessed before it is built. The virtual model becomes a reference for better construction. BIM offers more than just geometry, traditional building plans, elevations, sections were in the form of two-dimensions (2D) technical drawings and BIM extends the drawings to three-dimensions (3D), augmenting the primary spatial dimensions (width, height, and depth) with time as a fourth dimension (4D) and cost as a fifth dimension (5D) ([20] #7). It is an intelligent project model in which information about spatial relationships, geographic information, and properties of building components are embedded and shared between stakeholders throughout the process ([7] #122).

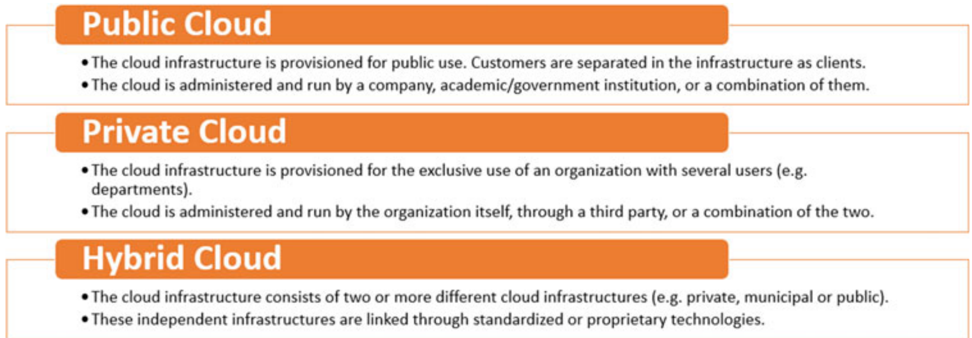

Fig. 39.1 Types of Cloud models

39.2.2 Overview of Cloud Computing

Cloud computing is a Web-based model for purchasing and provisioning IT services that include memory, storage, and complete applications. The main characteristics of Cloud computing are flexible, on-demand usage and the invoicing of IT services ([16] #6). Cloud computing delivers computing resources as services to end users by Cloud service providers (CSP). High-quality cloud services are provided by CSP to end users on request. Cloud computing is comprised of three layers: the system layer, the application layer, and the platform layer.

The system layer known as Infrastructure-as-a-service (IaaS) provides computational resources such as network devices, the infrastructure of servers, memory, and storage services as on-demand services [4]. This approach with the use of virtualization technology provides virtual machines that replace the physical equipment and eases a load of network administration as the clients are not required to monitor the health of the physical networks ([5] #30). The platform layer known as Platform-as-a-Service (PaaS) provides tools and libraries for application development where users can deploy and configure the settings ([4] #106). It provides a development platform for developers to design their specific applications, and hence developers are not required to purchase software development tools thereby reducing the cost ([9] #6). Finally, the application layer known as Software-as-a-Service (SaaS) is most commonly used by companies to reduce the cost of owning an application ([4] #106). Users can request applications from the CSP as per their requirements.

39.2.2.1 Various Types of Cloud Models

There are three different models of Cloud namely Public, Private and Hybrid. The Cloud model is selected based on the type of the data involved in the business, the level of security required, and the management desired ([12] #1). Figure 39.1 provides details about the various types of Cloud computing models.

39.3 Cloud-Based BIM Framework Development

The development of the framework is based on the analysis on security challenges involved in implementing BIM in the Cloud, directing a basic study concentrated on the following principal elements: (a) data breaches; (b) online cyber-theft; (c) cybersecurity attacks; (d) misuse of cloud computational resources. This analysis is followed by the development of the countermeasures that address the security challenges by implementing a prototype that provides a secure environment for BIM collaborators ([5] #9). The software development life cycle (SDLC) process is the underpinning methodology for the development of Cloud-based BIM platform. Model-View-Controllers (MVC) that consist of API, interfaces and governance strategies were chosen as the technical specifications for architecture development ([2] #1). Finally, the hosting Cloud environment was chosen for implementing the framework. The Amazon Web services(AWS) Cloud services was chosen as the hosting platform. The flow of the process of how the paper progresses to implement the Cloud-BIM framework is shown in is shown in Fig. 39.2.

Validation of the proposed Cybersecurity Cloud-BIM framework is through the implementation of countermeasure techniques for scenarios of possible cyber-attacks. Common cyber-attack scenarios include external and internal threat agents ([26] #1). An example of an external attack includes malicious outsiders who are not stakeholders in the construction project but who seek access to the BIM data for reconnaissance purposes. An example of internal attack is when stakeholders who are involved in the design, delivery, and operation of the project in some capacity abuse of their privilege of accessing BIM data by leaking sensitive information to the public ([23] #2). The framework also discusses research challenges in Cloud-BIM integration and the vision for this paradigm as it promises to change the use of information technology across the

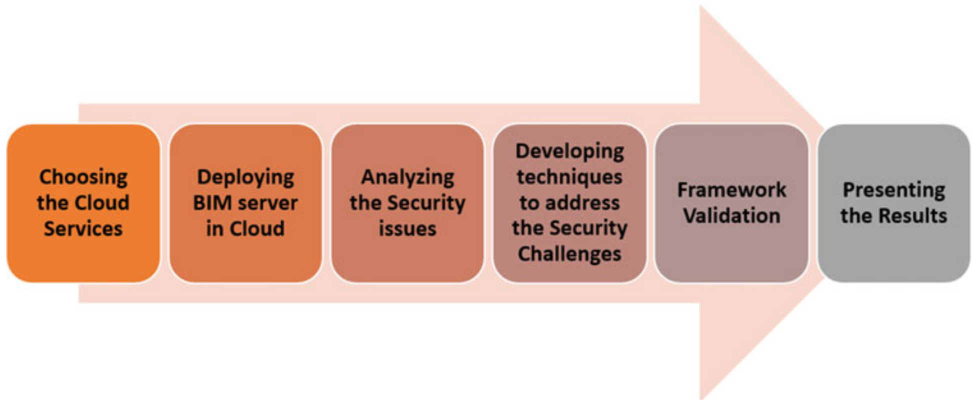

Fig. 39.2 Work flow of the framework development

construction industry ([8] #3). The following subsections discuss the analysis of the extensive study of security challenges in the Cloud environment and the countermeasure techniques that address the security challenges.

39.4 Prototype Implementation

39.4.1 Security Challenges in Cloud Computing

When using BIM in collaborative work environments, it is required to ensure information security and privacy. It is important to provide information access to the right people under the right circumstances ([5] #30). There are possibilities that collaborators may as well be competitors and have vested interests which lead to the stealing of the information. BIM, however, handles the access management in a single standalone system. It is important to maintain high access management standards in the collaborative platforms where multi-actors share common platforms ([14] #10). Lack of high standards, policies, and governance models leads to uncertainties and vulnerabilities as a result of the openness and highly decentralized nature in existence. Breaches may include loss of intellectual property, for instance, design or tendering related information ([7] #115). The BIM models have a proprietary governance approach and the governance policies must be compatible with the Cloud service provider.

The evolution of standardizations in Cloud computing is fragmented and hence it is difficult to define a unified approach that addresses the security, privacy, and governance of Cloud service providers. CSP's access management service requires advancements in privacy-reserving techniques. This includes maintaining the privacy agreements and implementing policies that suit the client's requirements. Maintaining poor standards and policies in virtualizations may lead to risks that include propensities to physical attacks, malware, viruses, and hacking ([22] #9). There also remains a general lack of understanding on the implication of data loss from BIM's perspective and the role of the CSP in data breaches. Perceptions of the increased risks are the biggest challenges in the process of integrating BIM and Cloud Technologies. As a result, project actors may be reluctant to adopt Cloud-based BIM for data sharing and exchange. In the following subsections, security threats in Cloud computing are explored from three perspectives: abuse use of Cloud computational resources, data breaches, and Cloud security attacks. The most common type of security challenges in Cloud computing is shown in Fig. 39.3.

39.4.2 Cloud-BIM Framework Architecture

The architecture of the Cloud-BIM framework is analogical to software architecture and is based on Cloud application architecture (SaaS) and Model View Controller (MVC) pattern. It consists of four main components: User Interface (UI), Cloud-BIM platform, Cloud Service Provider's infrastructure services and the countermeasure techniques represented in Fig. 39.4 ([2] #1).

Front End—User Interface (UI): The UI allows the user to perform necessary actions like insert, retrieve, edit, and delete on the BIM data. UI is a web page accessed via the web browser or a server over the Internet and is responsible for communication between Cloud-BIM and end-users ([2] #1).

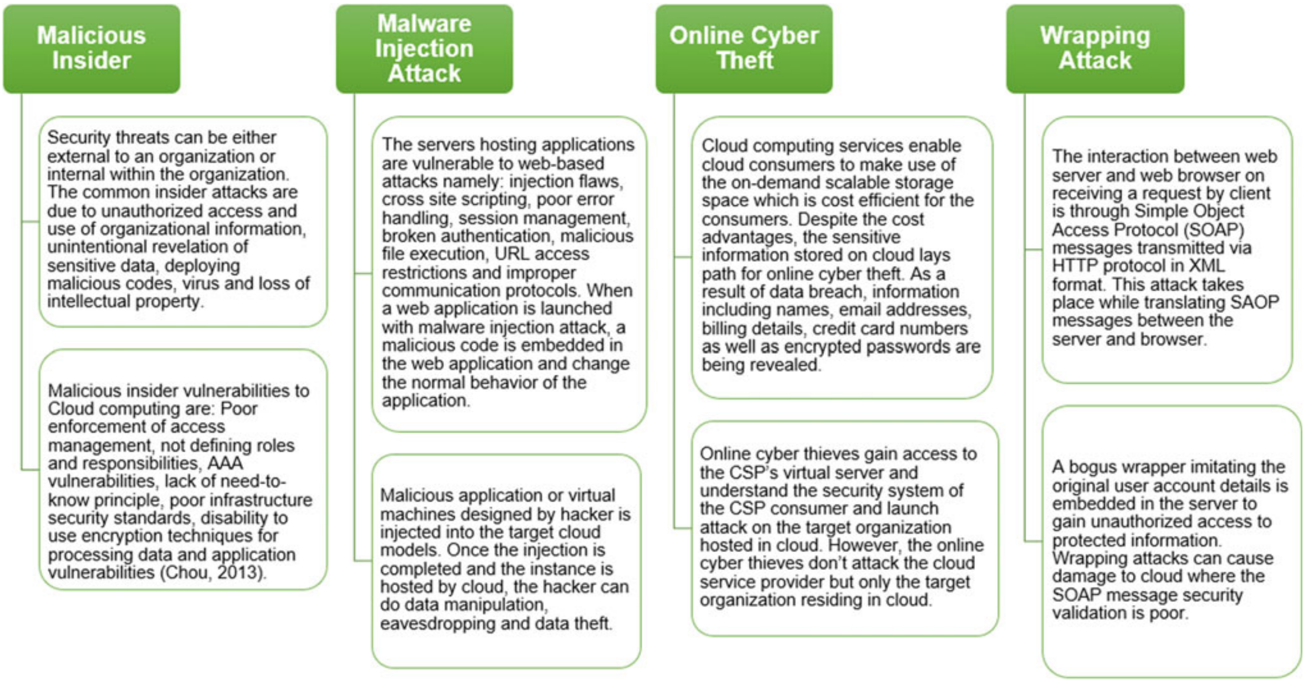

Fig. 39.3 Security challenges in Cloud computing

BIM Layer: The BIM framework layer plays a major role in the proposed architecture. It consists of three main parts:

- **BIM access API (Presentation Layer)**: This layer encompasses the View and Controller enabling end-users to access and use the framework services. The View represents the graphical representation of the Cloud-BIM model's back-end data ([3] #6). The Controller is responsible for the data flow between Cloud-BIM model and view. When the data in the model changes the view updates accordingly. Model and view are maintained separately by the controller ([2] #1).
- **BIM platform business and management logic (Application Layer)**: This layer comprises of the Model and is responsible for controlling different actions performed by end users. This represents the backend data of Cloud-BIM framework and contains the required logic to update the controller when the data changes ([2] #1).
- **BIM storage API (Database Layer)**: This layer is responsible for storing and retrieving Cloud-BIM data. This provides the mechanism to change the data to match the hosting environment i.e. Cloud service, database, and the underpinning technology with the help of DAO (Data Access Object) ([2] #1).

Hosting Cloud Service Provider and Infrastructure: This tier is managed by the CSP and provides the required infrastructure for hosting the Cloud-BIM project in Cloud ([16] #4). The CSP offers many services namely: security services, storage services, document handling, deployment services, communication services, and network services ([2] #1).

Countermeasures: The AEC industry is highly fragmented and has an exceptionally high perception of risk for Cloud computing because of the unique nature of the industry ([15] #123). In view of the Cloud-based BIM's multi-domain nature, there is the need for improving security and privacy management approaches for developing a secure collaborative platform. Solutions are multi-layered and can be categorized into infrastructure, agreement, information, and confidence ([24] #4). The suggested solutions span around technological, process and people issues. Secure, collaborative work environments with real-time data exchange are relatively novel within the AEC industry and require significant development. The requirements for a secure, collaborative Cloud-based BIM platform are reviewed in the following subsections. The most common countermeasure techniques fall under one of the areas namely (a) Access Management, (b) Governance approach, (c) Data Protection, (d) Secure Collaboration and (e) Security Policies ([15] #123).

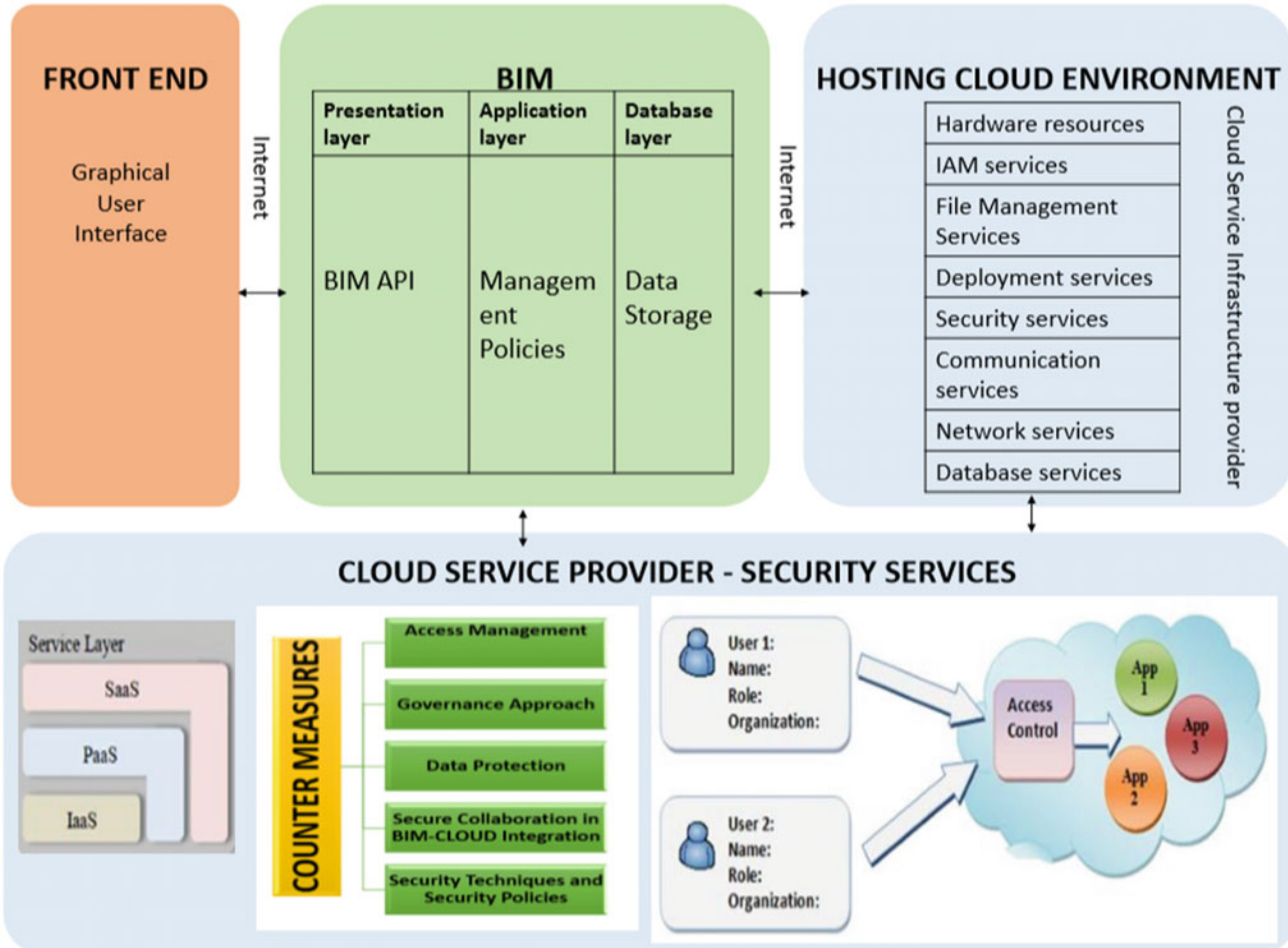

Fig. 39.4 Cloud-BIM framework architecture

39.5 Experimentation

The experimentation approach used for the prototype of Cloud-BIM framework is the simulation technique. The experimentation outcomes are demonstrations of the developed Cloud-BIM platform. The following concepts resulted in the demonstration of the developed Cloud-BIM platform prototype.

(a) **Access Management**

The user's access privileges consisting of authorization and authentication, which are key to the successful deployment of Cloud-based BIM for information exchange. It is required to combine role-based access privileges and visual quality such as Level of Detail (LOD) requirements together ([27] #2). BIM data stored in the Cloud is sensitive and private. The access control mechanisms, with the help of Identity Access Management, provided by CSP could be implemented to ensure that only authorized users may access the data. The continuous monitoring of data is required to ensure privacy in the physical computing systems where data is stored, especially with the increased use of mobile devices across geographically dispersed project environments where various stakeholders have access rights to shared data and models ([11] #120). Intrusion detection systems and configuring firewalls are common tools used to restrict unprivileged access and to monitor malicious activities ([6] #3).

When a user logs in as an administrator, the user is able to create roles for the actors, assign projects to the actors, create new project groups, assign domains, upload/remove BIM projects, track user activities, allow users to modify sensitive information based on the requests received, define access rights to actors working from different locations, and assign stakeholder rights ([3] #6). Access rights assigned to BIM projects differ from one role to another. BIM objects are not completely removed from the database but are versioned and archived for future reference ([3] #6).

(b) **Data Protection**

Involving a third party in the collaborative BIM platform is common and the data can be accessed by multi-actors from multi-disciplines. Causes of data breaches by actors or by third-party users could be intentional or accidental. It is important to protect data from insider's threats as it is difficult to identify the insider's behavior. Security tools must be implemented to protect against insider threats ([1] #4). The security tools include: data loss prevention systems, authentication and authorization technologies, user behavior profiling, decoy technology, anomalous behavior pattern detection tools, and format preserving and encryption tools. These tools provide functions such as real-time detection for monitoring traffic, audit trails recordings for future forensics, and trapping malicious activity into decoy documents ([4] #106). Data can be classified based on the BIM data standards for masking, partitioning, and privacy protection to complement the access management policies. These must take into account, web-specific security challenges ([11] #118). Data protection techniques must be carefully tailored through standardization in order to not exacerbate interoperability across applications and infrastructure ([11] #118). Data partitioning and protection for a project in the AEC industry must be monitored through systematic risk assessment.

(c) **Governance Approach**

In collaborative work environments, it is recommended to use legal promises and guarantees in regulating relationships between collaborators to reduce the risks related to information usage. In the construction industry, relationships are mainly mediated through contracts and legal issues are critical when multi-actor communications are mediated by IT technologies ([13] #21). Regulation of information management must be drawn between the value of information sharing contractual types and the level of provisions. Lack of governance and data management in Cloud for contractual agreements and other legal issues might lead to a compromise of data integrity and privacy ([25] #2). The contractual issues and data ownership in shared web platforms are major barriers to the adoption of Cloud-based BIM environments. A governance approach addresses the contractual issues and provides clarity over data ownership. The governance approach establishes inter-organizational relationship management and develops trust, a critical attitudinal construct among the collaborators.

(d) **Security Techniques and Security Policies**

Implementation of security policies can reduce the risk of abusing Cloud technologies in collaborative work environments. Well established rules and regulations to terminate and isolate the spam or malware instances can help network administrators manage the Clouds more effectively. The malware injection attack is the major security concern in BIM Cloud integration. By implementing the File Allocation Table (FAT) system architecture, malware injection attacks can be prevented. The FAT table recognizes the instances consisting of the code well in advance. It compares the new instance with the previously executed instances in the customer's machine and validates the credibility of the new instance. Another way to prevent malware injection attacks is to store a hash value as an image file on the original service instance. The original and new service instances are compared to perform integrity checks and malicious instances are identified.

(e) **Secure Collaboration in BIM-CLOUD Integration**

The perceptions of risk and vulnerability slow down the process of adopting of BIM and Cloud technology in the AEC industry. In the AEC industry where large amounts of data are generated during a construction project, handling data including timeliness, completeness, or quality is critical. Data related risks are unacceptable and inconsistent with the goal of the AEC industry ([11] #120). To achieve secure, desirable, collaboration through BIM-Cloud integration, there is a need to address the risk issues as risk-related issues are the major inhibitors to achieving BIM Cloud Integration. A risk assessment framework, comprised of the following requirements, is postulated to establish a secure collaborative work environment:

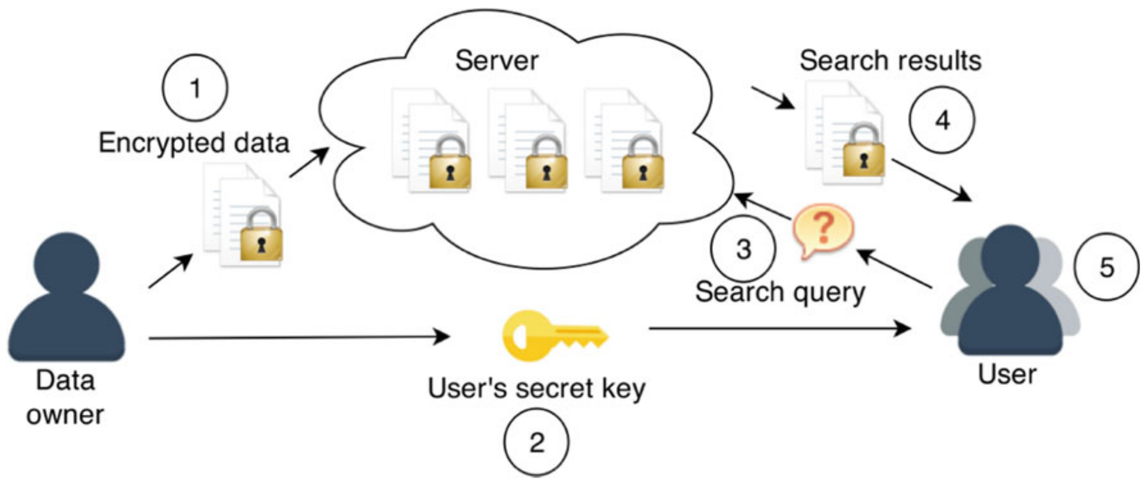

Fig. 39.5 Work flow in collaborative environment

- Secure BIM collaborative requirements are characterized by the cognizance of industry-specific needs: Infrastructure requirements, Technology requirements, Information Management and Data Governance, Contractual and Legal issues, and Relationship issues.
- Decisions on the selection of which IaaS, SaaS and PaaS options to adopt for the requirements of the construction project which meets the security standards during the data exchange and establishes interoperability throughout the lifecycle of the project.
- Cloud provider's security strengths based on technological and commercial factors must be incorporated into the client's policies to develop a stable governance model.

Secure Techniques for Collaboration Process: The project information varies depending on the domain. It is essential to adopt collaboration standards and have the administrator ensure that the common IFC standard is maintained throughout the project lifecycle ([2] #1). The standards are integrated automatically into the governance platform. Multi-actors practice this standard throughout the project lifecycle. The process and sharing of the secret key in a collaborative work environment are shown in Fig. 39.5.

39.6 Conclusion

There are many benefits of using Cloud computing such as cost efficiency, quick deployment, improved accessibility, etc. Despite the many advantages provided by Cloud computing for using BIM in a Cloud platform, the security challenges emanating from Cloud computing impinges the successful adoption of the Cloud-based BIM platform. Designing a secure, collaborative requirement for the BIM Cloud integration is a logical approach towards the development of the Cloud-based BIM platform for mitigating Cloud security risks. BIM-Cloud integration can be established successfully by tailoring Cloud technologies, according to the standards of the AEC industry, to bridge the gap between the AEC industry and the security risks in Cloud computing. An extensive study on the common security challenges faced in Cloud computing when integrated with BIM and their countermeasures is conducted and the results of implementing the framework with countermeasure techniques are presented in this paper.

Although our review has explored the field, further studies are needed to confirm the obtained results. Future work includes the extension of this review by including more sources (conferences, journals, and workshops) and questions. A future plan is to explore other security issues in the Cloud computing environment and we are also aiming to design an enhanced security model using encryption algorithms for data concealment in Cloud computing.

References

1. Alpcan, T., Başar, T.: Network Security—A Decision and Game-Theoretic Approach (2011)
2. Alreshidi, E., Mourshed, M., Rezgui, Y.: Cloud-based BIM governance platform requirements and specifications: software engineering approach using BPMN and UML. J. Comput. Civil Eng. **30**(4) (2016). https://doi.org/10.1061/(asce)cp.1943-5487.0000539
3. Beach, T., Rana, O., Rezgui, Y., Parashar, M.: Cloud Computing for the Architecture, Engineering & Construction Sector: Requirements, Prototype & Experience, vol. 2 (2013)
4. Chou, T.-S.: Security threats on cloud computing vulnerabilities. Int. J. Comput. Sci. Inf. Technol. **5**(3), 79–88 (2013). https://doi.org/10.5121/ijcsit.2013.5306
5. Das, M., Cheng, J.C.P., Kumar, S.S. Social BIMCloud: a distributed cloud-based BIM platform for object-based lifecycle information exchange. Vis. Eng. **3**(1) (2015). https://doi.org/10.1186/s40327-015-0022-6
6. El Mir, I., El Mehdi, K., Hanini, M., Haqiq, A., Kim, D.S.: A Game Theoretic Approach Based Virtual Machine Migration for Cloud Environment Security, vol. 9 (2017)
7. Gerrish, T., Ruikar, K., Cook, M., Johnson, M., Phillip, M.: Using BIM capabilities to improve existing building energy modelling practices. Eng. Constr. Architectural Manage. **24**(2), 190–208 (2017). https://doi.org/10.1108/ecam-11-2015-0181
8. Han, Y., Alpcan, T., Chan, J., Leckie, C., Rubinstein, B.: A Game Theoretical Approach to Defend Against Co-resident Attacks in Cloud Computing: Preventing Co-residence Using Semi-supervised Learning, vol. 11 (2015)
9. Hashizume, K., Rosado, D., Fernández-Medina, E., Fernández, E.: An Analysis of Security Issues for Cloud Computing, vol. 4 (2013)
10. Lu, Y., Wu, Z., Chang, R.-D., Li, Y.: Building Information Modeling (BIM) for green buildings: A critical review and future directions, vol. 83 (2017)
11. Mahamadu, A.M., Mahdjoubi, L., Booth, C.: Challenges to BIM-Cloud Integration: Implication of Security Issues on Secure Collaboration. Paper presented at the 2013 IEEE 5th International Conference on Cloud Computing Technology and Science, 2–5 Dec. 2013
12. Mlotshwa, L., Leonard, A., Ntawanga, F.: A Conceptual Framework for Cloud-Computing Management: An End-User Environment Perspective. Paper presented at the 2015 IST-Africa Conference, 6–8 May 2015
13. Pauwels, P., Zhang, S., Lee, Y.-C.: Semantic web technologies in AEC industry: a literature overview. Autom. Constr. **73**, 145–165 (2017). https://doi.org/10.1016/j.autcon.2016.10.003
14. Rao, T., Haq, E.: Security Challenges Facing IoT Layers and its Protective Measures, vol. 179 (2018)
15. Redmond, A. M., Smith, B., Deke, M.: Environmental Performance of Buildings: Linking Practical BIM/ICT to Practical Policymaking (2014)
16. Rezgui, Y., Beach, T., Rana, O.: A governance approach for BIM management across lifecycle and supply chains using mixed-modes of information delivery. J. Civil Eng. Manage. **19**(2), 239–258 (2013). https://doi.org/10.3846/13923730.2012.760480
17. Salih, A.: A survey of Cloud Computing Security challenges and solutions, vol. 14 (2016)
18. Shen, Y., Li, K., Shi, W.: Advanced topics on cloud computing. J. Comput. Syst. Sci. **79**(8) (2013). https://doi.org/10.1016/j.jcss.2013.02.002
19. Shi, X., Jiang, H., He, L., Jin, H., Wang, C., Yu, B., Chen, X.: Developing an optimized application hosting framework in Clouds. J. Comput. Syst. Sci. **79**(8), 1214–1229 (2013). https://doi.org/10.1016/j.jcss.2013.02.003
20. Singh, V., Gu, N., Wang, X.: A theoretical framework of a BIM-based multi-disciplinary collaboration platform, vol. 20 (2011)
21. Soofi, A., Irfan Khan, M., Amin, F.-e.: A Review on Data Security in Cloud Computing, vol. 94 (2014)
22. Suryateja, P.: Threats and Vulnerabilities of Cloud Computing: A Review, vol. 6 (2018)
23. Tchernykh, A., Schwiegelshohn, U., Talbi, E.-g., Babenko, M.: Towards Understanding Uncertainty in Cloud Computing with risks of Confidentiality, Integrity, and Availability (2016)
24. Whitman, M., Mattord, H.: Principles of Information Security (2005)
25. Wong, J., Wang, X., Li, H., Chan, G.: A review of cloud-based BIM technology in the construction sector, vol. 19 (2014)
26. Yesilyurt, M., Yalman, Y.: New approach for ensuring cloud computing security: using data hiding methods, vol. 41 (2016)
27. Yu, S., Xiaolin, G., Jiancai, L., Xuejun, Z., Junfei, W.: Detecting VMs Co-residency in Cloud: Using Cache-based Side Channel Attacks, vol. 19 (2013)

Check for updates

A System for Early Detection of Maintainability Issues Using BIM

40

Bahadir Veli Barbarosoglu and David Arditi

Abstract

The terms maintainability and maintenance are interrelated and often perceived to be difficult to distinguish from each other. Maintainability refers to the measures and actions taken during the design phase of a product in order to assure that the equipment and the system to which it belongs, can be easily maintained at minimum downtime and cost. On the other hand, maintenance refers to the measures and action taken during the operation phase in order to keep the components at the desired operational condition. The variance between the designers' and facility managers' priorities concerning maintainability creates a gap between the design and operation phases. Maintainability is not often considered in design nor is it a priority for designers. Designers consider maintenance access to be one of the least important factors related to maintenance. However, design-related maintainability issues such as maintenance access problems make maintenance activities impractical if not impossible in building operation, and increase the life cycle costs of facilities. These issues can be detected in the design phase if an appropriate tool is available, and can prevent maintenance-related problems in the operation phase. This research proposes a system that can be used alongside BIM and that can bridge the gap between the design and post-construction phases if deployed in the design phase.

Keywords

Maintainability • BIM • Equipment maintenance access

40.1 Introduction

Maintenance refers to measures and actions taken during the operation phase to assure that building components are at the desired operational condition. The facility manager is in charge of managing maintenance, and maintenance activities are carried out by maintenance personnel. These activities include cleaning, inspection, repair, and replacement of building components. The owner is responsible for maintenance, which is encouraged and regulated by the government, because the efficiency of maintenance affects the facility as well as the environment [1].

Maintainability is a design practice that assures maintenance activities can be performed easily, accurately, safely and at minimum cost. Building maintainability is taken into account by incorporating operations and maintenance experience and needs into the design [2]. Incorporating maintainability considerations into design requires a constant feedback from facility manager to designer, so that a common understanding between the design and post-construction phases is established [3]. However, designers and facility managers have different priorities and perspectives concerning maintainability [4–6].

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40.1.1 Research Problem

The difference between designers' and facility managers' priorities concerning maintainability creates a gap between the design and post-construction phases. This gap results in maintenance inefficiencies related to facility life cycle cost, safety of maintenance personnel, and satisfaction of facility owners and users.

40.1.2 Research Objective

This research proposes a system that can be used alongside BIM and that can bridge the gap between the design and post-construction phases if deployed in the design phase. The proposed system is applicable to all building components that can possibly be in a structure. It allows designers to check their designs from the maintainability perspective without creating extra workload.

40.2 Background

Maintainability affects the downtime of systems (i.g., MEP) and their components. Design for maintainability aims to evaluate and improve the maintainability of systems and components in case of failure or during planned maintenance. In other words, a design that considers maintainability ensures that a failed piece of equipment can be restored effectively and safely within an expected period of time and according to the prescribed operations and maintenance procedures. Considering maintainability issues in the design phase requires identification of physical design characteristics related to maintainability, reform the practices that cause fragmentation in the building design process, evaluate maintenance needs by facility type and function, understand the impact of maintainability issues on cost, and implement an automated maintainability review tool in the design phase.

40.2.1 Physical Design Characteristics Related to Maintainability

The integrity of the design in terms of maintainability requires consideration of physical design characteristics such as visual access, ergonomics, and maintenance access [7].

Visual Access. Lack of visual access to equipment significantly increases the maintenance time spent on the equipment [7]. Visual access to the display of the equipment allows maintenance personnel to perform maintenance activities safely and comfortably, because the display of the equipment often contains color codes, symbols and labels that are instructive for maintenance personnel [8]. The level of visual access is determined by whether maintenance personnel can inspect a particular piece of equipment without moving other building components [9, 10]. Especially in mechanical rooms, lack of visual access makes it almost impossible for maintenance personnel to carry out maintenance activities [11]. Lack of visual access can be considered to be a result of a design that does not consider maintainability issues properly [12].

Ergonomics. The science that aims to enhance workplace conditions and activities according to workers' physical capabilities and limitations is called ergonomics. The primary focus of ergonomics is to eliminate or minimize work-related illnesses and injuries that affect the parts of the human musculoskeletal system [13]. The minimum working space is a subject of ergonomics, and it is related to the clearance around equipment and building components. Most project specifications refer to manufacturers' manuals regarding the clearance requirements for maintenance. However, manufacturers' manuals do not provide minimum clearance requirements for all types of equipment and building components. In case the clearance requirements are not provided within the manufacturer's manual, it becomes the designer's responsibility to make a sound decision related to the maintainability of the system. Unfortunately, there is no universal clearance criterion that covers all equipment and building components. Even though a 20 to 24-in. maintenance clearance around equipment may be sufficient considering human ergonomics, applying such clearance around all equipment and building components would be inefficient from the architectural space perspective [14]. When determining the maintenance clearance around a particular piece of equipment, the type of maintenance activity must be considered, because the position that maintenance personnel must take in order to perform the maintenance activity and the size of the necessary support tools affect the minimum maintenance clearance requirement [15]. The most critical factors that cause maintenance problems in green buildings is bad human factor design [16]. According to the U.S. Department of Energy [10], in order to perform maintenance in a "green" way, equipment maintenance access must be considered in the design, from the human ergonomics perspective. Maintenance access is a universal requirement that is related to human factors and ergonomics, and it should be stated in the general conditions section in project specifications [14].

Maintenance Access. Maintenance access to building components is the most important characteristic of maintainability. Poor maintenance access affects the status of building components, jeopardizes the safety of maintenance personnel, causes rework, and requires extra work and cost. When the time spent on maintenance activities varies from the anticipated durations, it is likely that there is a maintenance problem related to maintenance access [7]. Design must consider maintainability issues in a way that equipment with low reliability are the most accessible building component that can be maintained easily, safely, and economically [8]. Maintenance access can be easily overlooked in the design phase. Checking the design from the maintenance access perspective could be the responsibility of a project member, exclusively [17].

40.2.2 Fragmented Structure of Building Design

Achieving maintainability in the design of facilities requires a common understanding established by the communication and collaboration among the various parties involved in a construction project [18]. However, these parties often have different priorities and perspectives concerning maintainability. For example, while maintenance practicality, in general, is very important to owners, it is not important to designers and contractors [4]. The key aspects of maintainability such as ease of cleaning and maintenance access are top concerns of building users while designers consider these aspects to be the least important factors related to maintenance [5]. The different priorities between the parties involved in the design and post-construction phases create a fragmented construction industry [19]. Even though the designer must receive feedback from facility managers in order to design facilities with optimal life cycle performance, this is not the case [3]. Whether maintainability is taken into consideration in the design phase depends on the designer's experience. However, it is often assumed that all designers have sufficient experience to produce a design that fully considers maintainability [20].

The current content of the programs offered at schools of architecture do not give prospective designers the opportunity to become aware of maintainability issues [21]. Facility managers have little or no involvement in the design phase. The facility manager's first involvement in the project often starts with the occupancy phase where the contribution to the design is very limited and the most influential design decisions have already been made [22]. The information related to facility management requirements, such as maintenance access, is not considered in the traditional design phase, and inappropriate space allocation occurs as a result [23]. It is suggested that early involvement of facility managers in the design phase can bridge the gap between the design and post-construction phases and can improve overall maintainability by identifying issues and avoiding potential maintenance problems [24]. When maintainability is taken into consideration in the design phase, it improves overall facility performance, enhances safety, effectiveness and efficiency of maintenance [25].

Consequences of the Gap. One of the most common problems faced by facility managers is the inability to maintain some building components in both new and remodeled buildings. Design with no maintainability consideration does not only increase the cost of maintenance activities but sometimes makes it impossible to perform maintenance [6]. Maintenance goals are not set in almost one out of every two projects, and very few of the projects meet the goals in the post construction phase [17, 24, 26–28].

The most common maintenance problems faced by facility managers due to lack of maintainability consideration in the design are as follows.

- Lack of maintenance access
- Poor space layout
- Designer's limited experience gain from the operations of existing buildings
- Lack of understanding on how system design and layout affect maintainability
- Designer's failure to communicate with facility manager.

In addition to bridging the gap, facility managers' early involvement in the design phase can improve the overall performance of construction facilities [22, 25, 26]. The expected benefits of the involvement of facility managers in the design phase are as follows.

- Ease of adoption of future changes in building systems
- Ease of maintenance, cleaning, and replacement
- Enhanced safety, security, sustainability, and functionality
- Reduced energy consumption

- Environmental friendliness
- Increased facility management efficiency
- Improved overall maintainability.

The involvement of facility managers in the design phase must be facilitated in order to solve maintainability issues. Even though facility managers can be physically involved in the design phase by employing integrated facilities design delivery methods that values the facility manager's input, it is not common. The involvement of facility managers in the design phase can be achieved more practically by using computer-based tools (e.g., BIM) that can transfer the facility management knowledge to designers [29].

40.2.3 Understanding the Cost Effect of Maintainability Issues

The impact of operations and maintenance on building life cycle cost is well understood. However, the cost effect of considering maintainability issues in the design phase has not received much emphasis. The U.S. federal government has mandated its agencies to apply energy reduction measures to all federal facilities but neglected to address the cost caused by the inefficiencies of operations and maintenance that is commonly around 50% of the overall cost [30]. Considering that the U.S. industries spend over $200 billion each year on maintenance, addressing maintainability issues in the design phase can significantly reduce the life cycle costs of facilities [31]. In other words, even though consideration of maintainability in the design phase may require some extra up-front cost associated with design services, the up-front costs would be considerably low compared to the long-term savings to be achieved during the post-construction phase [32].

The decisions made in the design phase constitute 65% of a facility's life cycle cost [33]. 20% of maintenance are caused unnecessarily by design decisions and the majority of them are related to maintenance access problems [34]. Taking into account its impact on life cycle cost, design is the most cost-effective phase to detect and resolve potential maintenance problems by considering maintainability [35, 36].

40.2.4 Implementation of Maintainability in the Design Phase

In spite of its well-known benefits, maintainability reviews have been considered to be a burden by designers [37]. Maintainability review guidelines that owners require designers to follow in the design phase can encourage designers to pay more attention to detect and resolve maintainability issues. Even though a maintainability review guideline that contains the owner's needs is a good source of information, it is difficult to design a facility according to it, because design changes often, and because reviewing each change according to a maintainability guideline creates an extra burden on the design team [11]. The traditional maintainability review is often conducted over 2D drawings, the accuracy and efficiency of which highly depends on the designers' experience [38]. Instead of a manual effort spent on designing and following a guideline, a rule set can be implemented in a 3D design tool [39]. A 3D design tool can be used to implement maintenance simulations, multi-objective optimization models, and custom maintainability checking algorithms. For example, maintenance activities can be simulated on a 3D presentation and the design can be improved accordingly [38, 39]. The statistically significant relationship between equipment layout relative to maintenance access and maintainability can be used on a multi-objective optimization aiming to achieve maintainability in the design phase [40]. Similarly, an algorithm can be used to automatically generate a 3D equipment layout that accommodates maintenance access requirements and constraints [41]. BIM is the most suitable platform for implementing an automated maintainability checking process in the design phase, because the parametric and geometric information of building components that are required for maintainability checking already exist in the BIM model [42].

40.3 Proposed System

This research proposes a system for a comprehensive maintainability checking tool that can easily be put together on a BIM platform by using an algorithm template developed in this research. The algorithm template can be customized for different building components that can possibly be in a structure. The algorithm template consists of 14 steps (see Fig. 40.1).

- Step 1. The algorithm scans all building components in the BIM model and determines whether the building component of interest exists in the model. If the building component of interest does not exist in the model, there is nothing to check.

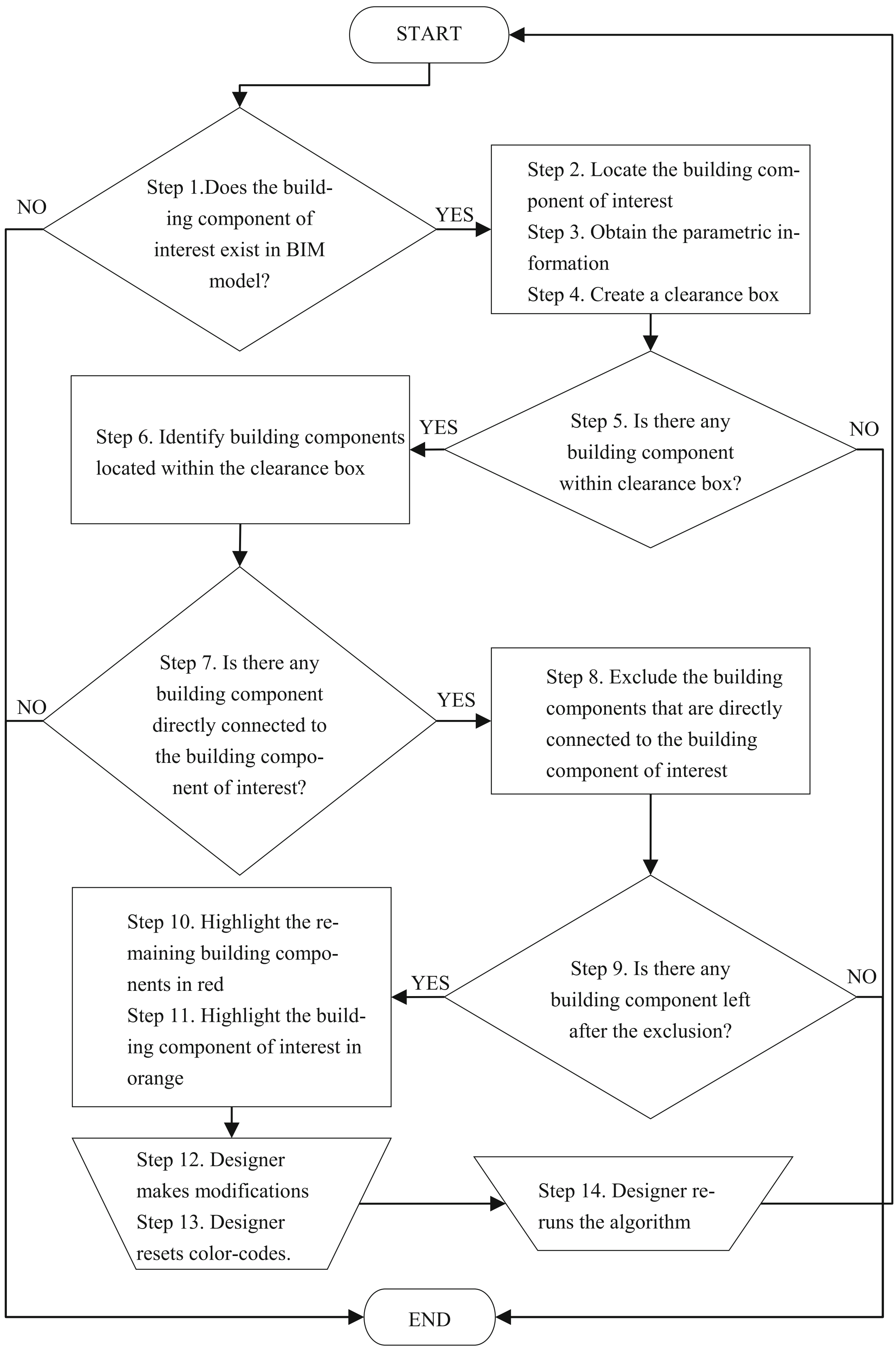

Fig. 40.1 Algorithm template

- Step 2. The location of the building component of interest is identified if it exists.
- Step 3. The parametric information of the building component of interest (e.g., local x-y-z coordinates, width, depth, and height) is obtained.
- Step 4. A clearance box around the building component of interest is created using the parametric information and the predetermined maintenance access criteria.
- Step 5. The algorithm determines whether any building component is partially or fully located within the clearance box around the building component of interest. No maintainability issue is found if there is no building component located within the clearance box.
- Step 6. The building components located within the clearance box are listed.
- Step 7. The algorithm checks whether any of the listed building components are directly connected to the building component of interest.
- Step 8. The building components that are directly connected to the building component of interest are removed from the list that is created in Step 6.
- Step 9. The building components that are located within the clearance box but not directly connected to the building component of interest are identified.
- Step 10. The building components identified in Step 9 are highlighted in red for the attention of the designer. The building components highlighted in red cause maintainability issues for the building component of interest.
- Step 11. The building component of interest is highlighted in orange in case there is (are) building component(s) causing maintainability issues. The color codes applied in Steps 10 and 11 remain until the maintainability issues are resolved by the designer.
- Step 12. The designer makes modifications on the BIM model in order to solve the maintainability issues detected by the algorithm.
- Step 13. The color-coded building components are reverted back to their default colors after the designer makes the necessary modifications.
- Step 14. The designer re-runs the algorithm to make sure the design complies with the maintainability requirements of the building component of interest.

40.4 Conclusion

Designers and facility mangers have different priorities concerning maintainability. This creates a gap between the design and the post-construction phase where maintenance-related problems occur. Some designs make maintenance activities impractical if not impossible in facility operation, and increase the life cycle costs of facilities. Potential maintenance problems can be detected and resolved in the design phase if maintainability considerations are incorporated into the design phase by an appropriate tool.

In this research, a maintainability checking system algorithm was proposed. The algorithm can be customized for all building components that can possibly be in a structure, and it can be implemented alongside a BIM tool such as Autodesk's Revit. BIM can bridge the gap between the design and post-construction phases without increasing the workload of designers, by allowing designers to produce a design that improves maintenance access and workplace safety, facilitates the cleaning and repair of building components, reduces the number of reworks, improves the efficiency of the commissioning process, and reduces the time spent on maintenance activities.

An automated maintainability checking process should be considered to be an essential part of the design process. The construction industry should create and adopt design for maintainability standards for every building component that can possibly be in a structure, and comply with them using BIM tools.

References

1. Zavadskas, E., Kaklauskas, A., Bejder, E.: Raising the efficiency of the building lifetime with special emphasis on maintenance. Facilities **16** (11), 334–340 (1998)
2. NASA: Designing for maintainability and system availability. Developed by the National Aeronautics and Space Administration, Washington, D.C. (1997)

3. GSA: GSA PBS-P100, Facilities Standards for the Public Building Service. Developed by U.S. General Services Administration, Washington, D.C. (2015)
4. Al-Hammad, A., Assaf, S., Al-Shihah, M.: The effect of faulty design on building maintenance. J. Qual. Maintenance Eng. **3**(1), 29–39 (1997)
5. Arditi, D., Nawakorawit, M.: Designing buildings for maintenance: designers' perspective. J. Architectural Eng. **5**(4), 107–116 (1999)
6. Schrag, S., Smith, K., Stollenwerk, B.: Designing for the care and maintenance of buildings. Buildings **101**(11), 34–35 (2007)
7. Stapelberg, R.F.: Handbook of reliability, availability, maintainability and safety in engineering design. Springer Science & Business Media, Berlin (2009)
8. Smith, D.J.: Reliability, maintainability and risk: practical methods for engineers including reliability centred maintenance and safety-related systems. Elsevier, New York (2011)
9. Putt, J.: Why equipment maintainability should not be an afterthought. In: Proceedings of Reliable Plant Conference (2013)
10. Department of Energy (DOE).: Human Factors/Ergonomics Handbook for the Design for Ease of Maintenance (2001)
11. Cavka, H.B., Staub-French, S., Pottinger, R.: Evaluating the alignment of organizational and project contexts for BIM adoption: a case study of a large owner organization. Buildings **5**(4), 1265–1300 (2015)
12. Kumar, R., Barabady, J., Markeset, T., Kumar, U. Improvement of performance of oil and gas production facilities in Arctic regions by applying human factors/ergonomic principles at the design phase. In: International Conference on Port and Ocean Engineering under Arctic Conditions: 09–12 June 2009
13. Sutton, I.: Plant design and operations. Elsevier, New York (2015)
14. Ellis, R.: What is accessible? Two feet, or not two feet: "Where?" is the question. Eng. Syst. **28**(6), 20 (2011)
15. Attwood, D.A., Deeb, J.M., Danz-Reece, M.E.: Ergonomic solutions for the process industries. Gulf Professional Publishing (2004)
16. Mohammad, I.S., Zainol, N.N., Abdullah, S., Woon, N.B., Ramli, N.A.: Critical factors that lead to green building operations and maintenance problems in Malaysia. Theor. Empirical Res. Urban Manage. **9**(2), 68 (2014)
17. Moua, B., Russell, J.S.: Comparison of two maintainability programs. J. Constr. Eng. Manage. **127**(3), 239–244 (2001)
18. BCA: Design for Maintainability Checklist. Developed by Building and Construction Authority, Singapore (2016)
19. Jalali-Sohi, A., Arditi, D., Jalali-Sohi, A.: Design Considerations for Maintenance—Facility Mangers' Perspective. In: Proceedings of the First European and Mediterranean Structural Engineering and Construction Conference (EURO MED SEC 1), Istanbul, Turkey, 24–29 May 2016
20. Ismail, N., Mohamad, M.I.: Factors in building design that improve building maintainability in Malaysia. Proceedings 31st Annual ARCOM Conference (2015)
21. Yilmaz, H.: Relationship between Building Design and Building Maintenance. Unpublished research (2011)
22. Mohammed, M.A., Hassanain, M.A.: Towards improvement in facilities operation and maintenance through feedback to the design team. Built Hum. Environ. Rev. **3**, 72–87 (2010)
23. Wang, Y., Wang, X., Wang, J., Yung, P., Jun, G.: Engagement of facilities management in design stage through BIM: framework and a case study. Advances in Civil Engineering (2013)
24. Meng, X.: Involvement of facilities management specialists in building design: United Kingdom experience. J. Perform. Constr. Facil. **27**(5), 500–507 (2013)
25. Moua Her, B., Russell, J.S.: Maintainability implemented by third-party contractor for public owner. J. Manage. Eng. **18**(2), 95–102 (2002)
26. Jensen, P.A.: Integration of considerations for facilities management in design. Design Management in the Architectural Engineering and Construction Sector: CIB W096 Architectural Management & TG49 Architectural Engineering, pp. 191–199 (2008)
27. Lewis, A.: Designing for energy-efficient operations and maintenance. Eng. Syst. **27**(8) (2010)
28. Nawi, M.N.M., Radzuan, K., Salleh, N.A., Ibrahim, S.H.: Value Management: a strategic approach for reducing faulty design and maintainability issue in IBS building. Advances in Environmental Biology, pp. 1859–1864 (2014)
29. Ugliotti, F.M.: BIM and Facility Management for smart data management and visualization. Doctoral dissertation, Politecnico di Torino (2017)
30. Foster, B.: BIM for Facility Management: Design for Maintenance Strategy. J. Build. Inf. Model. 18–19 (2011)
31. Meier, J.R., Russell, J.S.: Model process for implementing maintainability. J. Constr. Eng. Manage. **126**(6), 440–450 (2000)
32. NASA: Recommended techniques for effective maintainability. Developed by the National Aeronautics and Space Administration, Washington, D.C. (1994)
33. Schuman, C.A., Brent, A.C.: Asset life cycle management: towards improving physical asset performance in the process industry. Int. J. Oper. Prod. Manage. **25**(6), 566–579 (2005)
34. Chanter, B., Swallow, P.: Building maintenance management. Wiley, New York (2008)
35. Dessouky, Y.M., Bayer, A.: A simulation and design of experiments modeling approach to minimize building maintenance costs. Comput. Ind. Eng. **43**(3), 423–436 (2002)
36. Xu, X., Ma, L., Ding, L.: A framework for BIM-enabled life-cycle information management of construction project. Int. J. Adv. Rob. Syst. **11** (8), 126 (2014)
37. Ivory, C.J., Thwaites, A.T., Vaughan, R.: Shifting the goal posts for design management in capital goods projects: design for maintainability. R&D Manage. **33**(5), 527–538 (2003)
38. Zhou, D., Shi, J.M., Geng, J., Lv, C.: Virtual maintenance concepts and methods. In: Applied Mechanics and Materials, vol. 26, pp. 714–719. Trans Tech Publications
39. Lin, Y.C., Su, Y.C.: Developing mobile-and BIM-based integrated visual facility maintenance management system. Sci. World J. (2013)
40. Luo, X., Yang, Y.M., Ge, Z.X., Wen, X.S., Guan, F.J.: Layout problem of multi-component systems arising for improving maintainability. J. Central South University **21**, 1833–1841 (2014)
41. Luo, X., Yang, Y., Ge, Z., Wen, X., Guan, F.: Maintainability-based facility layout optimum design of ship cabin. Int. J. Prod. Res. **53**(3), 677–694 (2015)
42. Liu, R., Issa, R.: Design for maintenance accessibility using BIM tools. Facilities **32**(3/4), 153–159 (2014)

41 Towards Automated Analysis of Ambiguity in Modular Construction Contract Documents (A Qualitative & Quantitative Study)

Ali Azghandi Roshnavand, Mazdak Nik-Bakht, and Sang H. Han

Abstract

Modular coordination in building construction has become increasingly popular, particularly in Northern Europe and North America. Modular construction in Canada gained considerable attention over the last decade due to its positive impact on project constraints, safety, and preventing construction and demolition waste. However, the modular construction industry still adopts the same administrative procedures designed for the conventional construction industry even though the features of modular and conventional construction are different in terms of construction processes and methods. Due to this trend, ambiguities in administrative documents are widely occurred and are one of the main causes to generate conflict, disputes, and claims between owners and modular suppliers as general contractors. As a first step in the on-going research to overcome this challenge, the research team focuses on investigating the contents and structures of the current contracts, which are one of major confusion sources in modular construction, in order to mitigate and/or eliminate the ambiguities in the contracts based on the considering the features of modular construction processes and methods. In this respect, this paper presents a conceptual framework, which is: (1) to classify the major ambiguities in conventional and modular construction contracts; (2) to identify the similarities and differences between Canadian contract documents and benchmark countries. We use text mining to find top terms, including terms with high TF in each document, and high TF-IDF terms, which specifically occur in one document and not others then, we detect manually the three standard contracts and compare them with the output of literature review to identify the major issues that are common.

Keywords

Text mining • Taxonomy • Modular • Contract document • TF • TF-IDF

41.1 Introduction

'Modular Construction' is the ability to manufacture in different place and transport to the place of installation in one or more sections [1]. Modular coordination in the building became increasingly popular through countries which are located in geographically remote and cold areas such as Sweden and Northern Canada or where the feasibility of on-site construction is low [2]. This kind of construction was introduced to European and North American countries after World War II. Reports in 1996 show high precast levels in Denmark 43%, the Netherlands 40%, and Sweden and Germany 31% [3]. In the early 1970s, Eastern and Western Europe started using this method for construction of new suburbs, towns, and public buildings, thus, they set up specific standards for examining component specifications such as tolerance and installation standards [3]. Because of high demand and lower costs, this industry became popular in Asian countries as Malaysia and India. A Survey in 2003 shows 15% of construction in Malaysia was built, using the Industrialized Building System (IBS), therefore, the government started a program which insisted that all public projects must contain 70% IBS components [4].

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In North America, the Canadian construction industry has turned toward a new approach named Permanent Modular Construction (PMC) since the 1990s. Modular construction in Canada gained considerable attention over the last decade due to its positive impact on project constraints, safety, and preventing construction and demolition (C&D) waste. In 2002, the Canadian construction industry produced 3.3 million tons of Construction and Demolition (C&D) waste 30% of the total municipal solid waste deposited in landfills (Canadian Home Builders' Association, 2010). A workshop held at Concordia University in October 2015 to discuss about challenges and opportunities for modular construction in Canada. During this workshop, experts released some reasons, which have been determined as the barriers to off-site projects in Canada including standards, regulations, and procurement strategies that favor conventional construction technologies such as a value-based system [5]. Unfamiliarity with the transportation regulations and inability to convince the state government to allow transport the modules overstate highways caused $2 million US cost overrun for Kearl Oil Sand project in Canada [6]. In the U.S., the average cost per square foot of a manufactured home was $42, versus $86 for site-built homes, excluding land [1]. Furthermore, this new industry like other new industries, always hurdles and difficulties exist in the first steps such as lack of knowledge about the modular construction industry, design and construction culture [7]. Insufficiently grounded, qualitative, and quantitative research is another issue in the way of PMC [8].

The significant issues related to starting a modular construction are the site condition, inefficient standard contract documents, transportation conditions, local codes, skilled labor unavailability, design complexity, and organizational readiness [9]. Since the contracts have this ability to reduce the risk of the project in earliest stages, they have this potential to unfairly be abused by one of the parties to transfer the risk to other parties by using some unfair and unclear provisions or clauses. Therefore, the construction industry turned to use of standard contracts that are provided by experienced architects, contractors, owners, sub-contractors, engineers, and lawyers, and then approved by leading professional teams. Standard contract documents provide consistency and eliminating the ambiguities [6].

Many researchers have been studying the sources and effects of confusion in traditional construction contract documents, but there is not enough number of comprehensive research work for the modular construction contract. The present paper presents a conceptual framework for classification of the major sources of ambiguity in construction contracts (both general and modular), and applies it through text processing, to identify the similarities and differences between Canadian contract documents and some benchmark countries. Therefore, both of the literature review and our research shows that modular construction industry suffers from lacking of specific set of standard contract for itself that is one of the main sources of confusion in this industry.

41.2 Methodology

This study has two major phases; developing an analysis framework, and using text mining to analyze contract documents. In the first phase, an analysis framework was developed through a comprehensive review of the literature as well as existing standard contracts (Fig. 41.1). In this regard, publications related to the sources of ambiguity in (both on-site and off-site) construction contract documents, published since 1980 were reviewed and analyzed. That part of the study synthesizes results of 20 papers under five major categories (i.e. contract language, contract document, stakeholders, design-related issues, and external factors) as well as sub-categories. The results of that work are reported elsewhere, but, given the objective of the present paper, here we have limited our scope to the category called "contract documents". Sub-categories of this category in our conceptual framework, as well as some of the causes (reported in the literature) giving rise to each sub-category, are listed in Table 41.1.

In the second phase, we focused on standard contracts commonly used in modular construction in three English speaking countries (the US, UK and Canada), to investigate each of the subcategories (and causes) listed in Table 41.1. From the USA, the American Institute of Architects (AIA) standard contract was chosen and from the UK, the newest standard contract, New Engineering Contract (NEC3) Engineering and Construction Contract (ECC) was selected. We also chose the standard contract by Canadian Construction Documents Committee (CCDC), which is the most popular one in Canadian industry. Since the Design-Build (DB) delivery method is more commonly in use by the modular construction companies in those countries, we targeted standard DB contracts issued by the three organizations. Moreover, the studies indicate the Design-Build delivery method not only has more adaptability with the modular construction, but also the modular contract documents based on DB normally result in fewer ambiguities compared to other methods [10]. As a result, we selected the standard contracts: CCDC14 (Educational copy 2013), AIA141 (2014), and NEC3 (2013) as the input for this research. It should be noted that although NEC does not have a specific DB contract, according to our correspondence with the agency (http://www.nec-contract.com), the closest contract to Modular Construction is NEC3 Engineering and Construction Contract (ECC).

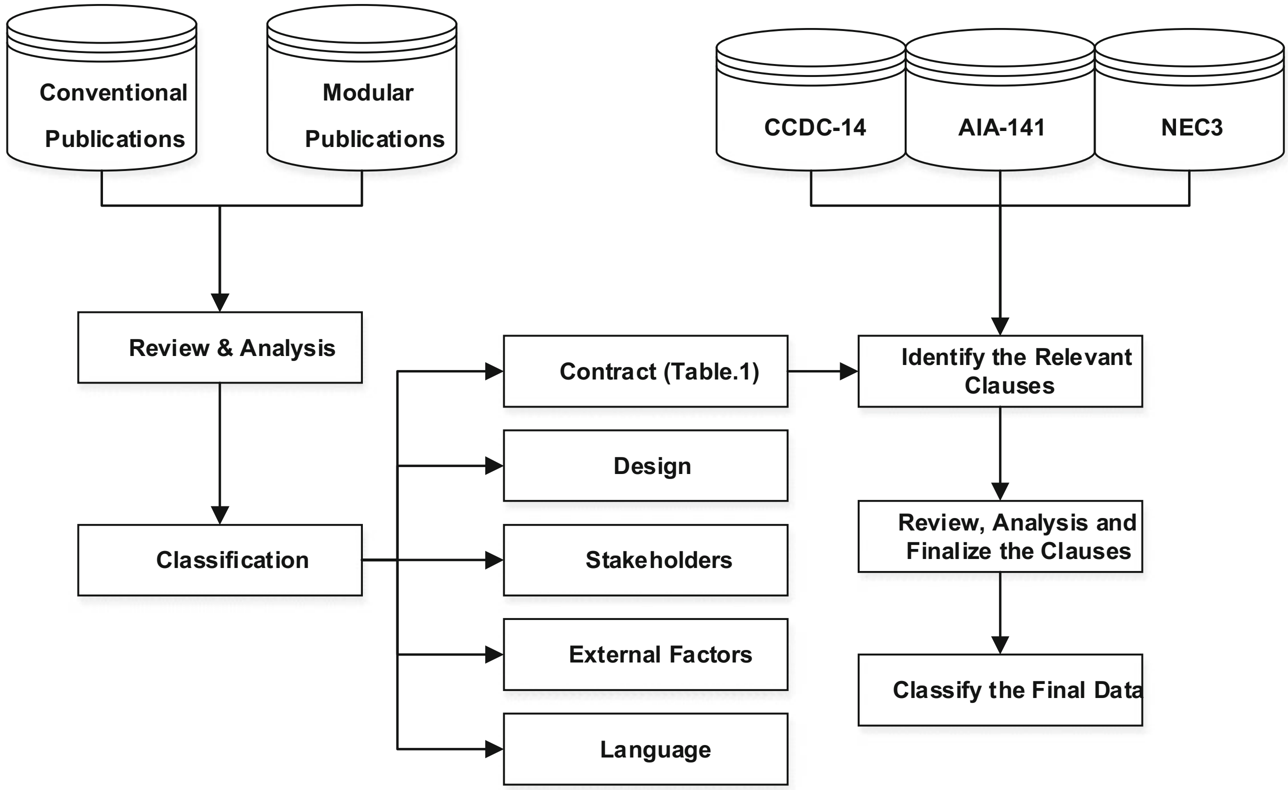

Fig. 41.1 Developing an analysis framework

We used text-mining tools, followed by interpretation of results, for a quantitative analysis and comparison of the three documents within our conceptual framework. More specifically, we evaluated similarities and distinctions among the documents, within the dimensions of our analysis framework, through evaluation of simple and basic text mining measures such as TF (Term Frequency) and TF-IDF (Term Frequency-Inverse Document Frequency). In this regard, we first classified clauses and terms in each contract, into the sub-categories shown in Table 41.1. From the 23 classes that we began with (one per each "cause" in Table 41.1), we had to exclude the ones for which we failed to find relevant clauses in all the three contracts. We also removed the classes for which the size of relevant clauses in the three contracts were significantly different; in this regard, we excluded the cases in which the size of text for one contract was 5 times less than the other two. As a result, we finally focused on seven classes, each of which associated with one major sources of confusion extracted from the literature review. Table 41.2 introduces those classes, and the size (i.e. the number of terms) of relevant clauses associated with them in each contract.

The collected text was mixed with unneeded information (including terms, characters, etc.) which must be filtered before the analysis. We converted all the collected texts into Unicode (since they were in different encoding formats), then used Regular-expression to remove unneeded characters as well as changing all the plural nouns to singular type (due to the aggressive nature of most stemmers available, which sometimes creates confusions in the final results, we decided to only turn the plurals to singular). Moreover, we used a stop list to clean the data from common words with no specific semantics (such as punctuations, conjunctions, articles, etc.). Next step of the preprocessing after the cleaning was tokenizing the input text (to their terms). In this regard, specific compound words which communicate semantics in the context of our study (such as 'Contract Price' and 'place of work'), as well as some specific terms (such as 'Design-Builder' and 'Federal Arbitration Act') were merged (to 'contractprice', placeofwork, 'designduilder', and 'federalarbitrationact' respectively). It is worthwhile emphasizing that merging such terms happened before applying the cleaning step. The cleaned and tokenized data were used as the input of text analysis.

We start text mining by evaluating frequency metrics, taking advantage of the Natural Language Toolkit (NLTK), which is a suite of Python libraries for symbolic and statistical natural language processing for English language. We focused on top terms in the corpus, including terms with high TF (frequency of occurrence) in each document (i.e. accumulation of

Table 41.1 Sources of confusion related to the "contract documents" and sub-categories according to the literature review

Sub-category	Cause	Code
Poor Draftmanship	False presentation of facts and other similar abuses [6]	1.1
	Not following guidelines and standards [11, 12]	1.2
	Lack of the knowledge and training by draftsmen [12, 13]	1.3
Missing Information	Being silent about construction method/technology [14]	2.1
	Being silent about production and installation machinery [11, 14]	2.2
	Lack of tolerance criteria [15, 16]	2.3
	Unclear Quality audit and control criteria [15]	2.4
Ambiguity of the Information	Complexity of Workers Compensation Board (WCB) [17, 18]	3.1
	Unclear scope definition [17–19]	3.2
	Unclear acceptance performance definition and criteria [20]	3.3
	Inconsistent statutory obligations [21]	3.4
	Unclear payment conditions [11, 19]	3.5
	contradiction and inconsistency between the warranty and contract [17]	3.6
	Errors and mistakes in technical specifications [15]	3.7
	Dispute resolutions complexity [5]	3.8
	Inconsistencies and contradictions among different documents [20]	3.9
Redundant Information	Contradictory and erroneous info. In the mass of documents [22, 23]	7.1
Lack of Local Regulations and Best Practices Contingencies	Poor Project integration [11, 17, 18, 24]	4.1
	Poor Project financial planning [13, 23, 25]	4.2
	Lack of familiarity with local force majeure [4]	5.1
	Lack of contingency planning strategies [17]	5.2
	Inadequate bonds and insurance to cover failure of the parties [18]	5.3
Mismatch between Project Delivery Method and the Contract Type	Difference of terminology for contracts used in different delivery methods [16, 21, 26]	6.1

related clauses from each contract in each topical class), and high TF-IDF (high frequency of occurrence, uniquely in each document). Therefore, if term i appears fij times in document j, then [27]:

$$\mathrm{TF}_{ij} = \frac{f_{ij}}{m_j} \tag{41.1}$$

in which $m_j = \max(f_{ij})$ and if n shows the number of documents to be compared, then:

$$\mathrm{IDF}_i = \log(n/1 + d_i). \tag{41.2}$$

TF-IDF is then calculated for each term in each document as the product of its TF and IDF.

Terminology difference in different countries was one of the challenges in this research. Even-though all three contracts were selected from English speaking countries; differences in the names used to refer to the same concept in the three countries, caused confusion in our text-mining engine and the results. For instance, NEC3 uses the term 'employer' to refer to the 'owner', as called by CCDC14 and AIA141. As another example, the term 'place of the work' in CCDC14 is the same as the term 'site' in AIA and NEC. In this regard, we had some limitations of the work such as lack of systematic method also, TD-IDF limitations in terms of detecting the synonyms, proverbs, compound words, expressions, etc. (For large document collections, this could present an escalating problem). In order to resolve this issue, we applied some post-processing, where we systemically detected synonyms among terms with high TF or TF-IDF, and replaced them by uniform equivalents. In this paper, we selected CCDC14 as the basis for synonyms and changed terms of other two contracts to their synonyms in CCDC14. We iteratively performed the TF and TF-IDF process, followed by the post-processing until the no synonyms were left among top TF and/or TF-IDF words. Figure 41.2 shows the process of our method.

Table 41.2 Major causes of confusion in contract documents investigated in this study, and the associated size of relevant clauses in the three standard contracts studied

Feature (topical class)	Standard Contracts (count*)			
	Codes (Link to Table 41.1)	AIA 141	CCDC 14	NEC3
Acceptance performance and criteria	3.3	1149	306	563
Payment conditions	3.5 and 4.2	2533	1829	2245
Claims and dispute resolution	3.8	1743	2362	2194
Quality, inspection and tests	2.4 and 3.7	372	269	346
Contingency strategies and delays and extension of the time	5.2	289	386	319
Bonds and insurance	5.3	2172	829	541
Job site condition and information (storage space, accessibility etc.)	3.2 and 5.1	493	115	184

*Size is based on the total number of words in each class

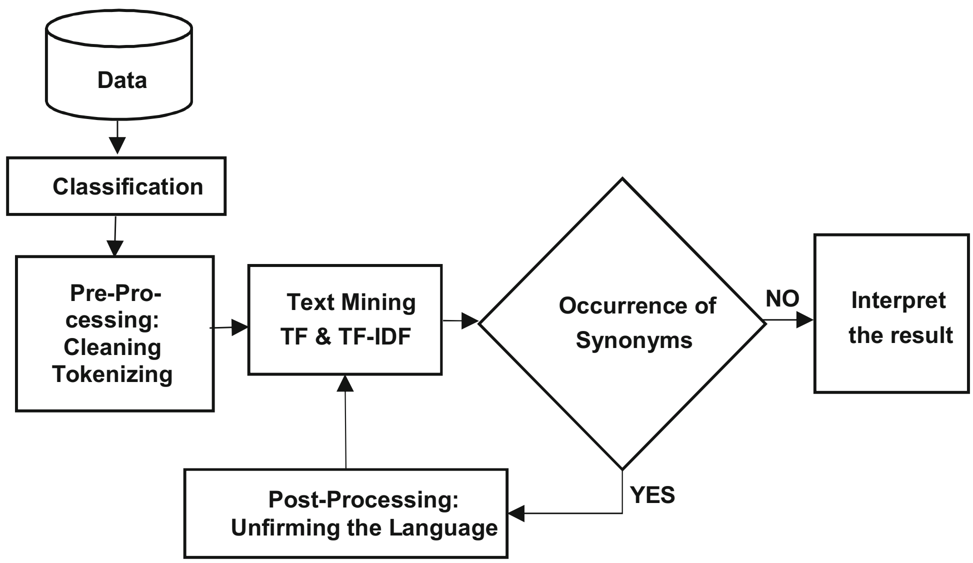

Fig. 41.2 The process of text mining

By trial and error, we decided to select the top 25 TF and TF-IDF terms for each of the seven topical classes, in each contract. This number was set so that the terms in the lists have meaningful frequencies (more than one) in the text they come from. This is due to the fact that the chance is low for a term with frequency of one, to have an important semantic role in a document. The lists of high TF and high TF-IDF terms, although being good indicators, providing at starting point for interpretation, are not enough for making a meaningful comparison among the texts. Therefore, after finishing TF and TF-IDF analysis, we searched for the instances of occurrence of those terms in the documents, and manually reviewed those parts, to complete the comparison between standard contracts. The following section summarizes the results of the study.

41.3 Results

We started the comparison among standard documents by looking at different actors and roles in the three documents. Table 41.3 summarizes the major roles in each document; as shown, while AIA141 and CCDC14 introduce the same roles (with the same terminology), NEC3 uses a different terminology. For example, ‘Employer’ instead of ‘Owner’, ‘Contractor’ instead of ‘Design-Builder’ and ‘Supervisor’ instead of ‘Consultant’. More importantly, NEC3 introduces an additional role, the ‘Project Manager’, whom is hired by the owner, and is given a high level of authority to communicate with the contractor and the supervisor. This alteration might be partially due to the fact that NEC3 is inherently different from the other two contracts, and is not specifically a DB contract (but the closest one to that delivery method). Moreover, a project manager with high experience with modular construction hired by owner can be beneficial for items such as ‘project integration

Table 41.3 Different roles in three standard contracts

AIA141	CCDC14	NEC3
Design-builder	Design-builder	Contractor
Owner	Owner	Employer
–	–	*Project manager*
Consultant	Consultant	Supervisor
–	*Payment certifier*	–
Insurer	Insurer	Insurer

Table 41.4 Main roles related to dispute resolution in the three standard contracts

AIA141	Freq. of occurrence	Size of document	CCDC14	Freq. of occurrence	Size of document	NEC3	Freq. of occurrence	Size of document
Mediator	1	1743	Project Mediator	7	2362	adjudicator	95	2194
Arbitrator	4		Arbitrator	0		Arbitrator	4	
Joinder (Person)	4		–	–		–	–	

(codes 4.1 and 4.2)', 'Dispute resolutions complexity (code 3.8)', 'contingency planning strategies (5.2)'. In addition, CCDC14 has the additional role of 'Payment Certifier', assigned by the owner to review and certify the Design-Builder's application for payment and issuance the certificates of payment. A 'Payment Certifier" can be help to reduce the effect of items 'Unclear payment conditions (code 3.5)' and 'Poor Project financial planning (code 4.2)' shown in Table 41.1. As mentioned in the literature review, one of the issues in modular construction is organization readiness.

On the other hand, as shown in Table 41.4, the process and roles involved in the dispute resolution procedure are different among the three standard contracts. The major roles defined include 'adjudicator' in NEC3 and 'joinder person' in AIA. From the comparison of related clauses in the two contracts, it appears that 'adjudicator' in NEC3 has the same role as 'project mediator' in CCDC14, but with more detailed responsibilities. Occurrence frequency results for terms such as 'project mediator' in CCDC14 (and 'mediator' in AIA141), compared to 'adjudicator' and 'arbitrator' in NEC3, could indicate that the North American contract contracts would recommend resolving disputes through negotiation than judicial authorities.

In terms of the schedule, Units for measuring the time are different in these contracts. AIA141 uses the term 'day' (mean Calendar Day) and NEC3 uses the 'week' as the time unit. On the other hand, CCDC14 is using its two different units of time for different parts of the contract. It uses the term 'Working Day' for part 6 (changes in the contract), part 7 (right to suspend or terminate), and part 8 (dispute resolution) while it is using the term 'Calendar Day' for part 5 (payment), part 11 (insurance and contract security), and part 12 (indemnification, limitation of liability, waiver of claims, and warranty). This can be an indicator of providing more objectively and clearly defined duration units by CCDC14 (for both windows of submitting new claims and reasons for more disputes).

The concept of "defect certificate", suggested by NEC3 contract, helping to monitor the defected portion of the work, does not exist in CCDC14 and AIA141. This certificate is either a list of defects, provided by the supervisor (who is issuing his certificates to the Project Manager and the Contractor), to be corrected by the contractor during a defect correction period; or a statement that there are none, at the end of the defect correction period. This term is specifically used for some of the categories mentioned in Table 41.1, such as performance acceptance criteria (code 3.3), payment criteria (code 3.5) and bond and insurances (code 5.3). NEC3 has some clauses about the delay, and associated responsibilities or extra costs due to repeating the tests and/or inspection. However, there is only one sentence in AIA141 indicating that the cost of additional tests and inspection shall be at the design builder's expense. In this matter, CCDC14 has only one clause, saying that delays by "common carriers" entitle the design-builder for extra time.

AIA141 has a clause mentioning the acceptance and payment for materials, equipment, and products stored outside the place of the work must be approved in advance by the owner, at a location agreed upon in writing. Similarly, in CCDC14, the payment certifier approves the products delivered to the place of work as of the last day of the payment period. More considerably, NEC3 has a clause mentioning that the materials and plants, which are outside the site, are not allowed to be transported to the site before approval of tests and inspections (as required by contract in the work information). These

Table 41.5 Dispute resolution steps in three standard contracts

AIA141	Freq. of occurrence	CCDC14	Freq. of occurrence	NEC3	Freq. of occurrence
Initial Decision	14	Negotiation	6	Adjudication	10
Mediation	19	Mediation Negotiation	5		
Arbitration	25	Arbitration	14	Arbitration	6
Court	8	Court	5	Tribunal	24
Litigation	1	–	–	–	–

findings are specifically important for modular construction projects, as they normally have large amounts of modules built off-site in the factory. Lack of information regarding terms and conditions of transportation, inspection, acceptance and payment for such modules is normally one of the main sources of ambiguities reported in the literature. This paragraph can be related to items 'Unclear payment conditions code (3.5)' and 'Unclear scope definition (3.2)' as shown in Table 41.1.

Based on the literature review, lack of efficient local codes is one of the major issues for modular construction contract documents. The term 'Quebec', as a Canadian province with fundamentally different standards, rules and regulations, has been mentioned nine times in CCDC14. The Canadian standard contract tries to support cross-provincial projects (i.e. companies based outside Quebec, planning to work in this province or Quebecer companies, willing to use a Canadian standard contract). The information provided include the duration of holdback amount for the design-builder, sub-contractor and suppliers, Quebec sales tax, Quebec pension plan and different civil code for substantial performance of the work. This can be an evidence of providing support for the lack of local regulations and best practices, reported in our conceptual framework (subcategory 4, Table 41.1).

Finally, in the category of "claims and dispute resolution", on our findings (summarized in Table 41.5), shows considerable differences among the three standard contracts. The difference, partially has roots in terminology difference of the documents, and partially shows variations in the process of claim and dispute resolution. In CCDC14 dispute, resolution is suggested to solve the problems with amicable negotiations at first, if unsolved, then to proceed with mediation by assigning a 'project mediator', and at the end, it offer the arbitration process. In AIA141, 'initial decision' (inherently similar to 'negotiation' but with a longer procedure) is explained, and the details of communication between parties to manage the dispute are elaborated. Initial decision is followed by 'mediation' and then either 'arbitration' or 'litigation'. Lastly, NEC3 offers different terminology and process. In this contract, 'adjudicator' has the main role for the dispute resolution. Disputes are referred to the adjudicator in accordance with an 'adjudication table'. If the parties cannot resolve the disputes through the adjudication process, they then go to the 'tribunal' as the last step of dispute resolution. Administrative tribunals are set up to be less formal, less expensive, and a faster way to resolve disputes compared to the traditional court system.

41.4 Conclusion

The features of modular and conventional construction are different in terms of construction processes and contract documents then, ambiguities in administrative documents are widely occurred and are one of the main causes to generate conflict, disputes, and claims between owners and modular suppliers as general contractors. Our findings based on comparison among 'Dispute Resolution' parts of these three contracts show considerable differences in this subject among three standard contracts. (Shown in Table 41.5) The different words which showing differences in the process of the claim and dispute resolution also different names of the main actors (See Table 41.4). In case of Modular Construction, Dispute resolution becomes more complex and sensitive because of either new types of modular disputes or different types of stakeholders in this method such as 'Manufacturer', 'Transporter', 'Installer', 'Machinery suppliers', etc. (as shown in Table 41.1. Code 3.8)

Among our findings from the comparison of these three standard contracts, we found some clauses related to the transportation, the inspection and payment criteria for stored material and equipment outside of the site, which is essential for our case, which is modular construction and majority of the work, should be done off-site and deliver to the site.

The differences between measures for the time among these contracts is important since one of the three main scopes of each project is time and if the measures of the time are not clear, drive the project to more claims and disputes.

Even though all three contracts are from English speaking countries but our findings show that there are considerable differences among these three based on the names, idioms, measures, processes of dispute resolution, payment criteria, etc.

While the scope of this research was determined by the level of analysis needed to answer the questions posed earlier, future work can add more insights by looking at more resources among more benchmark countries. In term of text analysis, going beyond single terms into bi-grams and tri-grams in the feature extraction may add into the meaning of these results. In addition, testing analyses with a different scope (adding more benchmark countries) can help to verify or add to the findings of this paper. Finally, adding private modular construction contracts helps this research to take the outputs into a new level and shed more light on the content of the modular contract.

References

1. Frederick L.P.: Issues in Manufactured Home Construction Litigation. In: 9th Annual Construction Law Institute, Montana (2013)
2. Mayra, D.L.T.: A review and analysis of modular construction practices (1994) [Online]
3. Zhang, X., Skitmore, M., Peng, Y.: Exploring the challenges to industrialized residential building in China. Habitat International **41**, 176–184 (2014)
4. Kamar, A.M., Hamid, Z.A., Azman, N.A.: Industrialized building system (IBS): revisiting issues of definition and classification. Int. J. Emerg. Sci. 120–132 (2011)
5. University, C.: Challenges and opportunities for modular construction in Canada. Concordia University, Montreal (2015)
6. Carriker, M.L.S.: Factors affecting large scale modular construction projects. Associated Schools of Construction, p. 8 (2014)
7. NIBS_OSCC.: National Institute of Building Sciences(NIBS) 2015 annual report. MBI, Virginia (2015)
8. Smith, R.E., Rice, T.: PERMANENT modular construction, Utah: Modular Building Institute Foundations, 2015
9. Azhar, S., Lukkad, M.Y., Ahmad, I.: Modular v. stick-built construction: identification of critical decision-making factors. In: 48th ASC Annual International Conference Proceedings, Florida, 2012
10. S. R. E.: Permanent modular construction. Modular Building Institute Foundations, Utah, 2015
11. Harvey, C.: Factors that influence the adoption of modular construction in Western Canada. Royal Roads University, Victoria, British Columbia, Canada (2016)
12. Larsson, J., Eriksson, P.E., Olofsson, T.: Industrialized construction in the Swedish infrastructure sector: core elements and barriers. Constr. Manage. Econ. 83–96 (2014)
13. Eriksson, P.E., Olander, S., Szentes, H., Widén, K.: Managing short-term efficiency and long-term development through industrialized construction. Constr. Manage. Econ. 97–108 (2014)
14. Čuš-Babič, N., Rebolj, D., Nekrep-Perc, M., Podbreznik, P.: Supply-chain transparency within industrialized construction projects. Comput. Ind. 345–353 (2014)
15. Molavi, J., Barral, D.L.: A construction procurement method to achieve sustainability in modular construction. Procedia Eng. **145**, 1362–1369 (2016)
16. Rausch, C., Nahangi, M., Perreault, M., Haas, C.T., West, J.: Optimum assembly planning for modular construction components. ASCE 14 (2016)
17. Marc, D.Z.L.Z.B.: Key considerations before integrating modular construction: adaptation to the traditional French construction processes. Researchgate 13 (2015)
18. O'Connor, J.T., O'Brien, W.J., Choi, J.O.: Industrial project execution planning: modularization versus stick-built. Am. Soc. Civil Eng. 1–13 (2015)
19. Kamar, K.A.M., Alshawi, M., Hamid, Z.: Barriers to industrialized building system (IBS): the case of Malasyia. In: 9th International Postgraduate Research Conference (IPGRC), BuHu (2009)
20. Kamali, M., Hewage, K.: Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. J. Cleaner Prod. 3592–3606 (2017)
21. Fateh, M.A.M., Mohammad, M.F., Shukor, A.S.A.: Review in formulating the standard form of contract for Industrialized Building System (IBS) construction approach in Malaysia. MATEC Web of Conferences, p. 7 (2017)
22. Choi, J.O., O'Connor, J.T., Kim, T.W.: Recipes for cost and schedule successes in industrial modular projects: qualitative comparative analysis. ASCE 9 (2016)
23. Tap, T.N.A.K.M.M.M.: Critical success factor for industrialized building system process protocol map by lean construction management. J. Civil Environ. Eng. 6 (2016)
24. Shahtari Yasaman, J.N.M., Rausch C., West.: Risk mitigation through tolerance strategies for design in modularization. Researchgate 9 (2015)
25. Nik Bakht, M., Kinawy, S.N., El-Diraby, T.E.: News and social media as performance indicators for public involvement in transportation planning: Eglinton Crosstown Project in Toronto, Canada. TRB 94th annual meeting, At Washington, D.C., USA, p. 9 (2015)
26. Musa, M.F., Mohammad, M.F., Yusof, M.R., Ahmad, R.: Industrialised building system modular system (IBSMS) organisational readiness framework. Procedia Soc. Behav. Sci. **222**, 83–92 (2016)
27. El-Abidi, K.M.A., Ghazali, F.E.M.: Motivations and limitations of prefabricated building: an overview. Appl. Mech. Mater. **802**, 668–675 (2015)

Adopting Parametric Construction Analysis in Integrated Design Teams

42

Alireza Borhani, Carrie Sturts Dossick, Christopher Meek, Devin Kleiner, and John Haymaker

Abstract

This paper reports on an industry-academia collaboration for integrating construction and engineering analyses into a graduate-level architecture design studio, including the developed workflow and curriculum, and lessons learned from the students' and instructors' experiences. The studio program pursues two learning goals namely implementing multi-variate analyses to develop a sustainable design concept as well as practicing collaboration and communication inside an interdisciplinary team. The results of this paper are mostly useful for students and new professionals in the AEC field who want to take most advantage of the emerging data-driven built environments and adopt a new mindset that supports the integration of construction information into the design process. Specifically, the outcomes of the design studio effort are summarized in the following three categories: (1) the development of a generalized and standard workflow for implementing parametric, computational, and performance-based design and construction approach that assists project teams to create design concepts, evaluate their design performance, and visualize the results, (2) the establishment of a framework for evaluating the quality of design process and collaboration in an integrated design team, and (3) the creation of visual programming methods and tools and design/construction software applications for systematic design programs' analysis and data visualization/interpretation for knowledge-based decision making (this work is in progress).

Keywords

Parametric design and construction • Computational design and construction • BIM • Performance-based design • Team collaboration and communication • Interdisciplinary team • Design studio

42.1 Introduction

The emergence of data-driven built environments has affected the Architectural, Engineering, and Construction (AEC) industry significantly over the last decade. It has helped the industry to improve its current practices, increase productivity, and reduce risks associated with design and construction. It has also required practitioners from all disciplines to reconsider

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their workflows, to practice communication and collaboration more effectively, and to adopt new technologies. As a result, experts from both academia and industry aimed to find new solutions for their traditional problems (e.g. fragmented design and construction processes) through applying the new approach of design and construction. For this purpose, professionals need to gain the related technical skills such as computational and parametric methods for performance-based design development and analysis as well as organizational skills including effective communication and working inside integrated multi-disciplinary teams.

42.1.1 Motivations for Integrated Design Studio Program

The fast-growing demand for gaining the mentioned technical and organizational skills in the AEC industry is the basic motivation for creating integrated design studio programs in the academia. An integrated design studio has students from multiple disciplines working together on a shared design project. The main purpose of such program is to develop a practical curriculum for training a new generation of professionals who have adequate understanding of other disciplines in the built environments (e.g. architecture, construction management, and related engineering fields) and have ability to collaborate and communicate with project team members to achieve best possible solutions.

In addition, the integrated studio program contributes to the aim of reducing the current fragmentation between design and construction processes. Traditionally, construction teams have a limited understanding of design intent and design teams have also a limited understanding of cost estimation and constructability considerations at the early stages of design. The result of such limitations is increase in RFIs and change orders as well as cost overruns during the construction phase and discrepancy between designed and actual building's performance during the occupancy phase [1]. More integrated project delivery systems such as Design-Build (DB) and Integrated Project Delivery (IPD) addressed this issue by providing project teams a method for better collaboration. However, finding the professionals prepared for collaborative design and decision-making is still a challenge. In this case, the integrated studio program is considered as a long-term solution that prepares such professionals.

Finally, the integrated studio program is a potential opportunity for industry and academia collaboration. This is specifically critical for implementing scientific and data-driven practices in the industry that leads to more knowledge-based decision making and fill the existing gap between construction and non-farm/manufacturing industries in terms of labor productivity [2]. Proper utilization of building data collection, analysis and visualization helps project teams to revise their purely experience-based design and construction methods. In this regard, the academia plays a key role by transferring computational and analysis methods from other science disciplines into the built environments for developing new methods and the integrated studio program serves as a research and development (R&D) environment for testing new methods and technologies.

42.1.2 Definition of Parametric Design Approach

The core of the integrated design studio program is learning about the parametric, computational, and performance-based design approach. Existing literatures have different definitions for the terms "parametric design", "computational design", and "performance-based design" [1, 3, 4]. In the context of the developed studio curriculum, parametric design is defined as determination of specific design-related parameters for creation of different design alternatives by changing in the parameters' values. Additionally, the computational design refers to applying computer-aided methods and applications to generate design intent, automate the process of design generation/alteration, and make different analyses for the generated design. Last, the performance-based design is defined as identification and consideration of building's performance-related criteria at the conceptual design stage in order to develop a design intent that meets the project team's established performance requirements.

Accordingly, the parametric, computational, and performance-based design approach consists of determining desired building's performance, identifying relevant design parameters to generate design intents/alternatives, and using computational methods to analyze/revise design intents till achieving the desired performance. Also, the explained design approach guides project teams to gather all the data required for leveraging data-driven methods and technologies not only during the design phase but also at the construction and operation phases.

42.1.3 Selected Building Design Project's Background

This paper reports on an integrated studio program developed by a team of faculties and TAs at the University of Washington department of Architecture and Department of Construction Management with architects and researchers from Perkins+Will, an Architecture firm. The coursework was structured around a graduate design studio co-led by a faculty member in Architecture and a practicing architect. Two course-linkages were created comprised of construction management students and structural engineering students led by faculty in the Construction Management Department and the Architecture Department respectively. These course linkages were intended to foster collaboration and to provide technical feedback in the area of costing, economic value analysis; and structural systems selection and design. This team (called instructor team) defined the studio project as developing design proforma for a high-performance multi-story mixed-use building that meets the city's sustainability program (Seattle's Living Building Pilot Program). For this studio, the instructor team selected a real project at the downtown Seattle (which is in design phase) as a case study. Students had access to the project location and were provided a preliminary design package including zoning information, relevant codes and standards, and early design studies.

The instructor team is currently working on improving the studio program based on the gained experiences and completing the computational tools visualization platform for the next round of the studio class.

42.2 Methodology

42.2.1 Structure of the Integrated Design Team

In this studio, the team formation was based on the idea of Integrated Design Process (IDP) which is defined as "an approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints. It relies upon a multi-disciplinary and collaborative team whose members make decisions together based on a shared vision and a holistic understanding of the project" [5].

Accordingly, the students worked inside multi-disciplinary teams consisting of two-three architecture students as designers, one construction management student as construction management (economy and constructability) consultant, and one civil engineering student as structural consultant. Each discipline was led by a faculty and each consultant group had its own internal weekly meeting session during which students shared their work progress with their peers and discussed their technical issues with each other and with invited experts from industry. Also, students shared their experiences with working inside an integrated team and learn about the effective ways of collaboration and communication with other groups. Core to the structure of the graduate design studio was the *Design Space Construction* framework [6], a process tool aimed at supporting problem formulation, alternative generation, impact analysis, and value assessment.

During the studio program, students had several training sessions including tools and software tutorial sessions. A custom suite of visual programming-based analytical tools aimed at supporting multi-variate criteria analysis was developed specifically to support the design studio project. The design studio syllabus and schedule structured installation and use of the intended computational tools, design critic meetings with professionals from architecture, engineering, and real estate fields for having studio teams presenting their design concepts and receiving feedbacks, and three technical design workshops for water efficiency, energy efficiency, and façade development.

42.2.2 Standard Workflow for the Integrated Studio Program

In general, the integrated studio programs are created based on a main task and objective, a step-by-step process (for achieving the objective) that specifies the required sub-tasks, and tools/methods needed for accomplishing those sub-tasks. Currently, there are several integrated design studio programs in U.S. universities. For instance, researchers at the Georgia Tech University developed a curriculum for design space exploration and analysis [7] and researchers at the University of Southern California and Stanford university developed a methodology for design optioneering and optimization [8].

The University of Washington instructor team determined two learning goals for the integrated design studio program namely 1. apply the parametric, computational, and performance-based design and construction approach for creating a high-performance building's design concept that reflects all three aspects of sustainability (ecology, economy, and experience), and 2. practice collaboration and communication with the built environment's disciplines inside the integrated design team. To achieve these goals, the instructor team developed a standard workflow that is summarized in Fig. 42.1.

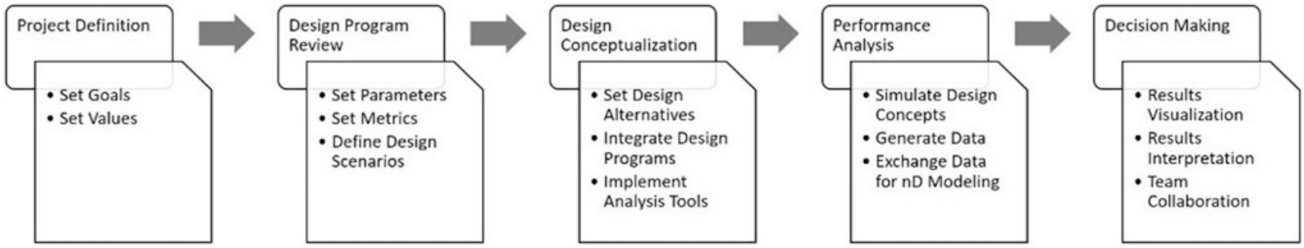

Fig. 42.1 Standard workflow for the integrated studio program

The standard workflow starts with project definition. In this step, the student team should set their goals for the project (e.g. designing an energy-efficient, profitable, or ecological building). Also, the student team should determine its weighted values which reflects the priorities and importance of different characteristics of design program (in practice, it is provided by owners and main stakeholders). The values will be later used for making decisions between generated design alternatives.

The next step is design program review, during which the student team sets design parameters that significantly impact the building performance (e.g. wall/window ratio in the enclosure, building envelope shape/orientation, and structural system). Also, the student team identifies all important metrics for performance analysis (e.g. energy efficiency, initial cost, and embodied carbon), and defines design scenarios for the project (in this studio it was defined as maxing out economy, ecology, and experience scenarios)

The third step is design conceptualization that includes creating design concepts' alternatives, integrating design programs based on the trade-offs between design scenarios in order to create one preferred alternative or a set of revised alternatives, and customizing design analysis methods/tools based on the determined design parameters and metrics.

In the next step, performance analysis, the student team simulates design concepts in the provided computational tools for architectural performance analysis such as energy, water, and daylight efficiency. The analyses results are generated/stored, and subsequently the consultants' required data is transferred into BIM-oriented platforms for construction performance analysis including design alternatives' economic, structural, and constructability analysis.

The last step is decision making. The student team imports all required information into a design dashboard that effectively visualizes design intents. The dashboard facilitates the data interpretations and serves as a platform that team members use for collaboration and knowledge-based decision making.

42.2.3 Project Evaluation Framework

In addition to the proper implementation of the explained technical workflow, the success of an integrated design studio will depend on the collaborative design development and communication of performance-based spatial, material, and formal solutions and synergies that evolve from the performance metrics. As a result, the instructor team developed an evaluation framework based on the idea of experiential learning in which students learn through experience and reflect on their work results. This framework evaluates studio teams' dynamics and performance using two groups of criteria.

First, it measures the quality of outcome-based criteria such as technical data generated, use of intended technologies, and created visuals (e.g. floorplans, rendered images, and axonometric diagrams). In terms of data generated as the results of architectural and construction analyses, the instructor team determined a list of metrics that students had to use for analysis and report. Figure 42.2 shows these metrics categorized in ten main groups.

Second, the framework evaluates process-based criteria including team collaborations, internal/external team communications, and design progress documentations. In particular, the design students had weekly desk critics to share their ideas, design approaches and any work created and to receive feedbacks from the instructors. Also, the construction management consultants documented their progress through submitting weekly work plans (WWP) and using plus/delta technique for reflecting on their team's performance in terms of technical, collaboration and communication effectiveness. Specifically, the technical factor evaluated weekly goals and questions students defined for balancing tradeoffs between design intent, constructability, and budget constraints. Also, the collaboration factor measures students' performance in the multi-disciplinary team-based decision-making process and communication factor evaluates the use of group discussions and visualization techniques to support communication across disciplines.

Categories	Building Morphology	Program Distribution	Energy Efficiency	Water Efficiency	Experience
Metrics	GSF [ft^2] Height [ft] Floors [#] Enclosure Surface-Area [ft^2] Roof Area [ft^2] WWR [%]	Retail [ft^2] Office [ft^2] Residential [ft^2] Other [ft^2]	Heating/Cooling-EUI [kBTU-ft^2/yr] Total Building EUI [kBTU-ft^2/yr] Total Energy Use [kBTU/yr] EUI Target [kBTU-ft^2/yr]	Rainwater on Site [Gal./yr] Potable Water-Demand [Gal./yr] Graywater-Produced [Gal./yr] Graywater Reuse [Gal./yr]	Average Lux [lux] Lux that meet target-illuminance UDI [%]
Categories	Living Building Pilot	Affordable Housing	Economics	Structure	Business Cases
Metrics	Zero Energy Petal [Y/N] Zero Water Petal [Y/N] Materials Petal [Y/N]	Affordable Housing Units [#] Fee Paid [$] Construction Cost [$, $/ft^2] Potential Loss [$] Value of Bonus FAR [$] Total Value Added [$]	Total Construction Cost [$, $/ft^2] Enclosure Cost [$] Renewables Cost [$] Gross Revenue [$, $/ft^2] Residual Value [$, $/ft^2] Payback Period [yrs]	SF of Concrete [%] SF of Steel [%] SF of Wood [%] Embodied Carbon-Estimate [kg/ft^2]	Developed Business Cases for the Innovative Design Programs

Fig. 42.2 Pre-determined metrics for the outcome-based evaluation

42.3 Provided Tools and Methods

The instructor team provided different tools to implement the sub-tasks determined in the standard workflow. However, students encountered some challenges in interoperability between tools. In addition, some of the subtasks (such as structural and economic analysis) were accomplished manually and students could not take advantage of a fully model-based analysis using the existing tools. Therefore, the instructor team started creating new tools and a data flow map between these tools. Some parts (including structural/constructability analysis and design dashboard) are currently being prepared or optimized. Figure 42.3 indicates the suggested mapping diagram.

The process starts from creating a 3D model inside Rhino software. At the conceptual design phase, the model contains most important architectural and possibly structural elements. The created model is then used for architectural analysis and it is also transferred into Autodesk Revit for construction analysis. The construction management consultants use the Revit model for economic analysis, import the model into other tools (e.g. Navisworks) for constructability analysis, and share it with structural consultants for structural analysis. Once analyses are done, all the results are organized and stored in an Excel file. Also, another Excel sheet is created that contains project metadata including design concepts' morphology and weighted values. Finally, these two Excel files are imported into Microsoft Power BI as the visualization tool to create the design dashboard.

42.3.1 Architectural Analysis

The studio teams used a Grasshopper script (developed by Perkins+Will) to run multi-variate architectural analyses including parameters of geometry, as energy, and daylight performance. The provided tools and methods have been developed over two years of curriculum refinement at UW [9]. Students could change their intended design parameters

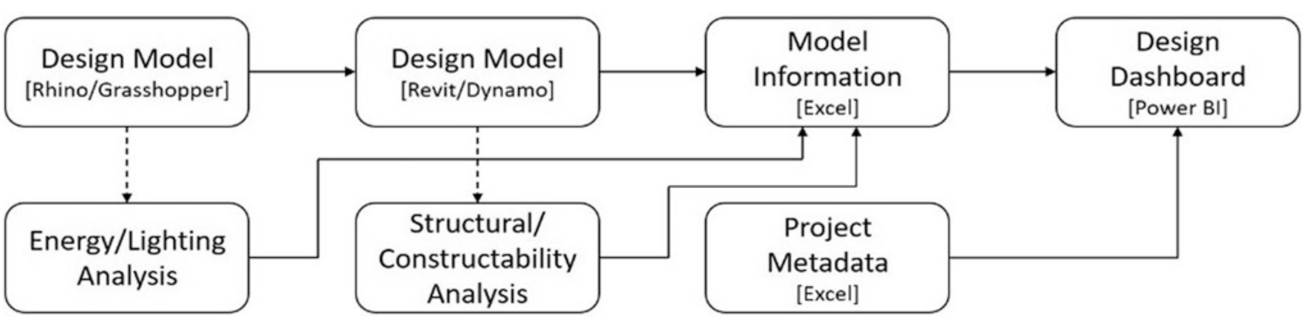

Fig. 42.3 Mapping between authoring, analysis, and visualization tools

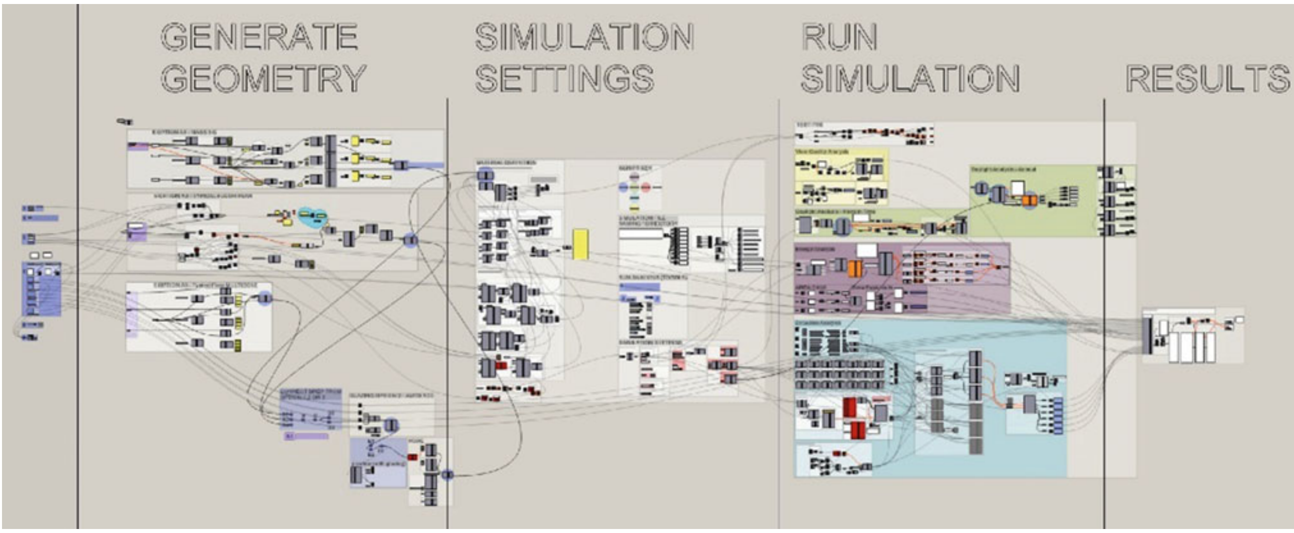

Fig. 42.4 Rhino/Grasshopper script for automating architectural analysis

inside the script and run the program for multiple alternatives to realize how those parameters impact the performance of their design concepts. Figure 42.4 shows the categorizations of nodes/code blocks in the developed script.

Once the analysis is complete, an Excel sheet was generated automatically that showed the results (including but not limited to calculated areas for floors, roof, and walls, window/wall ratio (WWR), zone peaks for heating/cooling, Energy Use Index (EUI), and lux) for the input design alternatives.

42.3.2 Construction Analysis

The main responsibility of the construction management (CM) consultants was to provide feedback on economic analysis. For this purpose, the CM consultants developed a business case for each design alternative, which included cost estimation and real estate analysis using the provided metrics. CM Consultants employed two methods for cost estimation including conceptual estimating (using RSMeans square foot cost book) at the early stages and then more parametric estimating (based on building systems) as design matured. Also, regarding the real estate analysis, students developed a project proforma consisting of effective gross income (EGI) based on design program distribution (commercial, residential, retail, etc.), total annual revenue, total project residual value, and payback period. During the team meetings, CM consultants were asked to share not only the results but the process/methods of economic analysis with other students, discuss the cost impacts of various design ideas, and provide recommendations based on the cost/benefit tradeoffs.

Based on the studio experience, the instructor team decided to create a computational script to automate the process of economic analysis. Figure 42.5 shows the primary functions of the developed script which are creating and exporting quantity takeoff (QTO) of the building elements that are identified as most important cost drivers, and creating user-defined visuals (sheet of floorplans, elevations, sections, and 3D views) for the purpose of visualization.

42.3.3 Data Visualization

As a brief definition, "visualization represents a product in a form that is meaningful to a divers group of stakeholders. Visualization creates understanding of what the product looks like and how it will function" [10].

Data visualization is an important part of the workflow because it is the preliminary tool for collaboration and communication inside an integrated team. Moreover, it is critical to find an optimized point between standardization of visualization (e.g. using pre-established template for all teams) for the ease of comparison and innovation of creating the visuals that best communicate the design intent.

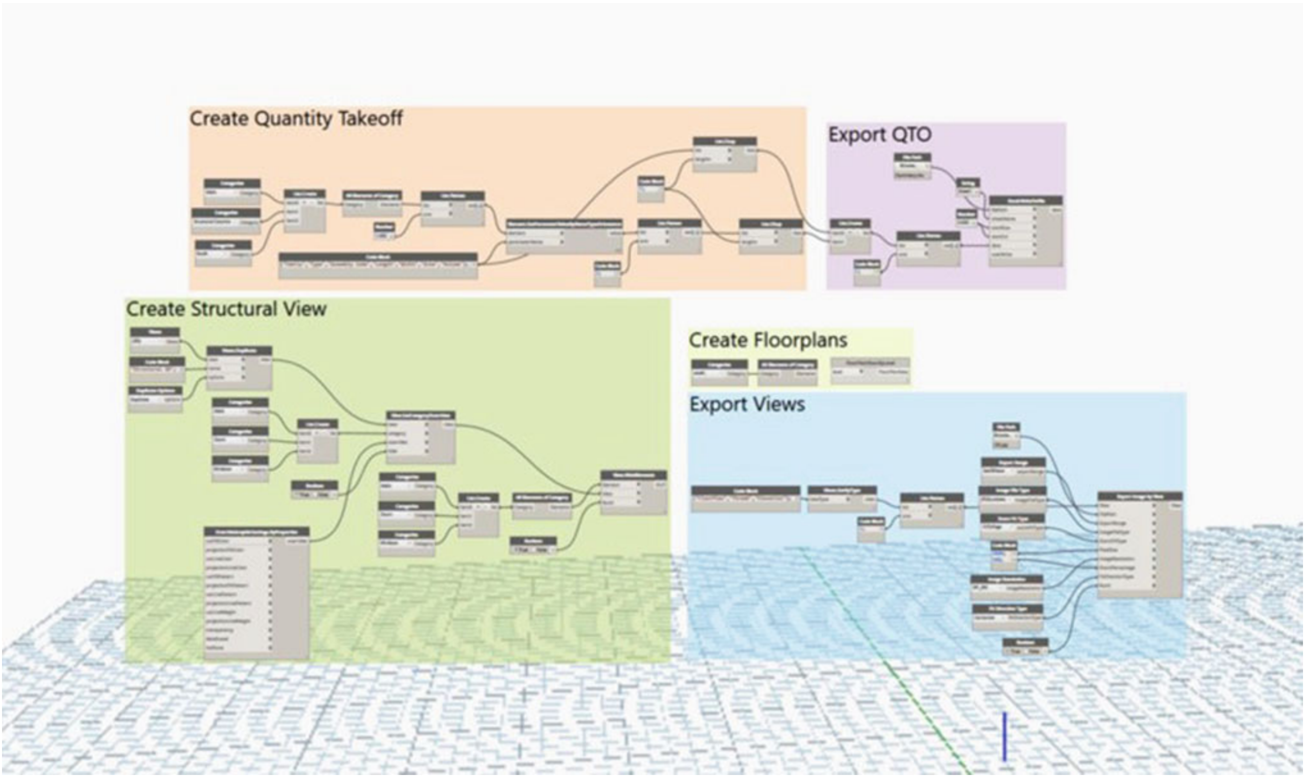

Fig. 42.5 Revit/Dynamo script for automating economic analysis

During the studio program, students used various methods to visualize their design intent and results of analyses. A lesson the instructor team learned was that creating a design dashboard helps students to prepare the required visualization items in a more consistent manner. Therefore, a last step is added to the developed workflow, during which studio teams visualize their work output by importing architectural and construction analyses' data as well as other useful information (e.g. 2D/3D views, analysis images, etc.) into a dashboard. For this purpose, the instructor team is currently developing a design dashboard template using the Microsoft Power BI.

42.4 Conclusion

This paper shares the experience of an integrated design studio program in terms of forming an integrated multi-disciplinary team, implementing a standard framework for parametric, computational, and performance-based design, developing a framework for evaluating the design decisions based on multi-variate empirical performance metrics, and adopting new computational tools for design development, analysis, and visualization.

The integrated studio program is a fast-growing pedagogical practice in the academia as it responses to the current demand for integration between design and construction processes and enables project teams to benefit from the emerging data-driven built environment and also provides an opportunity for industry-academia collaboration.

In this studio, the instructor team aimed to make a balance between the three teaching scopes of computational methods namely BIM tools, and Visual Programming Language (VPL) tools (Grasshopper and Dynamo), discipline-specific knowledge and practices, and integrated team collaboration and communication. As a result, although students took advantage of computational methods for design generation and analysis they still had the freedom to explore design concepts from different perspectives and create design alternatives beyond the use of parameters and metrics. Additionally, students practiced their domain-specific methods using the provided assignments and in parallel learned to manage collaboration with other disciplines through early definition of roles and responsibilities, clear and timely communication of their data requirements, and implementation of divergent/convergent thinking during the process of idea generation, discussion and decision making.

References

1. Eastman, C., Teicholz, P., Sacks, R.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd edn. Wiley, New York (2011)
2. Deutsch, R.: Data-Driven Design and Construction, 25 Strategies for Capturing, Analyzing, and Applying Building Data. Wiley, New Jersey (2015)
3. Kwok, A.G., Grondzik, W.T.: The Green Studio Handbook: Environmental Strategies for Schematic Design, 2nd edn. Elsevier. Architectural Press, Amsterdam (2011)
4. Johnson, B.R.: Design Computing, An Overview of an Emerging Field, Routledge. Taylor & Francis Group, New York (2017)
5. Busby Perkins+Will, Stantec Consulting: Roadmap for the Integrated Design Process, developed for BC Green Building Roundtable (2007)
6. Haymaker J., Bernal, M., Marshall, T., Okhoya, V., Szilasi, A., Rezaee, R., Chen, C., Salveson, A., Brechtel, J., Deckinga, L., Hasan, H., Ewing, P., Welle, B.: Design Space Construction: A Framework to Support Collaborative, Parametric Decision Making. Accepted ITCON (2018)
7. Nicknam, M., Bernal, M., Haymaker, J.: A Case Study in Teaching Construction of Building Design Spaces, CAAD Curriculum, vol. 2, Computation and Performance (2013)
8. Gerber, D.J., Flager, F.: Teaching Design Optioneering: A Method for Multidisciplinary Design Optimization, Computing in Civil Engineering, ASCE, pp. 883–890 (2011)
9. Design Space Construction.org (A research initiative of Perkins+Will): University of Washington Department of Architecture Firestone Studio (ARCH 504) Winter 2017. http://designspaceconstruction.org/portfolio-item/seattle-lake-union-lbc/, Retrieved 13 June 2018
10. Fischer, M., Aschcraft, H., Reed, D., Khanzode, A.: Integrating Project Delivery. Wiley, New Jersey (2017)

Integrating BIM, Optimization and a Multi-criteria Decision-Making Method in Building Design Process

43

Elaheh Jalilzadehazhari and Peter Johansson

Abstract

European Energy Performance of Building Directive (EPBD) defined a target as all new constructed buildings within the EU region must be a zero-energy building by the end of 2020. Furthermore, all European countries must ensure the minimum comfort threshold in energy calculations. Reducing energy consumption and improving indoor comfort, including visual and thermal comfort, can contribute to economic benefits. However, the main problem is the exitance of conflicts among visual comfort, thermal comfort, energy consumption and life cycle cost. To solve the abovementioned problem and to fulfil the EPBD's target, this study aims to apply an integration between BIM, optimization and Analytical Hierarchy Process as a multi-criteria decision-making method on an office building in Sweden. Accordingly, 3 types of windows and 5 types of external wall, ground floor and external roof constructions were specified as optimization variables. The combination between the optimization variables generated 375 design alternatives. The performance of all 375 design alternatives were evaluated with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Later, AHP was used to find a trade-off design alternative. The results show that the combination between window type 1, external wall type 5, ground floor type 1 and external roof type 5 is the trade-off design alternative. Furthermore, the results show the integration enables to solve the abovementioned conflicts and to fulfil the EPBD's target.

Keywords

Building information modelling • Optimization • Analytical hierarchy process • Decision making

43.1 Introduction

The Energy Performance of Building Directive (EPBD) has determined a target as all new constructed buildings, within the EU region, must be near zero energy buildings by the end of 2020 [1]. In addition, the subsequent annex to the EPBD demands all European countries to ensure the minimum comfort threshold, defined at the national level, in the calculation of energy consumption [1]. In Sweden, office buildings gain a significant role in decreasing the total energy consumption. Because, office buildings, with a total area of 32.3 million square meter, make up the second greatest share among the non-residential buildings in Sweden [2]. Office buildings were responsible for about 6.25 TWh energy consumption[1] in 2016, which correspond to 32.5% of the total used energy within the non-residential building sector in Sweden [3].

[1]Total energy consumption comprised the energy need for space heating, cooling, domestic hot water, electricity need for lighting, ventilation and office equipment.

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According to International Energy Agency [4] decreasing the energy consumption contributes to a gradually reduction in greenhouse gas emissions and provides a steading increase in economic growth.

In addition to energy consumption, indoor environment in office buildings have also a substantial role in presenting economic benefits [5, 6]. Because, improving indoor environment, especially visual and thermal comfort, contributes to a higher level of productivity and enhanced health [7, 8], which can provide further economic benefits in the lifecycle of office buildings [5, 6]. Therefore, building professionals are expected to concurrently reduce energy consumption and cost also improve visual and thermal comfort. Accomplishing this task requires a constructive communication between building professionals, including architects, energy experts and engineers from different specialties [9, 10]. At this point, the use of object-based parametric modelling or Building Information Modelling (BIM) provides possibilities for interoperability information sharing between prevalent simulation tools and thereby between building professionals [10]. Having constructive communications between professionals through the implementation of BIM not only helps to improve buildings performance, but also can significantly reduce the required time, effort and unpredicted errors in building design process [11]. At this point, Sakikhales and Stravoravdis [12] and Rahmani Asl et al. [10] discussed that benefits from the implementation of BIM can be complemented by integrating it with optimization. Because, the integration not only provides abovementioned benefits with using BIM but also it allows to use optimization to expands the set of design alternatives investigated [10]. Furthermore, the integration helps professionals to resolve the conflicts among at the most three design objectives, such as visual or thermal comfort, energy consumption and life cycle cost [13] and find a trade-off design alternative. Accordingly, the integration allows professionals to make suitable decisions in early stage of building design process [14].

But, at the presence of more than three objectives, the integration between BIM and optimization is incapable of resolving conflicts. At this point, Mosavi [15] discussed that a multi-criteria decision-making (MCDM) method can help to overcome the limitation in using optimization. The integration between BIM, optimization and a MCDM method allows (i) to generate and use a BIM model for establishing a constructive communication between professionals, (ii) to generate multiple design alternatives using optimization and (iii) to solve conflicts between more than three objectives and find a trade-off design alternative using a MCDM method and making suitable decisions. However, to the best of authors knowledge, the integration between BIM, optimization algorithm and a MCDM method was not previously employed to solve conflicts among visual comfort, thermal comfort, energy consumption and life cycle cost. Considering the mentioned need, this study aims to apply the abovementioned integration on an office building.

43.2 Methodology

The applied methodology for employing the abovementioned integration on the office building follows three main sections, including the generation of BIM model, preparing the BIM model for performing an optimization, and performing the optimization and using a MCDM method.

43.2.1 BIM

A BIM model of an office building was generated using Revit Autodesk tool. The office building was in Gothenburg municipality, Sweden. It had three heated floors above the ground with a total area of 2821.5 m^2. Each floor comprised offices, meeting and lecture rooms. The fourth floor, with a total area of 278 m^2, was an unheated area and equipped with heating, ventilation and air conditioning (HVAC) systems.

Revit provides possibilities to develop a model of a building and allows several professionals to access the model simultaneously, thereby improves communications between them and reduces unpredicted errors in the building design process [16]. The generated BIM model was then exported as a Green Building xml (gbxml) format file. The gbxml format helps to share building information between different simulation tools [16]. In this study, the gbxml file included information regarding the location and geometry of the office building, material specifications of building envelopes, heating, ventilation and air conditioning system, occupancy and operation schedules. The information, included in the gbxml model, were provided by several professionals, including architects, energy experts and engineers from different specialties.

43.2.2 Preparing the BIM Model for Performing an Optimization

The gbxml file was converted to EnergyPlus Input Data File (idf) using Design Builder simulation tool, version 5.0.3.007. Design Builder is a graphical user interface for EnergyPlus and allows to perform various evaluations considering visual comfort, thermal comfort, energy consumption and life cycle cost [17]. The office building was connected to district heating system, which provided energy need for space heating and domestic hot water. Furthermore, the office building was equipped with an exhaust ventilation with a heat recovery system. The efficiency of ventilation fan and the heat recovery was 60 and 76% respectively. The air tightness was 0.1 (ach) at differential pressure of ±50 (Pa). The occupants' activity level was set to 1.2 (met) and their clothing resistance was set to 0.5 (clo) in summer and 1 (clo) in winter [18]. A fluorescent electrical lighting with 9.9 (W/m^2) power was also considered in the simulations. The heat gain from electrical lighting was assumed to be around 82%. The building occupancy schedule during working days was set to be between 07:00 am to 18:00 pm.

Finally, the idf file was modified using EnergyPlus version 8.5.0. Various building envelopes, including 3 types of windows and 5 types of external wall, ground floor and external roof constructions were specified in idf file. This decision was made due to efficacy of building envelopes in improving visual comfort, thermal comfort and reducing energy consumption and life cycle cost. Table 43.1 shows the considered building envelopes in this study. The U-values of external wall, ground floor and roof constructions were changed by modifying the thickness of insulation layer within the construction of these building envelopes. The U-value of the building envelopes in Table 43.1 were equal or lower than the requirements of the Swedish building code for new buildings (BBR 2015) [19].

The visual comfort evaluations in this study comprised the calculation of daylight illuminance and daylight glare index. For this purpose, 3 reference points on the second floor and 4 reference points on the fourth floor were specified at 0.8 m from floor level (Appendix 1). This decision was made because the large glazing area in the second and third floor may deteriorate visual or thermal comfort. The visual comfort evaluations were performed by (i) obtaining the number of hours, when daylight illuminance at the reference points exceeded 500 lx and (ii) obtaining the number of hours, when daylight glare index at the reference points exceeded 22. The reflectance of interior surfaces including walls, ceiling and floor follows the Swedish standard [20] and was defined as 60, 80 and 20% respectively.

Thermal comfort, energy consumption and life cycle cost evaluations were accomplished by calculating predicted percentage of dissatisfied (PPD), total energy consumption (E_t) and present value (K_n) respectively. Total energy consumption comprised energy need for space heating, cooling, electricity for lighting and ventilation system. According to National board of housing building and planning [19], the total energy consumption in office buildings in Sweden should be at most 70 kWh/m^2. To calculate the present value, the investment cost of different windows, external wall, ground floor and external roof constructions were obtained using EnergyPlus. The investment cost refers to the material cost, used in external wall, ground floor and external roof constructions, which was derived from Wikells construction calculations [21]. The investment cost of windows was based on the unit price of each window multiplied by the total window area, that was collected from Elitfonster [22]. Table 43.2 shows the U-value and investment cost per 1 m^2 of 3 types of windows and 5 types of external wall, ground floor and external roof constructions.

43.2.3 Optimization and MCDM

An optimization is mainly performed to find an optimal design alternative by interacting optimization variables [23]. According to Uy and Telford [24], Design of Experiment (DOE) is a statistical technique, which allows to optimize the performance of a system with determined optimization variables. To perform DOE, EnergyPlus was coupled to modeFRONTIER platform. The modeFRONTIER platform enable to perform an optimization and allows to use a MCDM method to find a trade-off design alternative [25]. The coupling process was accomplished by writing a DOSBatch file.[2] DOSBatch file allows to run the EnergyPlus via modeFRONTIER.

Later, optimization variables and constraints were defined in modeFRONTIER platform. In this study, all building envelopes, stated in Table 43.1 were considered as optimization variables. The combination of 3 types of windows and 5

[2]modeFRONTIER has various of nodes including logic nodes, data nodes, file nodes, application nodes, script nodes, CAD nodes, CAE nodes and networking nodes. Nodes are executable components, which have data and accomplish some transformations over the data, later forward the data to the next node [26]. DOSBatch node is one of the available script nodes.

Table 43.1 Considered building envelopes

	Building envelopes
Windows	Three types of glazing systems with U-value of 1.2, 1 and 0.9 W/K.m^2
External walls	Five types of external walls with U-value of 0.18, 0.14, 0.12, 0.1 and 0.09 W/K.m^2
Ground floor	Five types of ground floors with U-value of 0.15, 0.12, 0.1, 0.09 and 0.08 W/K.m^2
External roof	Five types of external roofs with U-value of 0.13, 0.12, 0.1, 0.09 and 0.08 W/K.m^2

Table 43.2 Different building envelopes

Building envelopes	U-value (W/K m^2)	Investment cost (SEK/m^2)[a]
Windows		
Type 1	1.2	3786
Type 2	1	4360
Type 3	0.9	5831
External walls		
Type 1	0.18	1403.6
Type 2	0.14	1433
Type 3	0.12	1505.7
Type 4	0.1	1530
Type 5	0.09	1599
Ground floor		
Type 1	0.15	589.5
Type 2	0.12	711.4
Type 3	0.1	758
Type 4	0.09	880
Type 5	0.08	956
External roof		
Type 1	0.13	389
Type 2	0.12	411
Type 3	0.1	426.2
Type 4	0.09	445.4
Type 5	0.08	463.4

[a]SEK: Swedish crowns

types of external wall, ground floor and roof constructions generated 375 design alternatives. The DOE allowed to analyze the performance of the all 375 design alternatives with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Furthermore, PPD less than 10 was considered as an optimization constraint. According to Pourshaghaghy and Omidvari [27], a PPD less than 10 represents a comfortable thermal environment.

Considering life cycle cost, investment cost of building envelopes and the energy consumption for space heating, cooling, electricity for lighting and ventilation system were obtained by EnergyPlus. The total investment cost of 3 types of windows and 5 types of external wall, ground floor and roof constructions were calculated based on total area of the building envelopes multiply the unit price of them, stated in Table 43.2.

Later, a calculator node in modeFRONTIER was used to calculate the present value of all 375 design alternatives using Eq. 43.1.

$$K_n = \sum_{t=0}^{n} (D_t + U_t) * \frac{1}{(1+r)^t} + I_0 \qquad (43.1)$$
$$D_t = E * \alpha(1+\beta)^t$$

where

K_n	is present value during lifespan of n year;
U_t	is annual maintenance cost;
D_t	is annual energy consumption cost;
r	is interest rate;
t	is lifespan of n years;
E	is annual energy consumption (kWh/m^2);
α	is energy price per kWh/m^2;
β	is inflation in energy price (%); and
I_0	is the investment cost.

In calculating the present value, a discount rate of 3%, an inflation rate of 1% and a lifetime of 30 years were considered. The heating and electricity energy price was set to be 0.74 (SEK7 kWh) and 1.38 (SEK/kWh) respectively [28]. Table 43.3 shows the lifetime of investigated windows, external wall, external roof and ground floor constructions and their maintenance cost.

Equation 43.2 shows the mathematical formulation of the optimization problem in this study.

$$\begin{gathered} \min_{x \subset X} F_1(x) = [H_{DGI>22}, E_t, K_n] \\ \text{and} \\ \max_{x \subset X} F_2(x) = [H_{illu>500}] \\ \text{Subject to: PPD} < 10 \end{gathered} \tag{43.2}$$

where

$H_{DGI>22}$	represents the number of hours, when daylight glare index at the reference points exceeded 22;
$H_{ill>500}$	refers to the number of hours, when daylight illuminance at the reference points exceeded 500 lx;
E_t	refers to the total energy need for space heating and electricity for lighting and artificial ventilation;
K_n	represents the net present value of different window designs;
PPD < 10	refers to the predicted percentage of dissatisfied smaller than 10, which was considered as an optimization constraint.

The developed workflow in modeFRONTIER platform was illustrated in Appendix 2.

To find a trade-off design alternative among all 375 alternatives, Analytical Hierarchy Process (AHP), as a MCDM method, was employed using modeFRONTIER platform. AHP was used to find a design alternative based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost by using mode-FRONTIER platform. The first step in using AHP is to develop a hierarchy model, which comprises the goal of using AHP, objectives and their respective criteria [29].

Figure 43.1 shows the developed hierarchy model in this study.

Later pairwise comparisons, based on a scale of importance, presented in Table 43.4, were performed between objectives of AHP and their criteria [29].

Performing pairwise comparisons generates a comparison matrix. Matrix A shows the performed pairwise comparisons among the objectives in Fig. 43.1. The weight of each objective was calculated (i) by calculating the sum of each column in the matrix A; (ii) by dividing each value in the matrix to its respective column sum, calculated in previous step and (iii) by obtaining the average of each row.

Table 43.3 Lifetime and maintenance cost of building envelopes

Building envelopes	Lifetime (years)	Maintenance cost (SEK/m^2)
All 3 types of windows	30	0
All 5 types of external walls	30	0
All 5 types of ground floors	30	0
All 5 types of external roofs	30	0

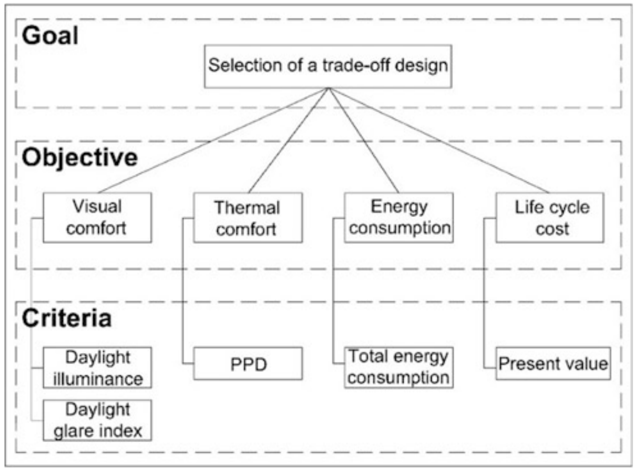

Fig. 43.1 An illustration of the developed hierarchy model

Table 43.4 Scale of importance applied in using AHP

Scale	Description
1	Two objectives/criteria are equally importance
3	Objective/criterion *i* is moderately more importance than the objective/criterion *j*
5	Objective/criterion *i* is strongly more importance than the objective/criterion *j*
7	Objective/criterion *i* is very strongly more importance than the objective/criterion *j*
9	Objective/criterion *i* is extremely more importance than the objective/criterion *j*

$$A = \begin{array}{l} \\ \text{Visual comfort} \\ \text{Thermal comfort} \\ \text{Energy consumption} \\ \text{Life cycle cost} \end{array} \begin{array}{c} \begin{array}{cccc} \text{Visual comfort} & \text{Thermal comfort} & \text{Energy consumption} & \text{Life cycle cost} \end{array} \\ \begin{bmatrix} 1 & 2 & 7 & 7 \\ 1/2 & 1 & 7 & 7 \\ 1/7 & 1/7 & 1 & 1 \\ 1/7 & 1/7 & 1 & 1 \end{bmatrix} \end{array} \begin{array}{c} \text{Weight} \\ 0.52 \\ 0.36 \\ 0.06 \\ 0.06 \end{array}$$

Matrix B shows the performed pairwise comparisons among visual comfort criteria. The weight of each criteria in matrix B was calculated following 3 abovementioned steps. Furthermore, the pairwise comparisons in matrix A and B follows the applied comparisons in the work presented by Jalilzadehazhari et al. [30].

$$B = \begin{array}{l} \\ \text{Daylight illuminance} \\ \text{Daylight glare index} \end{array} \begin{array}{c} \begin{array}{cc} \text{Daylight illuminance} & \text{Daylight glare index} \end{array} \\ \begin{bmatrix} 1 & 2 \\ 1/2 & 1 \end{bmatrix} \end{array} \begin{array}{c} \text{Weight} \\ 0.667 \\ 0.333 \end{array}$$

Considering thermal comfort, energy consumption and life cycle cost, since PPD, E_t and K_n were the only criteria, used for evaluating them, no pairwise comparisons were performed.

43.3 Results

Performing DOE allowed to analyze the performance of all 375 design alternatives with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Considering visual comfort criteria, the number of hours, when daylight illuminance exceeded 500 lx at 7 reference points was varied according Table 43.5.

Table 43.5 Variation in number of hours, when daylight illuminance exceeded 500 lx among 7 reference points

Reference points	Window type 1	Window type 2	Window type 3
	(h)	(h)	(h)
Second floor, point 1	1890.5	1722	1718
Second floor, point 2	1273	1076	1071
Second floor, point 3	3450	3362	3361
Third floor, point 1	1851	1684	1681.5
Third floor, point 2	1263	1082.5	1078
Third floor, point 3	1274.5	1140	1134.5
Third floor, point 4	1301	1207	1192

The daylight glare index was exceeded 22 on the second floor at point 2 and on the third floor at point 2 and 4. But, the daylight glare index was less than 22 at the other reference points during the full year. Table 43.6 shows the number of hours when daylight glare index was exceeded 22 with respect to 3 types of windows.

Considering thermal comfort, the PPD among the initial 375 design alternatives was changed between 6 and 13. As result, only 70% of design alternatives (262 of 375) had a PPD smaller than 10 and was considered as designs, which provided a comfortable thermal environment.

With respect to energy consumption, the E_t varied between 67 and 77 kWh/m^2. However, only 67% of the design alternatives (250 of 375) had a total energy consumption less than 70 kWh/m^2 and fulfilled the Swedish National board of housing building and planning [19] requirements. Considering life cycle cost, the K_n was changed between 8.4 million SEK and 9.5 million SEK.

In using AHP, only design alternative with a PPD less than 10 and E_t less than 70 kWh/m^2 were considered. This decision was made to ensure the minimum requirements considering thermal comfort and total energy consumption. Accordingly, AHP was applied on 250 design alternatives and remaining designs were excluded from the pairwise comparison process.

The results show that the combination between window type 1 with U-value of 1.2 (W/m^2. K), external wall type 5 with U-value of 0.09 (W/m^2. K), ground floor type 1 with U-value of 0.15 (W/m^2. K) and external roof type 5 with U-value of 0.08 (W/m^2. K) is the best design alternative based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost. Considering visual comfort, the window type 1 provided a larger amount of daylight into the interior environments. Since visual comfort was specified as the most important objective, the abovementioned design alternative with window type 1 was selected as the trade-off design. Considering thermal comfort, including or excluding PPD into the pairwise comparison had no effect on the results, because all 250 design alternatives had a PPD less than 10. With respect to energy consumption, the E_t of the trade-off design alternative was 67.3 kWh/m^2. External walls with a total area of 1872.3 m^2 shared the largest building envelop among the other building envelopes. Accordingly, external wall type 5 enabled to reduce the total energy consumption significantly.

The external roof and the ground floor had an identical area. However, the temperature difference between inside and outside of the external roof was larger than the temperature difference between inside and outside of the ground floor. Accordingly, the external roof type 5 could notably reduce the total energy consumption.

With respect to the life cycle cost, the K_n of the trade-off design alternative was 9.2 million SEK. About 80% of the investigated design alternatives (250 of 375) had a K_n smaller than the trade-off design alternative.

Table 43.6 Variation in number of hours, when daylight glare index exceeded 22

Reference points	Window type 1	Window type 2	Window type 3
	(h)	(h)	(h)
Second floor, point 2	2164	2010.5	2010.5
Third floor, point 2	2187	2045	2045
Third floor, point 4	1898	1729.5	1729.5

43.4 Conclusions

European Energy Performance of Building Directive (EPBD) demands all new constructed buildings, within the EU region, to be near zero energy buildings by the end of 2020. Furthermore, EPBD asked all European countries to ensure the minimum comfort threshold, defined at the national level, while calculating the total energy consumption. According to International Energy Agency, reducing energy consumption can contribute in economic growth at the national level. In line with abovementioned statements, improving indoor environment comfort, including visual and thermal comfort, can also provide economic benefits by enhancing occupants' health and productivity. At this point, building professionals are expected to reduce energy consumption and cost also improve visual and thermal comfort simultaneously. However, the main problem is the existence of conflicts between visual comfort, thermal comfort, energy consumption and life cycle cost. To overcome the abovementioned problem, this study aimed to apply an integration between building information modelling, optimization and a multi-criteria decision-making method on an office building in Sweden. Because, the integration allows (i) to establish a constructive communication between professionals for reducing unpredicted errors in the building design process, (ii) to generate multiple design alternatives and (iii) to find a design alternative based on trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost.

The office building model was generated using Revit Autodesk and exported as a gbxml format. Later, the gbxml file was converted to EnergyPlus idf file, using Design Builder simulation tool. Then, the idf file was modified in EnergyPlus to be used during the optimization process. In this study, the optimization was performed by running DOE technique in modeFRONTIER platform. The optimization variables comprised 3 types of windows and 5 types of external wall, external roof and floor constructions with different U-values. The combination between the optimization variables generated 375 design alternatives. Later, AHP method was used in modeFRONTIER to find a design alternative based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost. The results show that the combination between window with a U-value of 1.2 (W/m^2. K), external wall with a U-value of 0.09 (W/m^2. K), ground floor with a U-value of 0.15 (W/m^2. K) and external roof with a U-value of 0.08 (W/m^2. K) is the trade-off design alternative. The total energy consumption and present value (representing life cycle cost) of the trade-off alternative were 67.3 kWh/m^2 and 9.2 million SEK respectively.

Currently, making decisions based on the life cycle cost of various design alternatives is prevalent in Sweden. Because, present value not only considers the energy cost during the lifetime of a building but also takes the investment and maintenance costs into the account. At this point, the design alternative with 8.4 million SEK, corresponding the lowest present value, could be considered as a remarkable design alternative. However, the applied method is this study took one step further, as it integrated BIM, DOE and AHP and selected a design alternative based on trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost. Furthermore, the applied method enabled to fulfil the EPBD's target.

However, the result was strongly dependent on the pairwise comparisons, performed between objectives of AHP and their respective criteria. The applied methodology in this study, based on integration between BIM, optimization and a MCDM method, can be applied both in designing new buildings or retrofitting existing buildings.

The future work includes the expansion of the optimization variables, as various heating, cooling and air conditioning systems together with different window size and forms will be considered in the application of the integration. Furthermore, the sensitivity of the results considering changes in pairwise comparisons, will be analyzed.

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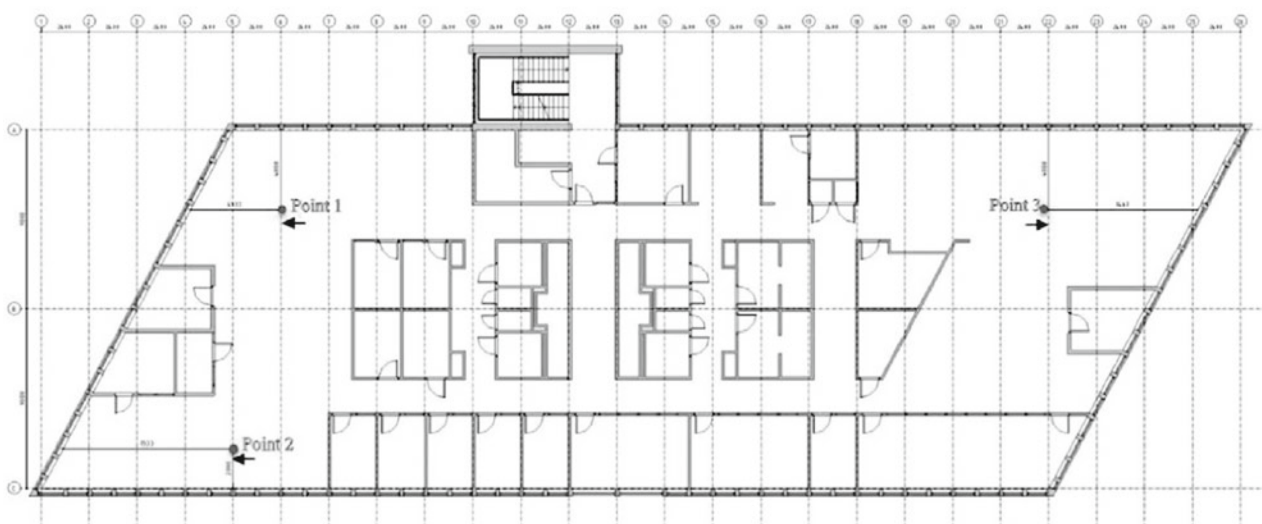
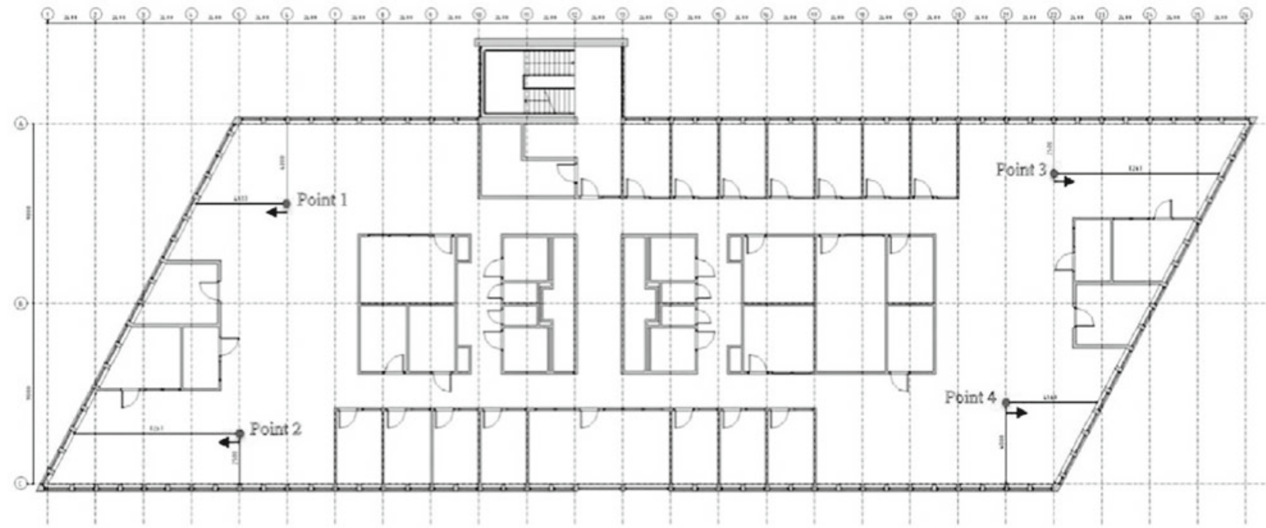
Appendix 1

First floor plan

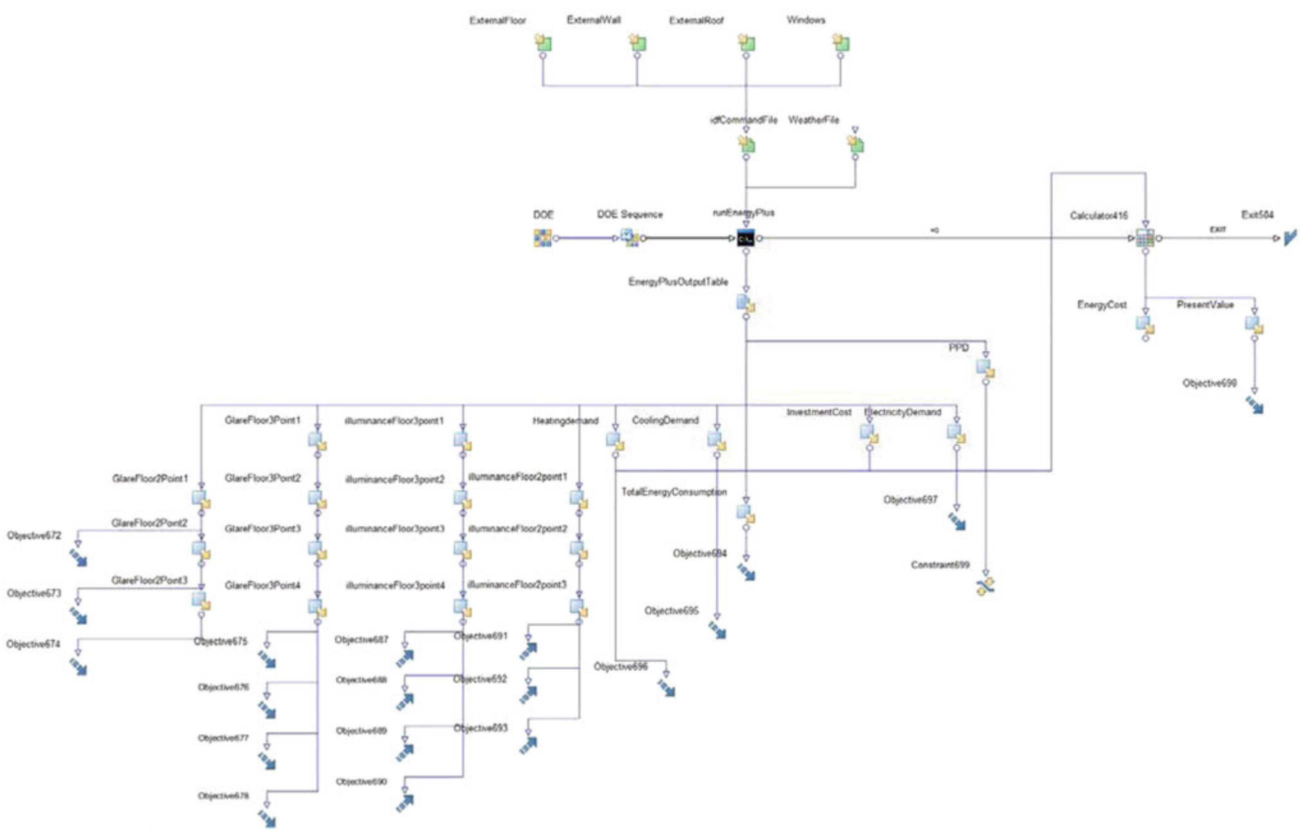


Second floor plan



Third floor plan

Appendix 2



References

1. EPBD, ANNEX to the Proposal for a Directive of the European Parliament and of the Council. Amending Directive 2010/31/EU on the energy performance of buildings. Annex I, point 2., Official Journal of the European Union (2016)
2. Swedish Energy Agency, Energy statistics for non-residential building 2016 [In Swedish: Energistatistik i lokaler 2016], Bromma, Sweden, p. 56 (2017)
3. Swedish Energy Agency, Energy Situation [Title in Swedish: Energiläget], Bromma, Sweden, pp. 1–86 (2017)
4. International Energy Agancy, Energy Policies of IEA Countries, Sweden, 2013 Review, France, pp. 0–28 (2013)
5. Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., Elsarrag, E.: Occupant productivity and office indoor environment quality: a review of the literature. Build. Environ. **105**, 369–389 (2016)
6. Kats, G., Alevantis, L., Mills, E., Perlman, J.: The costs and financial benefits of green buildings: a report to California's sustainable building task force, Sustainable Building Task Force, California (2003)
7. Aries, M., Aarts, M., van Hoof, J.: Daylight and health: A review of the evidence and consequences for the built environment. Lighting Res. Technol. **47**(1), 6–27 (2015)
8. Heerwagen, J.: Green buildings, organizational success and occupant productivity. Build. Res. Inf. **28**(5–6), 353–367 (2000)
9. Muller, M.F., Loures, E.R., Canciglieri, O.: Interoperability Assessment for Building Information Modelling, 5th International Conference on Structures and Building Materials (ICSBM 2015), 2015
10. Rahmani Asl, M., Stoupine, A., Zarrinmehr, S., Yan, W.: Optimo: a BIM-based multi-objective optimization tool utilizing visual programming for high performance building design. In: Martens, B., Wurzer, G., Grasl, T., Lorenz, W.E., Schaffranek, R. (ed.) Proceedings of the 33rd eCAADe Conference, Vienna University of Technology, Vienna, Austria, pp. 673–682 (2015)
11. Eastman, C.M., Eastman, C., Teicholz, P., Sacks, R.: BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. Wiley, New York (2011)
12. Sakikhales, M., Stravoravdis, S.: Using BIM to facilitate iterative design, building information modelling (BIM) in design. Constr. Oper. **149**, 9–19 (2015)
13. Chand, S., Wagner, M.: Evolutionary many-objective optimization: a quick-start guide. Surv. Oper. Res. Manage. Sci. **20**(2), 35–42 (2015)
14. Rahmani Asl, M., Zarrinmehr, S., Bergin, M., Yan, W.: BPOpt: a framework for BIM-based performance optimization. Energy Build. **108**, 401–412 (2015)
15. Mosavi, A.: Multiple criteria decision-making preprocessing using data mining tools, arXiv preprint arXiv:1004.3258 (2010)
16. Revit.: https://www.autodesk.com/products/revit-family/overview. Retrieved Dec. 2017
17. Design Builder.: www.designbuilder.co.uk (2017)
18. ISO7730-Standard, 7730. Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Organization for Standardization: Geneva, Switzerland (2005)
19. National board of housing building and planning, Building regulation, [In Swedish: Boverkets byggregler, BFS 2011: 6 med ändringar till och med 2015: 3], National board of housing, building and planning, [In Swedish: Boverket] 2015
20. Månsson, L., Schönbeck, Å.: Light & Room, guide for planning of indoor lighting [In Swedish: Ljus & rum: planeringsguide för belysning inomhus], Ljuskultur, Stockholm, Sweden (2003)
21. I.S.W.B. Wikells construction calculations, AB], Sectional Facts - NYB 12/13: Technical-Economic Compilation of Buildings, [In Swedish: Sektionsfakta - NYB 12/13: teknisk-ekonomisk sammanställning av byggdelar], 22 ed., Växjö: Wikells byggberäkningar, Växjö (2012)
22. Elitfonster.: www.elitfonster.se (2016)
23. Koziel, S., Yang, X.-S.: Computational optimization, methods and algorithms. Springer, Berlin (2011)
24. Uy, M., Telford, J.K.: Optimization by Design of Experiment Techniques, Aerospace Conference, 2009 IEEE, IEEE, pp. 1–10 (2009)
25. esteco.: http://www.esteco.com/modefrontier. Accessed Nov. 2017
26. Sousa, T.B.: Dataflow programming concept, languages and applications, Doctoral Symposium on Informatics Engineering (2012)
27. Pourshaghaghy, A., Omidvari, M.: Examination of thermal comfort in a hospital using PMV–PPD model. Appl. Ergon. **43**(6), 1089–1095 (2012)
28. Gustafsson, M., Gustafsson, M.S., Myhren, J.A., Bales, C., Holmberg, S.: Techno-economic analysis of energy renovation measures for a district heated multi-family house. Appl. Energy **177**, 108–116 (2016)
29. Saaty, T.L.: Decision making with the analytic hierarchy process. Int. J. Serv. Sci. **1**(1), 83–98 (2008)
30. Jalilzadehazhari, E., Johansson, P., Johansson, J., Mahapatra, K.: Application of analytical hierarchy process for selecting an interior window blind, Architectural Eng. Des. Manage. 1–17 (2017)

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A BIM-Based Decision Support System for Building Maintenance

44

Fulvio Re Cecconi, Nicola Moretti, Sebastiano Maltese, and Lavinia Chiara Tagliabue

Abstract

Available data about asset condition and performances can be conveyed into different Key Performance Indicators (KPIs). Many KPIs measuring technical, functional and economic/financial asset performances can be found in literature. Nevertheless, they are often strictly related to a specific scope, thus they provide an incomplete depiction of the whole assets performances. The objective of this research is to provide facility managers and asset owners with an easy instrument to prioritize maintenance. In order to reduce costs related to its use, the instrument, developed in the form of a Decision Support System (DSS), is based on existing and reliable performances metrics and leverages new technologies like Building Information Modelling (BIM). Accordingly, the Facility Condition Index (FCI) is combined with the D index, a KPI related to the age of building components, developed by the authors. The joint use of the FCI and the D index, allows facility managers to make more conscious decisions. The proposed DSS helps in the definition of the best maintenance plan, providing a ranking of building components which require more urgent maintenance interventions. Although the DSS should be tested measuring its ability to preserve buildings and their performances on a long term, the first results are positive, as confirmed by the application to a case study on an office building in Italy. Moreover, the usability of the instrument has been appreciated by the users in a medium size Italian company.

Keywords

DSS • Maintenance • FCI • Building condition assessment

44.1 Introduction

Management of building maintenance is one of the biggest challenges in Facility Management (FM) since in this sector, nowadays, most of the economic resources related to the construction industry are spent. Additionally, a more sustainable built environment can be reached only by improving energy and environmental performances of physical assets optimizing, as instance, the maintenance choices [1].

Despite the huge amount of data produced and recorded by new technologies during the whole lifecycle of a building, facility managers make decisions on maintenance with limited knowledge concerning buildings condition [1]. Available data

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about asset condition and performances can be conveyed into different Key Performance Indicators (KPIs) [2]. Nevertheless, KPIs are often strictly related to a specific field, thus they provide an incomplete picture of the whole assets performances.

The objective of this research is to provide facility managers and asset owners with an easy instrument to prioritize maintenance, based on existing and reliable performance metrics and leveraging new technologies like Building Information Modelling (BIM). For this purpose, a Decision Support System (DSS) based on the Facility Condition Index (FCI) and service life of building components has been developed. The DSS has been integrated within the Building Information Modelling (BIM) approach and a has been tested through a case study concerning an office building located in Erba, Italy.

44.2 Background of the Research

In this paragraph the background of the research is presented, stressing on the possibilities and advantages provided by the use of an effective Decision Support System (DSS) for Operations Maintenance and Repair (OM&R) management. Moreover, potentialities and criticalities of the Facility Condition Index (FCI), one of the most acknowledged KPIs for maintenance management are presented.

44.2.1 Decision Support Systems for Management of Buildings

Decision Support Systems (DSS) are frequently used when dealing with the built environment [3, 4]. Their importance lies in the possibility of comparing multiple features, computed both through subjective and objective parameters and calculation methods. DSS weaknesses generally include: the high influence of the weights used, the reliability of the parameters calculated and their need for large amount of data to be gathered and elaborated in order to produce reliable results. In general, they should be used in the early project phases, although their precision is higher when more data are available (and less changes are possible).

DSS can be based on several data processing techniques though, usually, they are all based on Multi-Criteria Analysis Techniques, which allow data normalization, elaboration, comparison and eventually, alternatives' ranking and selection.

A robust method, frequently used in association with a DSS [5], is the Analytical Hierarchy Process (AHP), which allows for parameters weights calculation. The method was first proposed by the mathematician Saaty in the 80s [6] and is frequently and successfully coupled with the Delphi method, no matter the topic, in order to enhance the quality of the weights calculated and achieving more precise results [7].

Another issue to be faced in the development of a DSS concerns the connection with the data to be gathered, the less work needs to be done, the faster will be the analysis, thus the connection with the BIM processes [8], can enhance a better information flow.

44.2.2 Facility Condition Index

The Facility Condition Index (FCI) is a metric widely exploited for assessment of assets [3], thanks to its scalability from the single component to the whole real property [9, 10]. Therefore, it is a powerful tool which makes assets comparable in measures of maintenance performances. In its basic form it is used for evaluation of costs of deferred maintenance (DM), over the Current Replacement Value (CRV) of the component [11]. The FCI allows to quantify in a scale from 0 to 100 (where 0 represents the best value) the condition of an asset based on the expense dedicated to maintenance operations [11]. The assessment phase is a crucial issue for the calculation of the metric. Nevertheless, the calculation methodology can vary according to the objective to be achieved [12]. Moreover, a standardized definition of algorithms to be used cannot be found in literature [13].

The FCI is affected by some other issues. For instance, the ratio calculated through the indicator does not represent the magnitude of the DM interventions, since the output value is mainly influenced by the CRV. For this reason, the FCI calculated for two similar components characterized by similar deferred maintenance interventions (with analogous cost), could be affected by substantial differences according to the value of the CRV. Accordingly, the FCI should be employed along with other indicators and coefficient, able to balance the effect of the CRV and to grasp the strategic importance of a component [14, 15].

44.3 Research Methodology

Building Information Modeling (BIM) can be considered the cornerstone of research in construction field in recent years [16, 17] and it is widely acknowledged that asset owners will gain considerable advantages from a comprehensive Asset Information Model (AIM) furthering the strategic framework for asset management [18]. The AIM, as defined in BSI PAS 1192-3:2014 [19], is the foundation of the proposed research methodology that can be described by two main steps:

1. the transition from the physical asset to the digital asset, namely the AIM;
2. the maintenance operations prioritization through the DSS, reading data from the AIM.

The first phase of the research (Fig. 44.1) consists in the creation of a template for the development of BIM models of existing buildings. The survey and the digitization of the building and its surroundings can be expensive issues [20], which frequently prevent the adoption of BIM processes for management of the built environment. Therefore, a BIM model characterized by a low level of detail, which can be incrementally upgraded during operation, has been developed. This choice allowed to create a model with approximately one day of work, starting from as-built CAD drawings and carrying out a streamlined survey of the asset and its parts. The BIM template must be constantly updated, to automate some activities and to improve the quality of the output. The BIM model has been developed, using Autodesk Revit, connecting the building objects to a specific phase of the management process, so to create a depiction of the asset status at a specific date. The model, intended as geometrical objects and information associated to them, can be considered the digital twin of the physical asset and is used, in this case, for maintenance prioritization. This approach can ease the building maintenance operation, reaching higher levels of automation in maintenance management process [21].

The data contained in the BIM model are associated with data coming from an external source, namely the maintenance costs database (DB). The maintenance cost DB is based on the Uniclass II standard [22]. This classification system has been used to define the minimum level of breakdown of the building, that would allow an effective association with maintenance interventions and costs. Costs of maintenance interventions and components' replacement values have been defined employing the Milan's Municipal pricelist [23]. From a methodological point of view, this allows to define a standard set of building components associated with maintenance interventions and cost, though a case-by-case analysis has to be carried out when the methodology is implemented.

Once the standard maintenance cost DB is defined, the Building Condition Assessment (BCA) survey phase can start. Through the BCA campaign, deferred maintenance interventions as well as the related costs are identified. Survey results are stored in the BIM model created following the bespoke BIM template that allows an easy data extraction by the DSS Dynamo script (phase 2).

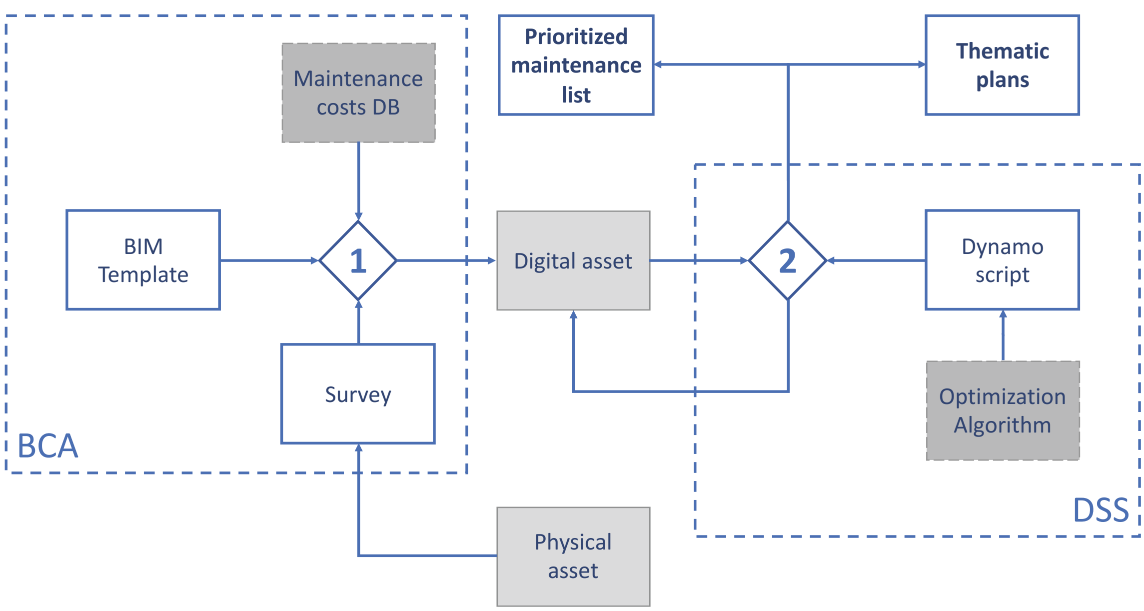


Fig. 44.1 Research schema

Among the information stored, the one related to building components' service life are of primary importance for the prioritization algorithm. Reference Service Life data are stored in the IFC2X4 property set named *Pset_ServiceLife*. This property set was introduced with the version 4 of the (Industry Foundation Classes) IFC standard [24] as a replacement of *IfcServiceLife* and is applicable to every *IfcElement*. For the purpose of this research, two are the property of the *Pset_ServiceLife* used: *ServiceLifeType* and *ServiceLifeDuration*. The first one describes the type of value stored in the *ServiceLifeDuration* property, it allows for 5 types of *IfcPropertyEnumeratedValue* and the only one used in this research is "REFERENCESERVICELIFE", i.e. the typical service life that is quoted for an artefact under reference operating conditions [25]. The *ServiceLifeDuration* property contains the *IfcDurationMeasure*, namely the length or duration of a service life [25]. The actual service life is not stored in the model since it is calculated by the Dynamo script from the *InstallationDate* value provided by Construction Operations Building Information Exchange (COBie) [26] information.

Once the data are available, it is possible to run the algorithm, obtaining two types of output: the list of prioritized maintenance operations and graphical representations, e.g. thematic plans and 3D views.

44.4 DSS Development

As stated in paragraph 44.2.2, FCI gives better results when combined with other KPIs for maintenance operations prioritization. The developed DSS is based on a combination of two KPIs for each component, the FCI and the D index: a metric that measures the service life of the component. The D index is derived from D^+ and D^- indexes developed by Dejaco et al. [27]. Since only two parameters are used in the DSS, no weighting system has been used, therefore the AHP method has not been applied.

The D^+ and D^- indexes cannot be used in their original form because the authors used respectively two different calculation methodologies, according to the age of the components, compared to the Reference Service Life (RSL). Moreover, although the two indexes are limited between 0 and 1, they work exactly the opposite way the FCI works, namely higher values indicate a higher performance. Thus, the D index employed in the DSS is computed with the same parameters defined by Dejaco et al. [27] but in a slight different way: starting from 0 when the component is newly installed, the D index increases when the component gets old (see Eq. 44.1).

$$D = \begin{cases} \frac{asl}{rsl} \times \frac{1}{2} \quad if \quad asl \leq rsl \\ \frac{1}{2} \times \left(1 + \frac{asl - rsl}{asl}\right) \quad if \quad asl > rsl \end{cases} \tag{44.1}$$

where

- *asl* is the actual service life of the component, i.e. the time span from when the component has been installed or built, until now;
- *rsl* is the reference service life of the component [28].

Equation (44.1) shows how the D index is computed with two different equations according to the age of the component. When the actual service life of the component is lower than its reference service life, D ranges from 0 to 0.5 and is calculated likewise D^+ by Dejaco et al. When component actual service life is bigger than the reference one, i.e. the component is too old, D ranges from 0.5 to 1 and is computed similarly to D^- by Dejaco et al. Noteworthy, in D index the value 1 is an asymptote, like it is 0 for D^-. Figure 44.2 shows how the D index varies with the actual service life of a component that has a reference service life of 25 years.

The proposed DSS contributes in easing informed decision-making through a graph where on the X axes is plotted the FCI of the component and on the Y axes the respective D index. This kind of graph allows to identify three areas delimited by two ellipses (Fig. 44.3):

- the critical condition ellipse: is an ellipse with the major axis parallel to the Y axis and passing through two points $C_1(0.10, 0)$ and C_2 (0, 0.50). Noteworthy, 0.10 is the FCI threshold for critical component (C_1) and D = 0.50 means that the actual service life of the component is equal to its reference service life;
- the poor condition ellipse: is an ellipse with the major axis parallel to the Y axis and passing through two points P_1(0.05, 0) and P_2 (0, 0.25). It may be highlighted that 0.05 is the FCI threshold for poor component (P_1) and D = 0.25 means that the actual service life of the component is half of its reference service life.

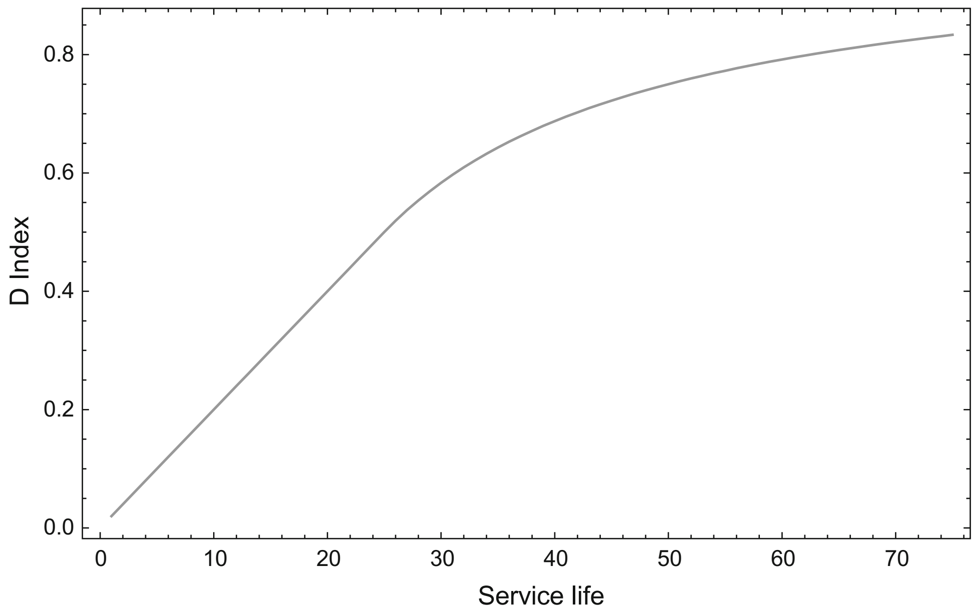


Fig. 44.2 Diagram of the D index for a component with RSL = 25 years

Other important information given by the DSS is the distance of each point (representing a component's condition) from the critical or poor ellipse. The bigger the distance the greater the need of maintenance of the component. Components in critical or poor condition are classified in 5 severity classes (Fig. 44.5), according to the distance from the boundary ellipse, either critical or poor. Decision makers can then focus maintenance budget for components that actually need more urgently maintenance.

44.5 Application of the DSS

To validate the proposed approach, a demonstration on an office building near Como (Italy) was carried out. The asset, built in 2006, is currently occupied by a construction company and a notary firm. It consists of one underground and three stories above ground (around 1000 m^2 of gross surface per story). According to the proposed methodology, the BCA has been carried out and the maintenance cost DB has been developed and adapted to the building under analysis. Figure 44.3 shows the condition of each component analyzed, highlighting that there are objects that may need maintenance even if their FCI is lower than 5%, since they are close to their reference service life (D = 50%) or even above. Among these latter, some parts of the mechanical system are very well maintained (FCI = 0%) but too old (D > 50%).

Structural components surveyed are characterized by a very good FCI (an average of 4.29%) and a very low D (around 8%), since the building is quite new. Although, most of the components are in critical conditions, as can be seen in Fig. 44.4, and 30% of the analyzed elements are in poor condition. If the budget for maintenance is not enough to intervene on all critical and poor components, the one on which resources should be spent can be identified by measuring the distance of each point from the boundary ellipse (Fig. 44.3).

To help decision makers, the distances from the boundary ellipse of critical and poor components have been classified according to five severity classes. Figure 44.5a shows that most of the critical components are in the first severity class (the less critical) and only one component among the critical ones is in the most severe condition (Severity 5). Figure 44.5b shows that most of the poor components are in the intermediate class of severity (Severity 3) and none is in the most severe one (Severity 5).

In Fig. 44.6 the BIM model of the case study is presented. Results computed through the DSS are stored in a custom property set called "MaintPrior". In Fig. 44.7 the property set filled with the values computed for the roof of the building is shown.

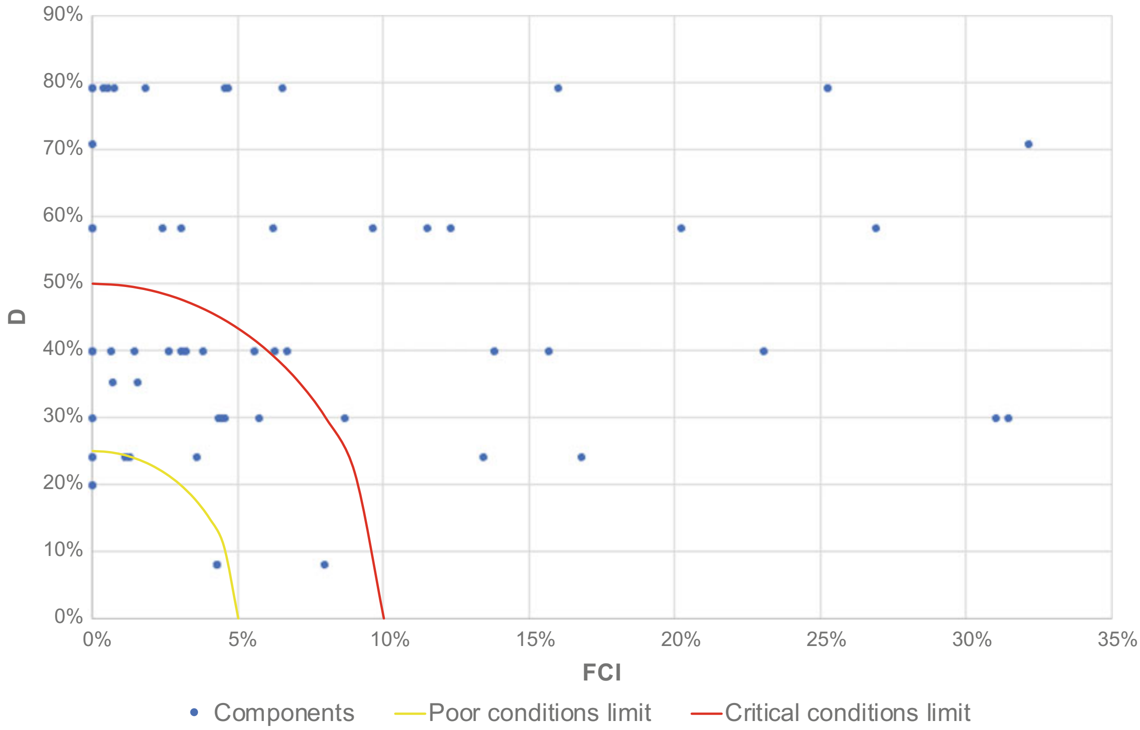
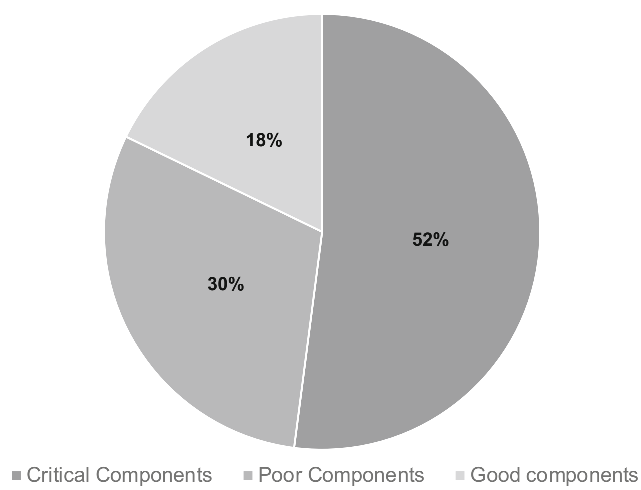


Fig. 44.3 Components condition

Fig. 44.4 Percentage of components in critical, poor and good condition



44.6 Discussion and Conclusions

Asset managers must often make decisions about maintenance and renewal alternatives based on sparse data concerning the actual assets' condition [29] wasting, as a consequence, a huge amount of economic resources. Thus, a DSS easing the prioritization of maintenance operations has a great importance for asset owners. The proposed DSS, based on two KPIs, the FCI and the D index, classifies building components according to their need for maintenance interventions. The use of the D index helps in overcoming the limitations of the FCI. The proposed DSS has led to good results in the case study, although some drawbacks still have to be addressed. For instance, the method does not take into account the cultural or historic value of the asset, the asset owner's peculiar requirements or necessities and the intended use of the building. Despite the limitations, the usability of the tools has been appreciated by the firms appointed for maintenance management of

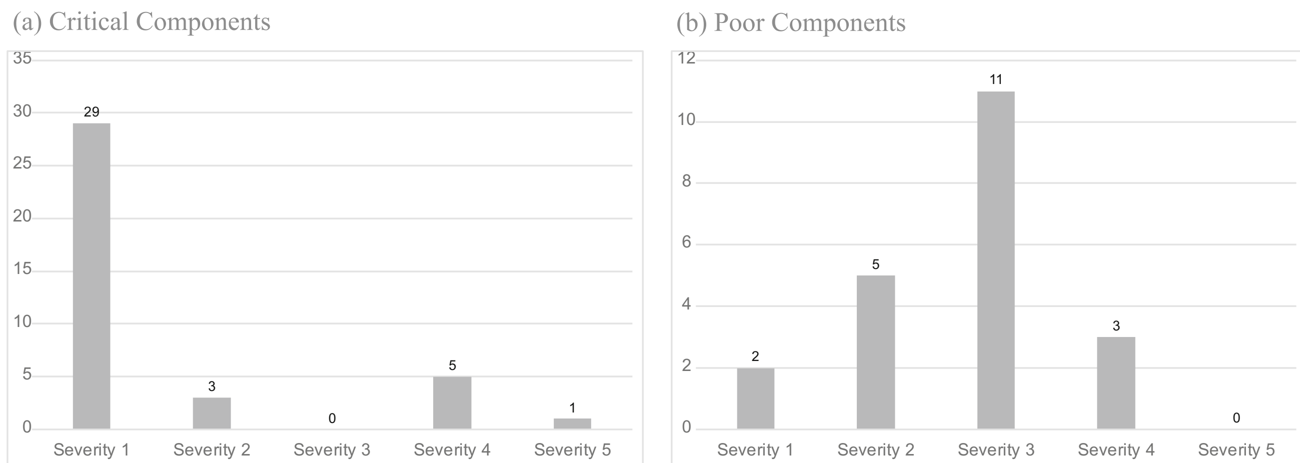


Fig. 44.5 Severity of the condition of components in critical (**a**) and poor (**b**) condition

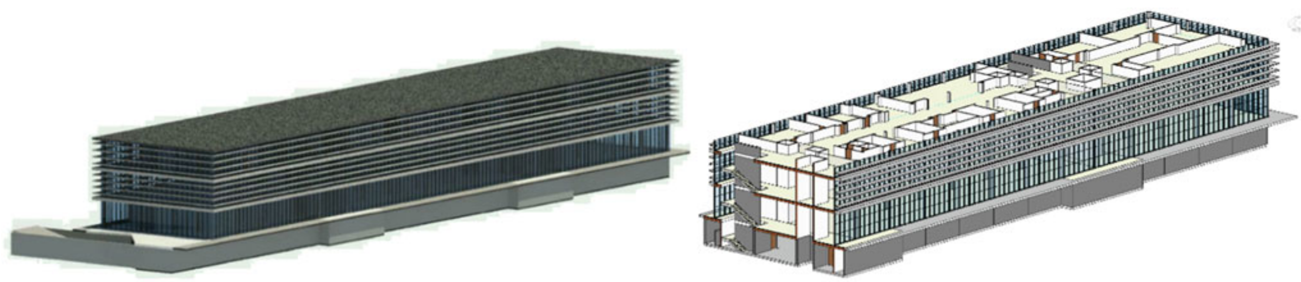


Fig. 44.6 BIM model of the case study

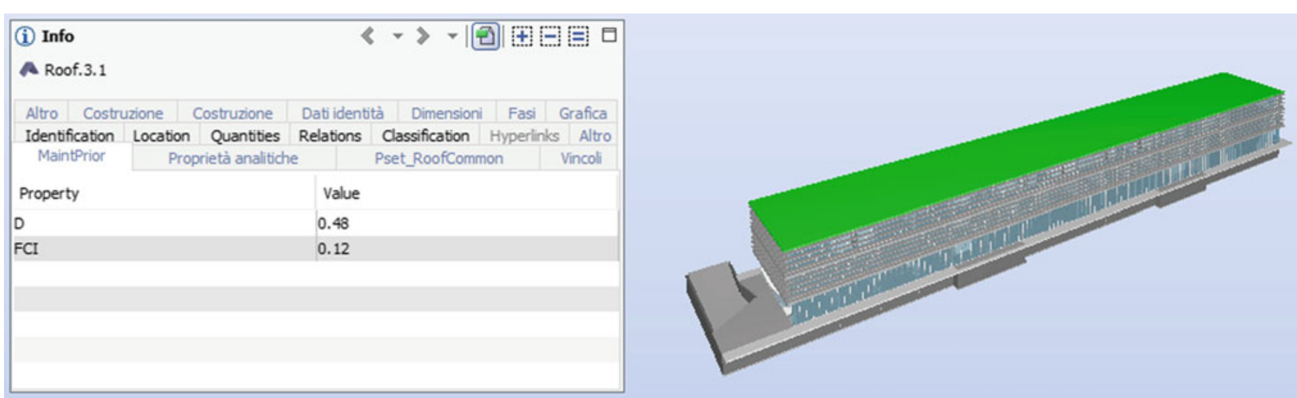


Fig. 44.7 Custom property set

the office building in Erba, Italy, on which the case study has been carried out, mainly because the DSS leverages semi-automated BIM processes to save and retrieve data. The future research work will be focused on widening the scope of the DSS, through the integration of further KPIs according to specific clients' needs and according to specific building types. Moreover, the DSS will be further integrated and automated within the BIM approach.

References

1. Pärn, E.A., Edwards, D.J., Sing, M.C.P.: The building information modelling trajectory in facilities management: a review. Autom. Constr. **75**, 45–55 (2017)
2. Lavy, S., Garcia, J.A., Dixit, M.K.: KPIs for facility's performance assessment, Part II: identification of variables and deriving expressions for core indicators. Facilities **32**(5/6), 275–294 (2014)
3. Kaklauskas, A., Zavadskas, E.K., Raslanas, S.: Multivariant design and multiple criteria analysis of building refurbishment. Energy Build. **37**, 361–372 (2005)
4. Caccavelli, D., Gugerli, H.: TOBUS—a European diagnosis and decision-making tool for office building upgrading. Energy Build. **34**, 113–119 (2002)
5. Wong, J.K.W., Li, H.: Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems. Build. Environ. **43**, 108–125 (2008)
6. Saaty, R.W.: The analytic hierarchy process—what it is and how it is used. Math. Model. **9**(3–5), 161–176 (1987)
7. Zhu, Q., Du Tina, J., Meng, F., Wu, K., Sun, X.: Using a Delphi method and the analytic hierarchy process to evaluate Chinese search engines: a case study on Chinese search engines. Online Inf. Rev. **35**(6), 942–956 (2011)
8. Jalaei, F., Jrade, A., Nassiri, M.: Integrating decision support system (DSS) and building information modeling (BIM) to optimize the selection of sustainable building components. J. Inf. Technol. Constr. (ITcon) **20**(25), 399–420 (2015)
9. Maltese, S., Dejaco, M.C., Re Cecconi, F.: Dynamic Facility Condition Index calculation for asset management. In: 14th International Conference on Durability of Building Materials and Components, 29–31 May 2017
10. U.S. Department of Defense U.S. Department of Defense. Available at: https://www.defense.gov/. Accessed 4 Feb. 2017
11. Rush, S.C.: Managing the facilities portfolio: a practical approach to institutional facility renewal and deferred maintenance. NACUBO (1991)
12. U.S. Department of interior, Policy on Deferred Maintenance, Current Replacement Value and Facility Condition Index in Life-Cycle Cost Management (2008)
13. Roberts, L.W.: Measuring school facility conditions: an illustration of the importance of purpose. J. Manuf. Technol. Manage. **20**(5), 547–567 (2009)
14. U.S. Department of interior, Asset Priority Index Guidance (2005)
15. Marzouk, M., Awad, E.: Establishing multi-level performance condition indices for public schools maintenance program using AHP and fuzzy logic. Stud. Inf. Control **25**(3), 343–352 (2016)
16. Bui, N., Merschbrock, C., Munkvold, B.E.: A review of building information modelling for construction in developing countries. Procedia Eng. **164**, 487–494 (2016)
17. Walasek, D., Barszcz, A.: Analysis of the adoption rate of building information modeling [BIM] and its return on investment [ROI]. Procedia Eng. **172**, 1227–1234 (2017)
18. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: Chapter 12: BIM for owners and facility managers. In: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, 1st ed., Wiley, Hoboken, pp. 93–147 (2008)
19. The British Standards Institution, PAS 1192-3:2014. Specification for information management for the operational phase of assets using building information modelling (2014)
20. Volk, R., Stengel, J., Schultmann, F.: Building Information Modeling (BIM) for existing buildings. Literature review and future needs. Autom. Constr. **38**, 109–127 (2014)
21. Chen, W., Chen, K., Cheng, J.C.P., Wang, Q., Gan, V.J.L.: Automation in construction BIM-based framework for automatic scheduling of facility maintenance work orders. Autom. Constr. **91**(March), 15–30 (2018)
22. The National Building Specification, Classification, https://toolkit.thenbs.com/articles/classification. Accessed April 2018
23. Comune di Milano, Listino Prezzi edizione 2018, http://www.comune.milano.it/wps/portal/ist/it/amministrazione/trasparente/OperePubbliche/listino_Prezzi/Edizione+2018
24. International Organization for Standardization, ISO/PRF 16739-1:2017, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries—Part 1: Data schema using EXPRESS schema definitions (2017)
25. International Organization for Standardization, ISO 15686-4:2014, Building Construction—Service Life Planning—Part 4: Service Life Planning using Building Information Modelling (2014)
26. The British Standards Institution, PAS 1192-4:2014 Collaborative production of information. Fulfilling employer's information exchange requirements using COBie. Code of practice (2014)
27. Dejaco, M.C., Cecconi, F.R., Maltese, S.: Key performance indicators for building condition assessment. J. Build. Eng. **9**, 17–28 (2017)
28. International Organization for Standardization, ISO 15686-1:2011 Buildings and constructed assets—Service life planning—Part 1: General principles and framework (2011)
29. Vanier, D.J., Tesfamariam, S., Sadiq, R., Lounis, Z.: Decision models to prioritize maintenance and renewal alternatives, in Joint International Conference on Computing and Decision Making in Civil and Building Engineering, 2006, Montréal, Canada, pp. 2594–2603 (2006)

45 Structural Behavior Analysis and Optimization, Integrating MATLAB with Autodesk Robot

Giulia Cerè, Wanqing Zhao, and Yacine Rezgui

Abstract

The concepts of structural behavior analysis and optimization have started to be combined in the latest decades with an increasing trend also due to the need of often meeting performance targets, high structural complexity and costs. Nonetheless, existing approaches tackled this issue mainly in the domain of static calculations or referring to a specific type of optimization (e.g., size, topology or geometry). A new methodology is proposed to systematically perform different types of analysis (e.g., linear and nonlinear), by exploiting the Autodesk Robot Structural Analysis API through MATLAB. This approach involves the adoption of ActiveX technologies for the manipulation of COM (Component Object Model) objects in the MATLAB environment. A real-world example of linear dynamic modal analysis is also presented and a synthetic diagnostic of the structure is conducted based on the displacements resulting from the calculation.

Keywords

Autodesk robot • MATLAB • Structural behavior analysis • Optimization

45.1 Introduction

With an increasing complexity in the design of structural shapes, a higher impact of natural hazards on the building environment [1] and a growing pressure for delivering projects within shorter timing, the software-based structural behavior analysis and optimization problem have been emerging significantly in the engineering domain, particularly in relation to the design phase [2]. The need of structural behavior analysis adopting a software has become widely implemented in worldwide building regulations, such as Eurocodes [3] and FEMA [4]. As a matter of fact, the introduction of software allowed the designer to avoid cumbersome hand-calculations which become extremely complex and difficult to handle especially for nonlinear analysis and when the simultaneous interaction of several materials has to be taken into account into non-static conditions.

As far as the mere structural behavior analysis is concerned, the commercial panorama of available software packages is wide and offers a considerable range of choices for this purpose. Some of these tools mainly focus on specific construction materials, such as ADAPT [5], which has been developed specifically for reinforced concrete (RC) constructions. On the other hand, a vast range of other software adopt a multi-material approach, qualifying as more versatile tools for building design and analysis. Examples of this category are for instance Tekla [6], SCIA, Midas, SAP2000 [7] and Robot Structural

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Analysis Professional [8]. In particular, SAP2000 is listed amongst the leading software in the field of structural analysis, given its straightforward and flexible functionalities. Although, the use of SAP2000 most of times requires the integration of Excel in order to conduct the structural members' verifications and additional post-analysis calculations.

The choice of Robot Structural Analysis Professional over other software grounds on several factors. In first instance, Robot is part of a suite, which allows a high interconnectivity and compatibility level between the different software. The two-way interconnectivity with Revit consists in a key feature of Robot, allowing a high quality bidirectional export of the files and hence reducing potential adjustments required by the designer [9]. An additional advantage can be found in the high integration level of the most influencing and up to date worldwide building regulations, while the majority of structural software are provided with local standard and hence confining the use of the tool to a limited area.

On the other hand, optimizing a process consists in matching the design objectives (e.g., performance) with the compliance of a series of constraints (e.g., costs, deflection, base shear), by tuning the design variables (e.g., building and structural elements' size, material) [10]. Several tools are available for this purpose, such as iSIGHT, DOT and MATLAB, the latter perhaps consisting in the most diffused being also implemented with a specific optimization toolbox [11]. Previous research addressed the use of MATLAB in combination with other software to simulate the effects of a seismic solicitation. One of these is the PBEE toolbox [12], which draws on linking MATLAB and OpenSees in order to perform seismic analysis on reinforced concrete (RC) frames. This grounds on the notion of plastic hinges development in correspondence of structural nodes as a representation of the ductile abilities of the building, although confining the work to a mere diagnosis of the structure.

An example of structural optimization can be found in the SMART Sizer plug in devised by Buro Happold in order to be coupled to Robot Autodesk Structural Analysis [2]. This tool allows to optimize the size of the structural members grounding on the results of a displacement analysis in order to evenly distribute the stiffness in the entire frame. Despite the novelty of this approach, this methodology addresses purely size optimization and it is not scalable for other structural analysis or optimization problems. To the best of our knowledge, the integration of the Robot API has been mainly exploited with programming languages such as Visual Basic, C ++ or C# [13], whereas the integration with MATLAB has not been explored thoroughly yet, given its renown in providing an accessible numerical computing environment.

As far as the optimizing strategies are concerned, most of the existing literature broadly identifies three categories, mainly operating on size, geometry (i.e., shape) or topology of the structural members [14, 15]. It has to be pointed out that the majority of the literature does not rely on any structural software, but perform the optimization independently and in most cases just in static conditions. In this sense, they are either site-specific or problem-specific, lacking generalization capability and transferability. Examples of optimization approaches in static conditions can be found in Sigmund [16], who devised and optimization methodology adopting MATLAB or in the work by Balling and colleagues [15]. The latter adopted a genetic algorithm (GA) to perform a more inclusive optimization (i.e., size, shape and topology) on skeletal structures but yet in a static load condition. Another application of GA can be found in the work by Rajan [17], focusing on the optimization of trusses.

This paper will present a simple, versatile and scalable methodology for the integration of Robot with MATLAB, with the primary purpose of automating structural behavior analysis and the potential for structural optimization. The authors would like to highlight that the proposed methodology is not meant to replace the engineers' judgement with an automated procedure, instead providing a tool that could be functional for reducing the amount of repeated calculations and allowing more time for the designer to investigate the technical solutions.

45.2 Methodology

45.2.1 Methodology Overview

The proposed methodology is presented, taking framed structure design as an example, where RC is considered as the structural typology. The reason behind this choice lies in the wide adoption of RC both in new and existing buildings, also consisting in a relatively more convenient technique both in terms of costs and employability. This approach can be adopted for both existing and new building and specifically in the second case, a preliminary dimensioning of the structure is needed as normally happens in the design practice prior to virtual modelling.

In detail, the methodology relies on the adoption of MATLAB in order to invoke systematically different Robot API components either to manipulate objects or perform specific operations, such as structural analysis (e.g., linear and non-linear).The overall structure of the API is briefly schematized in Fig. 45.1, including the main categories (e.g., Project,

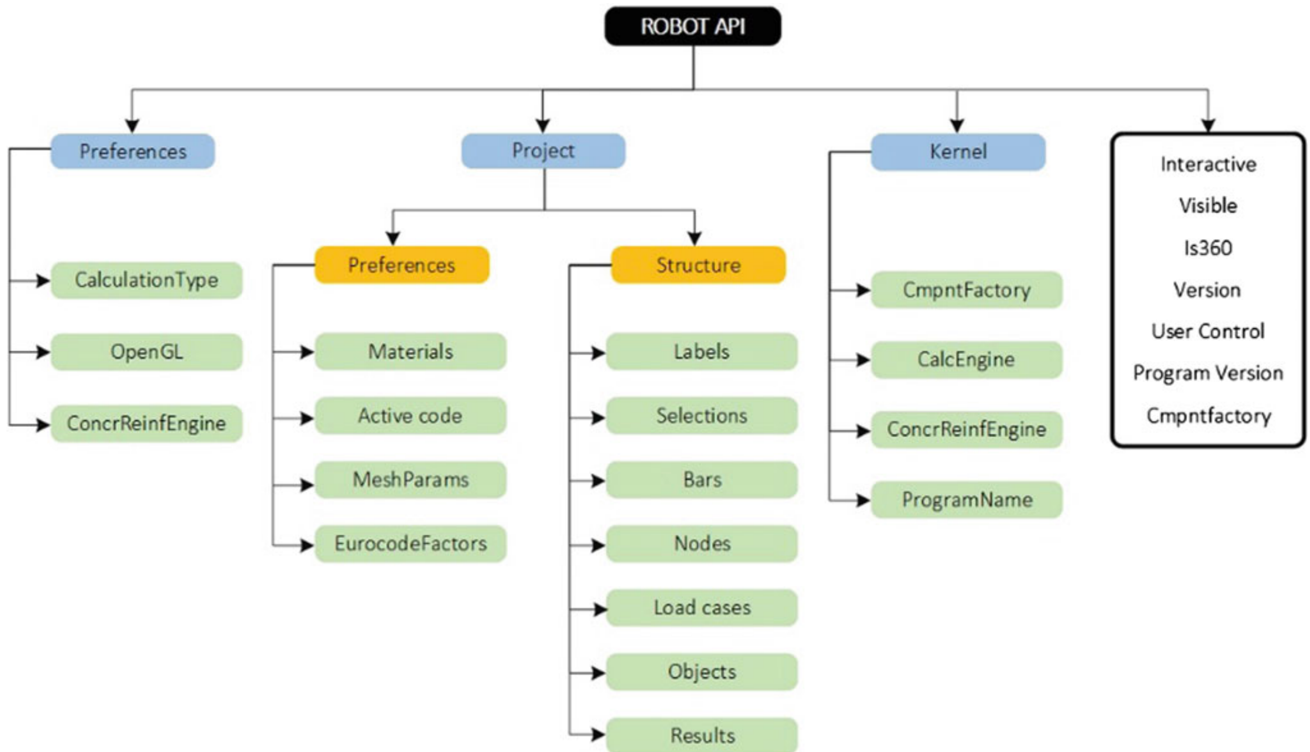

Fig. 45.1 Robot API main components

Preferences, Kernel) as well as the concerning subcategories (e.g., Preferences and Structure) adopting their original names. Figure 45.2 provides a comprehensive overview of the methodology. For each process within the methodology, the corresponding API component is also exemplified for performing specific tasks. The first step consists in the identification of the optimization objectives, which pertains both performance-related factors (e.g., displacement, deflection, buckling, distance between mass and stiffness centers) and costs. Examples of the design parameters that can be tweaked in the optimization phase to meet the targets can be identified in the following:

- Structural members' sections size;
- Characteristic resistance of concrete (R_{ck});
- Permanent non-structural loads on beams and slabs, since this feature reflects design choices such as partition walls and flooring;
- Steel class for reinforcement and type of reinforcement.

Following to the identification of the optimization targets, the user is asked to input a set of information needed to model the structure and perform the analysis. These dataset of information includes for instance the geometric data resulting from the preliminary dimensioning of the structure (e.g., interstorey, in-plan dimensions, storey number, section types), the hypothesized concrete and steel classes, loads to be considered (e.g., snow, wind, permanent, non-permanent and live loads). Grounding on these information the MATLAB code is able to remotely provide a graphic representation of the structure in Robot, combining the loads according to the chosen building regulation and consequently perform a linear dynamic analysis with response spectrum (i.e., modal analysis). Accessing the "results" section of the Robot API allows to tailor the output according to the typology of parameter to consider and then verify the desired elements.

Regarding the building modelling part, it is worth mentioning that some specific arrangements have been adopted in the modelling and calculation phases:

- Rigid diaphragms are introduced as horizontal structures, in accordance to what prescribed by Eurocode 8, §4.2.1.5 [3];
- Fixed constraints are imposed at the base of the building since just the superstructure's behavior is investigated;

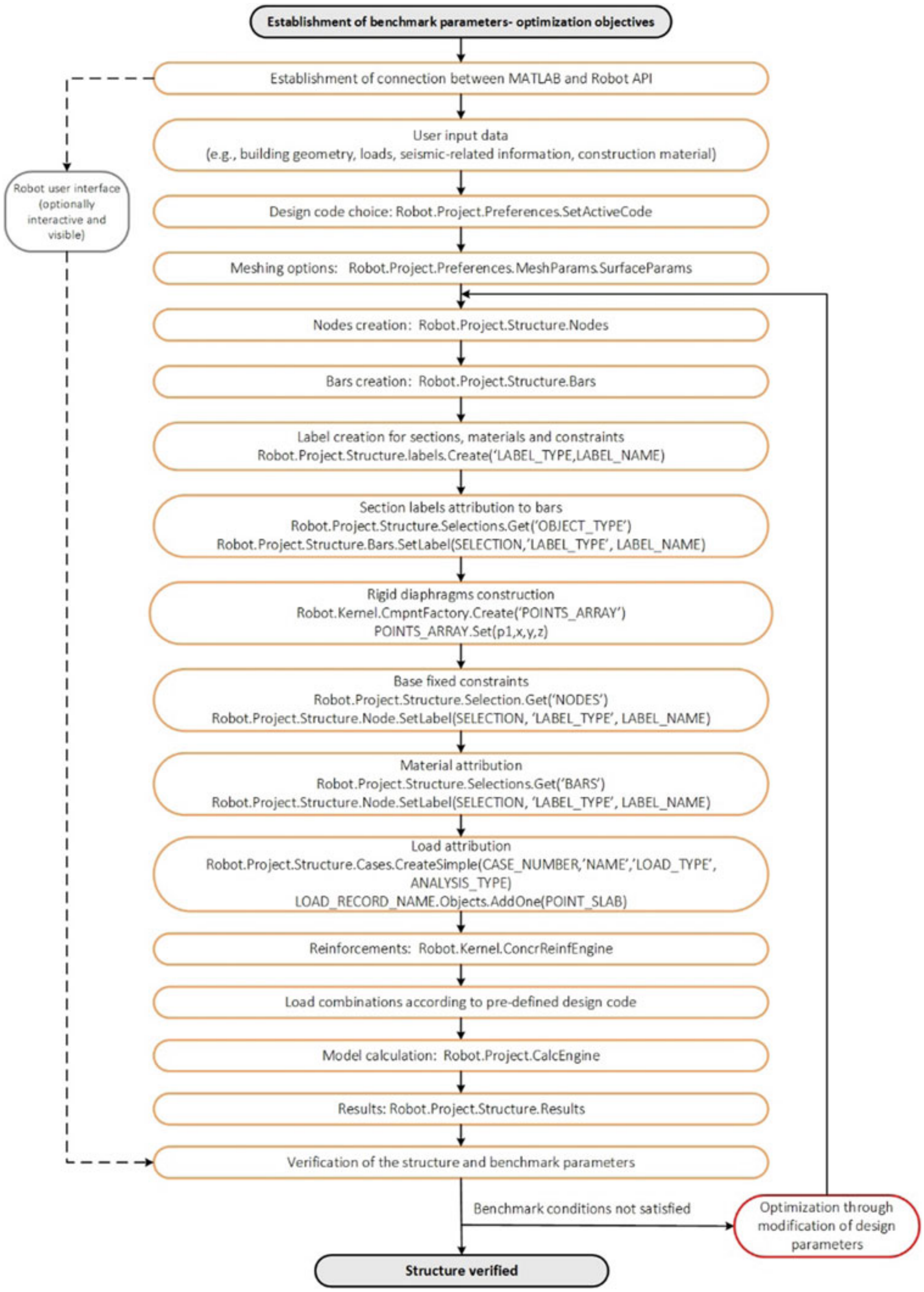

Fig. 45.2 Overall modelling methodology through Robot API in MATLAB

- Infill walls are modelled as linearly distributed loads over the beams;
- The flooring composition is computed through the application of permanent non-structural loads.

45.2.2 Integration Between Robot API and MATLAB

The dialogue between MATLAB and Robot relies on querying mechanisms that guide the path through the tree structure of the API itself invoking a specific function. Firstly, the Robot API is invoked from the MATLAB environment as in

Fig. 45.3 Establishment of the connection between MATLAB and Robot API

```
Robot=actxserver('Robot.Application');
Robot.Interactive=1;
set(Robot,'Visible',1);
Robot.Project.New('I_PT_SHELL');
```

Fig. 45.4 Example of use of invoke function for project preferences

```
invoke(ProjectPrefs)
GetActiveCode = ustring GetActiveCode(handle, IRobotCodeType)
SetActiveCode = int32 SetActiveCode(handle, IRobotCodeType, ustring)
Save = void Save(handle)
GetActiveCodeNumber = int32 GetActiveCodeNumber(handle, IRobotCodeType)
SetActiveCodeNumber = bool SetActiveCodeNumber(handle, IRobotCodeType, int32)
SetCurrentDatabase = bool SetCurrentDatabase(handle, IRobotDatabaseType, ustring)
GetCurrentDatabase = ustring GetCurrentDatabase(handle, IRobotDatabaseType)
```

Fig. 45.3, using ActiveX technology and renaming the querying process in the first line simply as “Robot” for ease of application in the rest of the script. This process will speed up the following steps in which the Robot.Application is invoked since the querying process follows the same path as in Fig. 45.1 and the different commands are separated by a dot. As an example, lines 2 and 4 in Fig. 45.3 clearly shows this process and its correspondence in Fig. 45.1, which guides MATLAB to access the desired command in the Robot API. Respectively, line 2 and 4 activate the User Interface of Robot and select the modelling typology. The options of making the Robot user interface visible and interactive are discretionary since the connection with the API already allows all the subsequent operations running in the background. To this regard it should be highlighted that when the Robot user interface is visible and interactive, any operation performed in one of the two environments (i.e., MATLAB and Robot) will reflect on the other one.

However, the set of operations available for each component of the API are documented in the Visual Basic, C++ and C# environments [13], but not for MATLAB so it has been of primary importance to apply the “invoke” function in order to get a precise description of the list of commands, including their input and output arguments. As an example, in Fig. 45.4 it is showed the result of the invoke function for the available operations on the Project Preferences. The corresponding path for this component, namely “Robot.Project.Preferences”, has been named as “ProjectPrefs” for ease of adoption in the script. It is worth to point out that the function “invoke” will provide results when applied to “Objects” and not to variables resulting from other operations (e.g., double, string).

The first step consists in the definition of the structural grid based on the user input by creating the nodes as showed in Fig. 45.2. The nodes are functional for the successive step of bar creation that is analogous for beams and columns. Following to that, the creation of the labels allows to specify the properties that have to be assigned to the different structural members. The assignment procedure is carried out by adding the elements to characterize into a selection of a desired type of objects in the context of the specific label. To clarify it, Fig. 45.5 shows the example of the label creation of fixed support constraints (i.e., FixedSupp), the iterative addition of the nodes to the selection (i.e., selectNodes) and the assignment of the label to the latter in the last line.

The material attribution follows an analogous procedure, while the assignment of rigid diaphragms differs in the sense that, as showed in Fig. 45.2, there is the need of creating a point array corresponding to the panel perimeter through the Kernel. Following to that, labels for relevant properties such as thickness can easily assigned directly to the array.

After the overall geometry has been defined and characterized the following entails load definition and assignation to the desired elements. Each Load Case should contain its sequential number, a name for identification, the load type (e.g., permanent, live) and the type of analysis to be performed (i.e., dynamic modal in the example). Figure 45.6 shows in particular this process in the context of dead loads (i.e., self-weights) applied to the whole structure. After the definition of the load case it is necessary to specify the direction of application (z axis in this example) and the elements to which the loads has to be applied (i.e., entire structure).

When the full characterization of the structure has been achieved, the calculation can be performed by referring to the CalcEngine component in the Kernel and successively results can be easily retrieved from the Results section as in Figs. 45.1 and 45.2. It is then possible to get, for instance, the value of the moment in a specific direction (e.g., x, y, z) for a specific beam at a certain point in its length and in relation to an established load scenario as shown in the example of Fig. 45.7.

Based on the results, verifications can be carried out in association with the compliance to the optimization targets. If the results of this step fulfill the objectives, then no further analysis is required, otherwise bespoke adjustments to the design

```
%creation of fixed support label
FixedSupp='Fixed support';
LabelFixed = Robot.Project.Structure.labels.Create('I_LT_SUPPORT',FixedSupp);
FixedData=LabelFixed.Data;
FixedData.UX=1;
FixedData.UY=1;
FixedData.UZ=1;
FixedData.RX=1;
FixedData.RY=1;
FixedData.RZ=1;
Robot.Project.Structure.labels.Store(LabelFixed);

%Assignment of the label to the nodes at the ground level

groundnodes=stnod/(stnum+1);
selectNodes=Robot.Project.Structure.Selections.Get('I_OT_NODE');

for i=1:groundnodes
  selectNodes.AddOne(i);
end
Robot.Project.Structure.Nodes.SetLabel(selectNodes,'I_LT_SUPPORT',FixedSupp);
```

Fig. 45.5 Label creation assignment for base fixed constraints in MATLAB

```
%selfweight of the structure
casePS=Robot.Project.Structure.Cases.CreateSimple(1,'PS',0,11);
%'I_CAT_DYNAMIC_MODAL'=11
%'I_CN_PERMANENT'=0
casePS.Records.New('I_LRT_DEAD');
LoadRec=casePS.Records.Get(1);
LoadRec.SetValue(2,-1); %I_DRV_Z = 2
LoadRec.SetValue(15,true); %I_DRV_ENTIRE_STRUCTURE = 15
```

Fig. 45.6 Label creation assignment for base fixed constraints in MATLAB

```
%Getting the results for beam n.5 and live load case (2)
disp('Bar 5, Live:');
My1=Robot.Project.Structure.Results.Bars.Forces.Value(5,2,0.5).MY./1000;
```

Fig. 45.7 Extrapolation of moment in y direction for a specific beam subjected to live load

parameters are made and the process is repeated iteratively till the complete satisfaction of the benchmark parameters. A suite of local (e.g., nonlinear programming) and global (e.g., genetic algorithm and particle swarm optimisation), constrained and unconstrained, and single-objective and multi-objective optimisation algorithms can be readily adopted to search for optimum design solutions with potentially conflicting objectives. This embodies the development of a MATLAB optimization client that progressively manipulates COM objects in the Robot simulation server through the use of ActiveX technologies. A local Robot simulation server is created to perform continuously structural design and analysis with selected design parameters iteratively tailored for a specific design scenario employing the MATLAB optimization toolboxes.

45.3 Case Study

The example structure presented in this paper is depicted in Fig. 45.8a and consists in a residential building in Old Beichuan County located in the Sichuan province, China. In detail, the building shows a six-storey RC frame structure with double-layer masonry infill walls. The clear extensive level of damage followed the 2008 Wenchuan seismic event, measuring 8.0 M_s. The process described above has been adopted to model the buildings as in Fig. 45.8b and in this section

(a) (b)

Fig. 45.8 State of the art (**a**) and Robot model (**b**) of a residential building in Old Beichuan County

Fig. 45.9 Residential building in Old Beichuan County

```
DispNodes=Results.Nodes.Displacements;

dispN356M4=DispNodes.DynCombValue(356,4,'I_MCT_NONE');
displacements(1,1)=356;
displacements(1,5)=dispN356M4.UX*1000;
displacements(1,6)=dispN356M4.UY*1000;
displacements(1,7)=dispN356M4.UZ*1000;
```

Table 45.1 Displacement data for accidental seismic combination at the different storey levels

Storey	Node number	UX (mm)	UY (mm)	UZ (mm)
Roof wall	356	1.520E+01	−1.302E−03	−2.409E+00
6	297	1.511E+01	3.204E−05	−2.402E+00
5	241	1.405E+01	2.414E−05	−2.311E+00
4	203	1.225E+01	1.880E−05	−2.090E+00
3	165	9.807E+00	1.350E−05	−1.745E+00
2	127	6.843E+00	8.166E−06	−1.280E+00
1	22	3.513E+00	2.773E−06	−6.978E−01
0	21	0	0	0

the focus is on how to retrieve the results and their interpretation in a real-case scenario. A preliminary assessment of the damage mechanism shows clear differential settlements, probably due to a liquefaction-prone soil combined with a superficial foundation system that led to the complete collapse of the ground floor storey. Given the lack of geotechnical information, only the superstructure is modelled and hence fixed constraints are placed at the base of the building, in order to isolate the uncertainties brought by soil-related aspects.

The displacements are collected through the Results server accessible through the path visible in Fig. 45.1, and hence consisting namely in moving from the Robot.Application main component, to the Project subsection and then to Structure, in which the section Results is located. Figure 45.9 shows in detail the use of the DynCombValue function, which allows to get absolute displacements (i.e., UX, UY and UZ) for a specific node of the structure (i.e., 356 in the example), given a certain combination (i.e., 4, accidental seismic). Another parameter to implement is the mode of combination adopted (e.g., CQC, SRSS) while more than one modes are presents, specifically in modal analysis. In this example it is presented the case of accidental seismic combination, which has been proved to be the more significant in terms of displacements. In Table 45.1 these data are listed in detail considering one node per each floor. This is allowed since the adoption of rigid diaphragms prevents relative displacements between points pertaining to the same diaphragm.

The displacement increases with the height although achieving a maximum value of about 1.2–1.5 cm in X direction, corresponding to the axis parallel to the longest side of the building. The node numbered as 21 shows no displacement because it is one of the fixed points at the base of the structure. In light of the preliminary load analysis and these results, the structure performed poorly due to the excessive weight of non-structural elements such as infill walls that intensified the differential settlements caused by the soil liquefaction. Hence, the seismic action alone did not trigger the collapse mechanism, but it contributed in combination to unsuitable design choices, such as the foundation system and the adoption of a heavy infill wall typology.

45.4 Conclusion

The paper focuses on a novel methodology for performing structural behavior analysis adopting MATLAB to access the Robot API and progressively manipulate objects. Different types of analysis can be performed and in this research specifically a RC framed structure has been analyzed through linear dynamic calculation. The overall process has been presented, from the connection between MATLAB and the Robot API to the extrapolation of displacement data, as an example. Future work will entail the implementation of multi objective optimization and different types of materials in order to embrace a wider percentage of design.

References

1. Cerè, G., Rezgui, Y., Zhao, W.: Critical review of existing built environment resilience frameworks: Directions for future research. Int. J. Disaster Risk Reduct. **25**, 173–189 (2017)
2. Fisher, A., Sharma, S.: Exploiting Autodesk Robot Structural Analysis Professional API for Structural Optimization, http://bimandbeam.typepad.com/. Last accessed 26 Apr. 2018
3. The European Union Per Regulation 305/2011, EN 1998-1:2004+A1:2003: Eurocode 8: Design of structures for earthquake resistance, Brussels (2004)
4. FEMA: 2015 NEHRP. Recommended Seismic Provisions: Design Examples, Washington D.C. (2016)
5. Adaptsoft, ADAPT Structural Concrete Software (2017)
6. Tekla, Tekla Structures. Administrator's Release Notes (2015)
7. Computers & Structures Inc, SAP 2000 User Manual, Version 19 (2016)
8. Autodesk, Autodesk Robot Structural Analysis Professional 2010 Training Manual (2009)
9. Autodesk, Autodesk Robot Structural Analysis. Metric Getting Started Guide (2010)
10. Collette, Y., Siarry, P.: Multiobjective optimization: principles and case studies, 1st edn. Springer, Berlin (2003)
11. MathWorks, MATLAB Optimization Toolbox, https://uk.mathworks.com/products/optimization.html. Last accessed 18 Apr. 2018
12. Dolsek, M.: Development of computing environment for the seismic performance assessment of reinforced concrete frames by using simplified nonlinear models. Bull. Earthq. Eng. **8**, 1309–1329 (2010)
13. Autodesk, Autodesk Robot Structural Analysis Professional 2018. Robot Object Model (2017)
14. Baldock, R.: Structural optimisation in building design practice: case-studies in topology optimisation of bracing systems. University of Cambridge (2007)
15. Balling, R.J., Briggs, R.R., Gillman, K.: Multiple optimum size/shape/topology designs for skeletal structures using a genetic algorithm. J. Struct. Eng. **132**(7), 1158–1165 (2006)
16. Sigmund, O.: A 99 line topology optimization code written in Matlab. Struct. Multi. Optim. **21**(2), 120–127 (2001)
17. Rajan, S.D.: Sizing, shape, and topology design optimization of trusses using genetic algorithm. J. Struct. Eng. **121**(10), 1480–1487 (1995)

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An Assessment of BIM-CAREM Against the Selected BIM Capability Assessment Models

46

Gokcen Yilmaz, Asli Akcamete, and Onur Demirors

Abstract

Although various BIM capability and maturity models have been developed to meet different BIM capability/maturity assessment purposes, there has not been a model which is broadly used and commonly accepeted in the literature. A Reference Model for BIM Capability Assessment (BIM-CAREM) was developed based on the meta-model of ISO/IEC 33000 to be used for assessing BIM capability levels of AEC/FM processes. This paper aims to compare the components of BIM-CAREM with the assessment questions of the identified models from the literature. Moreover, data collected from a previously performed case study was used to carry out self-assessments by using these models. Then, these assessment results were compared with the findings gathered from assessments performed with BIM-CAREM. The comparison indicated that, BIM-CAREM has more detailed and specified questions for assessing BIM capability of different AEC/FM processes and has comparable assessment results to that of identified capability models.

Keywords

Building information modeling • BIM capability assessment • BIM maturity

46.1 Introduction

Since use of BIM is mandatory in various countries such as North America, Finland and UK [1], adoption of BIM is increasing among AEC/FM organizations. In order to help organizations to adopt BIM seamlessly, several resources such as BIM guidelines have been published by governmental organizations of various countries. The two important and well-known example of these standards are, BS/PAS 1192 series of standards [2] which are published by The British Standards Institution and the National BIM Standard [3] which is published by buildingSMART. On the other hand, even after the BIM adoption, organizations need to measure their BIM performances to use BIM more efficiently. Thus, various BIM capability and maturity assessment models are developed for achieving different BIM assessment purposes. Among these, we have identified six BIM capability and maturity models by conducting a systematic literature review [4]. Later, we extended this review by including two recent models. Eight prominent BIM assessment models, which are NBIMS BIM Capability Maturity Model (NBIMS BIM CMM) [5], BIM Proficiency Matrix (BIM PM) [6], BIM Maturity Matrix (BIM MM) [7], BIM QuickScan [8, 9], Virtual Design and Construction Scorecard (VDC Scorecard) [10, 11], Organizational BIM Assessment Profile (Organizational BIM AP) [12], VICO BIM Scorecard [13], and Multifunctional BIM Maturity Matrix (Multifunctional BIM MM) [14], are analyzed based on several criteria [15]. It is identified that there is not a holistic model

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which enables BIM capability assessments of all AEC/FM processes [15]. Moreover, there is not a widely used and commonly accepted model which is developed based on established standards [15, 16]. In order to address this demand, a reference model for BIM capability assessments (BIM-CAREM) is created [15]. It is developed based on the meta-model of ISO/IEC 33000 [17, 18], and for assessing BIM capabilities of AEC/FM processes rather than capability or maturity of organizations and projects. The details about the structure of BIM-CAREM and its application areas can be found in the PhD dissertation of Yilmaz [15]. This paper aims to compare the structure and the components of BIM-CAREM with the structure of other two models which are BIM QuickScan and Organization BIM Assessment Profile. We investigated components and questions of each model in detail, and mapped the questions of each model to the elements of BIM-CAREM. Additionally, we performed self-assessments with these models by using the data collected from a previously performed case study. Later, we compared these assessment results with the findings gathered from assessments performed with BIM-CAREM. The methods used for the comparison and the self-assessment results are explained in Sects. 46.2 and 46.3, respectively.

46.2 BIM Capability and Maturity Assessment Models

46.2.1 Bim-Carem

BIM-CAREM was developed based on the meta-model of ISO/IEC 33000 [17, 18] and its applicability, generality, and coverage was tested by conducting case studies in four different AEC/FM firms [15]. It is composed of two major parts, namely BIM Measurement Framework (MF) and BIM Process Reference Model (PRM) as presented in Fig. 46.1.

BIM PRM comprises definitions of twenty-eight AEC/FM processes which are included in four different facility life cycle stages, namely conceptual planning, design (architectural, structural, and building services), construction, and facility management. Each AEC/FM process in BIM PRM is defined in terms of process purpose and BIM outcomes and the definitions of these processes are also included [15]. BIM MF is composed of BIM capability levels and their associated BIM attributes. As presented in Fig. 46.2, BIM MF has 4 levels of BIM capability. Level 1-Performed, Level 2-Integrated, and Level 3-Optimized have a total of 6 BIM attributes which are Performing BIM, BIM Skills, BIM Collaboration, Interoperability, Corporate-wide BIM Deployment, and Continuous BIM Improvement. Each BIM attribute has three components namely, BIM outcomes/BIM attribute outcomes (BO/BAO), generic BIM work products (G BIM WP) and generic resources (GR). BIM outcomes/BIM attribute outcomes are observable results of a BIM attribute achievement.

Users and assessors can use BIM-CAREM for conducting a formal appraisal to determine the BIM capability level of a selected AEC/FM process such as an architectural design process. In order to give ratings for each BIM attribute, assessors are required to investigate if the BIM outcomes/BIM attributes outcomes are achieved. Hence, generic BIM work products and generic resources are observed for understanding the achievement level of a BIM outcome/BIM attribute outcome.

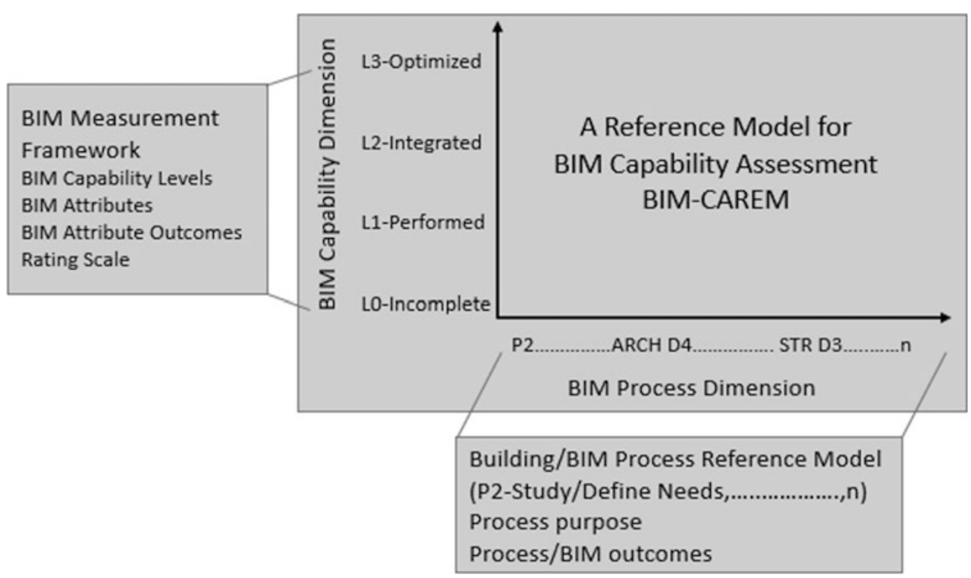

Fig. 46.1 Parts of BIM-CAREM [15]

Fig. 46.2 Components of BIM-CAREM

Grades of the associated BIM attributes are given according to these observations. Based on the assessment results, BIM improvement paths can be created for using BIM more effectively in the assessed processes. Thus, BIM-CAREM achieves to meet the different BIM assessment purposes of users by allowing process specific BIM capability assessments [15].

46.2.2 Assessment Models Used in the Comparison

We selected two of the eight models from literature, which are BIM QuickScan [9] and Organizational BIM AP [12], to include within the context of this comparison study. The extend of capability of the model and the availability of open source guidelines and tools were the criteria for including the models in this study. According to the first criteria, we selected the models which have more generic assessment purposes, hence we eliminated the BIM Proficiency Matrix [6] which is developed for assessing BIM performances of organizations for selecting designers or contractors in campus building projects. Moreover, models which are not very primitive, and have adequate number of metrics and two or more classification layers are included in the comparison. Only NBIM BIM CMM is eliminated based on the second criteria. The remaining models are presented in Table 46.1 with their number of classification layers and example metrics. Lastly, we looked at the availability of open source guidelines and tools for performing self-assessments. Except from BIM QuickScan and Organizational BIM AP, six models do not have open guidelines and tools, or the free versions of the tools contain limited contents. As a result, BIM QuickScan and Organizational BIM AP were included in this study.

BIM QuickScan provides insight about BIM strengths and weaknesses of the organizations [8]. It has a web-based online questionnaire which is composed of multiple choice questions. Free self-assessments can be performed by using this tool. It includes 44 questions in total. These questions are grouped under four categories which are Organization and Management, Mentality and Culture (People), Information Structure and Information Flow, and Technology and Applications. Total score

Table 46.1 Classification layers and example parameters of the models (which are found to be more elaborate)

Models	No. of classification layers	Example metrics
BIM MM	2 layers	Software, benchmarks/controls, activities/workflows
BIM QuickScan	2 layers	Vision and strategy of the company, BIM roles, linked BIM to geo-information
VDC scorecard	3 layers	Stakeholder formalization, VDC guidelines, data sharing, VDC training frequency
Organizational BIM AP	2 layers	Organizational mission and goals, facility data, software, education
VICO BIM scorecard	2 layers	Resource planning and cash flow analysis, 5D cost estimation, documented scheduling methodology, 3D coordination
Multifunctional BIM MM	2 layers	Software, BIM elements, spatial & coordination, clash analysis process

is the weighted sum of points for all categories. Resulting BIM level provides insight about BIM strengths and weaknesses of the construction organization [8, 9].

Organizational BIM AP can be used to evaluate the organization's BIM maturity focusing on six BIM planning elements which are Strategy, BIM Uses, Process, Information, Infrastructure and Personnel. These elements have 20 sub elements in total, and each sub element has six subsequent definitions which have been created based on the six maturity levels from 0 to 5. These six levels are; nonexistent, initial, managed, defined, quantitatively managed, and optimizing. For example, maturity level 0 for BIM project use is defined as no BIM uses for projects and maturity level 5 is defined as open sharing of BIM data across all project phases. Assessors can rate the elements by looking at these definitions and choosing the most appropriate ones. Organizational BIM AP has an excel-based tool which can be used for conducting self-assessments and also includes a user guideline [12].

46.2.3 Comparison of the Models

In order to perform the comparison, the assessment questions of the two models, i.e. QuickScan and Organizational BIM AP, were collected in separate excel sheets. Later, we compared the questions of these models with the questions of BIM-CAREM. For this, each question of BIM QuickScan was examined in detail and was mapped to corresponding (one or more) question/s of BIM-CAREM. If a question exists in BIM-CAREM and but not exist in BIM QuickScan, we marked that question of BIM QuickScan as not available. The same procedure was applied for the questions of Organizational BIM AP. The BIM-CAREM has 166 components whereas BIM QuickScan and Organizational BIM AP have 44 and 20 questions/elements in total, respectively. Table 46.2 presents the number of BIM-CAREM's measures within their respected categories and the number of these measures covered by BIM QuickScan and Organizational BIM AP. 0s presented as bold in Table 46.2 are metrics which exist in BIM-CAREM but do not in the two of the models.

Based on the same analysis, Fig. 46.3a shows the percentages of the BIM-CAREM's measures included in BIM QuickScan. For instance, 27% of Performing BIM measures and 40% of BIM Collaboration measures are included in BIM QuickScan. The metrics belonging to Interoperability are not defined in BIM QuickScan. Similarly, Fig. 46.3b shows the percentages of the BIM-CAREM's measures included in Organizational BIM AP. For example, only 6% of Performing BIM measures and 25% of Continuous BIM Improvement measures are covered by Organizational BIM AP. Furthermore, Organizational BIM AP does not have any measures related to Interoperability.

Figure 46.4 depicts the percentage of BIM QuickScan questions which are covered by metrics of BIM-CAREM. All of the questions of the Technology and Applications are included in BIM-CAREM. BIM-CAREM has 64, 50, and 75% of BIM QuickScan's questions defined under the categories of Organization and Management, Mentality and Culture (People), and Information Structure and Information Flow, respectively. Although BIM-CAREM does not include 13 questions of BIM QuickScan in total, derivatives of these questions are defined in the context of BIM-CAREM. For example, although short and long term objectives of BIM across the organization are not included in our model, BIM-CAREM has questions related to BIM goals as part of the development of BIM Execution Plan (BEP). Quality checks of the model and data, which is a question of Organization and Management, is not included in BIM-CAREM. Instead of the model and data quality, there are questions asking how organizations are performing quality assurance of a facility during the construction. BIM-CAREM does not examine the benefits of using BIM, since we thought that measured BIM capability levels can indicate whether BIM produces sufficient results or not. BIM-CAREM does not include questions related to the role of companies in terms of BIM uses. Instead, we conducted a literature review to identify different BIM uses, and included them as part of the process definitions.

In terms of Mentality and Culture, although BIM-CAREM has measures to assess the availability of BIM skilled employees within the company and if these employees are assigned to BIM related processes, it does not include questions related to existence of BIM champions. Questions related to the disadvantages and advantages of BIM are not included in BIM-CAREM. Although object libraries and facility data benchmarks are defined within the context of the BIM-CAREM, usage of object catalogue is not asked as a question which is defined under the categories of Information Structure and Information Flow of BIM QuickScan. We assess if the organizations use the model for several tasks such as costing, planning and design, but BIM-CAREM do not focus on re-usability of the model for performing these tasks.

Figure 46.5 depicts the percentage of Organizational BIM AP questions which are covered by the metrics of BIM-CAREM. All of the questions of the three categories, namely BIM Uses, Process, and Personnel, are covered with the questions of BIM-CAREM. BIM-CAREM has 40, 67, and 67% of the questions of Strategy, Information, and Infrastructure

Table 46.2 Components of BIM-CAREM included in BIM QuickScan and Org BIM AP

Components of BIM-CAREM	No. of components	No. of components covered	
		By BIM QuickScan	By Org BIM AP
BIM attribute performing BIM (Total)	*108*	*29*	*6*
BIM outcomes of conceptual planning	6	2	**0**
BIM outcomes of architectural design	19	5	2
BIM outcomes of structural design	9	1	**0**
BIM outcomes of building services design	10	**0**	**0**
BIM outcomes of construction	17	7	**0**
BIM outcomes of facility management	14	2	**0**
Generic BIM work products	9	**0**	**0**
Generic resources	24	12	4
BIM attribute BIM skills (Total)	*12*	*3*	*3*
BIM attribute outcomes	3	3	2
Generic BIM work products	5	**0**	1
Generic resources	4	**0**	**0**
BIM attribute BIM collaboration (Total)	*15*	*6*	*3*
BIM attribute outcomes	4	4	1
Generic BIM work products	6	1	1
Generic resources	5	2	1
BIM attribute interoperability (Total)	*6*	*1*	*0*
BIM attribute outcomes	1	1	**0**
Generic BIM work products	2	**0**	**0**
Generic resources	3	**0**	**0**
BIM attribute corporate-wide BIM deployment (Total)	*17*	*7*	*2*
BIM attribute outcomes	4	4	**0**
Generic BIM work products	6	1	1
Generic resources	7	2	1
BIM attribute continuous BIM improvement (Total)	*8*	*2*	*2*
BIM attribute outcomes	3	1	1
Generic BIM work products	2	**0**	**0**
Generic resources	3	1	1

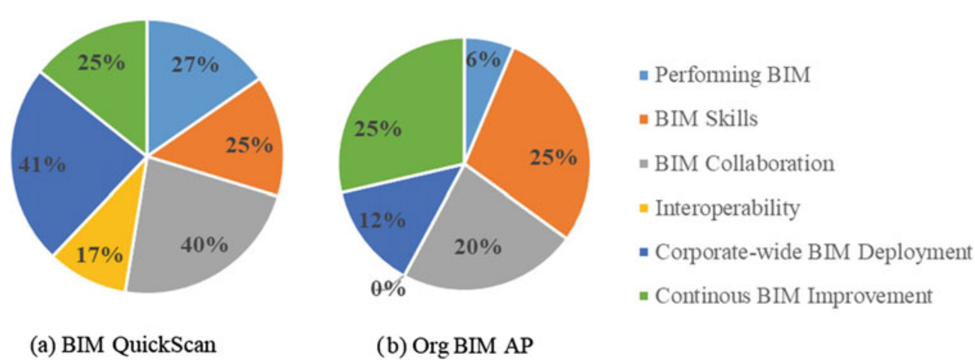

Fig. 46.3 Percentage of BIM attributes included in **a** BIM QuickScan and **b** Org. BIM AP

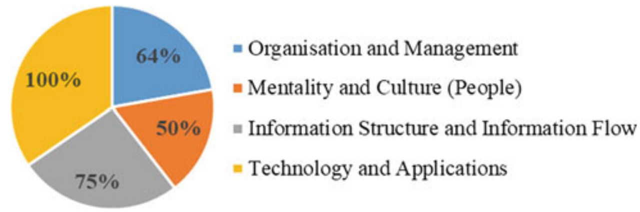

Fig. 46.4 Percentage of BIM QuickScan questions included in BIM-CAREM

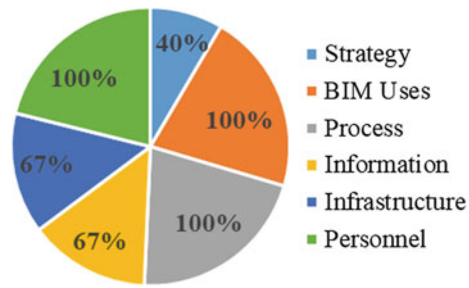

Fig. 46.5 Percentage of Organizational BIM AP questions included in BIM-CAREM

categories, respectively. BIM-CAREM does not include five questions of Organizational BIM AP, in total. Although BIM-CAREM includes questions related to BIM mission and BIM vision as part of required sections of BEP, defining organization-wide BIM missions and BIM visions are not included in the set of questions of BIM-CAREM. As mentioned previously, a question directly related to the existence of a BIM champion within the organization is not included in BIM-CAREM, which is a question of Organizational BIM AP too.

During the assessment of Corporate-wide BIM Deployment, which is a BIM attribute of BIM Capability Level 3-Optimized, we asked if model view definitions are used and if different views of the models are available. But, model element breakdown, which is defined as the identifiers assigned to each physical or functional element, is not included as a component of BIM-CAREM. Although, hardware adequacy of organizations for storing and sharing models are evaluated in our model, questions related to the existence of physical spaces are not included, which is defined in Organizational BIM AP as functional areas within a facility that are used to properly implement BIM.

There is not one to one relationship between the metrics of BIM-CAREM and the questions of evaluated models. For example, one question of BIM QuickScan has to be matched to several metrics of BIM-CAREM and vice versa. Furthermore, some categories cannot be mapped to each other. For example, BIM outcomes of Performing BIM in BIM-CAREM are mapped to the questions of Organization and Management, Information Structure and Information Flow, and Technology and Applications of BIM QuickScan. In other words, questions of BIM QuickScan are defined more generically than the metrics of BIM-CAREM. This was an expected result since BIM-CAREM has 166 questions while BIM QuickScan has 44. Organizational BIM AP is as comprehensive as BIM-CAREM too. For example, interoperability in BIM-CAREM, which is used to measure if interoperable formats are preferred for storing and sharing facility data, is not included by Organizational BIM AP as depicted in Fig. 46.3b. Additionally, metrics of BIM Collaboration are mapped to the elements in four areas of Organizational BIM AP, namely Strategy, BIM Uses, Processes, and Information. As presented in Table 46.2, 108 different metrics are defined for facility life cycle phases under Performing BIM which means that BIM-CAREM allows process specific assessments. Stakeholders from different organizations such as designers and general contractors can use BIM-CAREM for assessing their specific BIM tasks.

46.3 Evaluation Using Case Study Data

In order to test the generality and coverage of BIM-CAREM, we performed multiple case studies with four different AEC/FM companies [15]. Within this study, we used the case study data collected from one of those companies for performing self-assessments with the two selected BIM assessment models, namely BIM QuickScan and Organizational BIM AP. The selected company works on structural design and detailing of various facility types such as buildings, airports, sports facilities, and industrial plants. It is located in Ankara, Turkey and has less than 50 employees including civil

Table 46.3 Assessment results by using BIM-CAREM

Categories	BIM capability	
	Structural design of steel frames	Structural design of RC frames
Performing BIM	4/4	4/4
BIM skills	4/4	4/4
BIM collaboration	3/4	3/4
Interoperability	4/4	4/4
Corporate-wide BIM deployment	3/4	2/4
Continuous BIM improvement	2/4	2/4

engineers and technicians. During the case study, primary data has been collected through semi-structured interviews by asking the predefined interview questions. The secondary data has been gathered by observations of BIM artifacts (such as models) and BIM resources (such as BIM tools). Primary data was recorded in an excel sheet and secondary data was collected in a checklist. Based on these two data resources, a case study report has been written [15].

Ratings of the BIM attributes are given based on this case study report. We used the four-point ordinal scale which are Not Achieved (N–1 point), Partially Achieved (P–2 point), Largely Achieved (L–3 points), Fully Achieved (F–4 points) and Not Available (N/A). In order to achieve a BIM capability level, all of the BIM attributes should be rated as F or L. Ratings given for each of the BIM attributes are presented in Table 46.3. As the company is using BIM for performing their design processes and they have employees who have BIM skills, Performing BIM and BIM Skills attributes are rated as 4. They also use BIM for collaborating especially within the company. If their contractors want them to use BIM for collaboration, they also use BIM for external collaboration. They use IFC file formats for exchanging models. Based on these findings they received scores of 3 and 4 for BIM Collaboration and Interoperability, respectively. They facilitate digital fabrication from models for steel frames but not for reinforced concrete structures. Thus, while Corporate-wide BIM Deployment for steel frames was rated as 3, it was rated as 2 for concrete frames. They handle BIM problems with ad-hoc solutions. In other words, they do not have any strategies for identifying BIM related problems and for improving BIM usage. Thus, Continuous BIM Improvement was rated as 2. The structural design process for both steel and concrete frames were found at “BIM Capability Level 2-Integrated BIM”, since they received “P-2 points” for Continuous BIM Improvement.

The case study report of the company provided basis for performing self-assessments by using BIM QuickScan and Organizational BIM AP. We answered the multiple choice questions of the BIM QuickScan through the online questionnaire. Similarly, the excel-based assessment tool of Organizational BIM AP was used to assess the BIM capability of the selected company. Even though direct answers of 13 questions of BIM QuickScan do not exist in the assessment report of BIM-CAREM, we were able to answer these questions by looking at the details of the case study report and the secondary data. Likewise, although 5 questions such as organizational missions and goals have not been asked directly, the relevant information from the secondary data was used. BIM performance levels of the company with respect to each area of BIM QuickScan and Organizational BIM AP are given in Tables 46.4 and 46.5, respectively.

Table 46.4 Results by using BIM quickscan and the case study data

Category	BIM performance	
Organization and management	2.71/4	67.85%
Mentality and culture (people)	2.4/4	59.96%
Information structure and information flow	3.05/5	60.9%
Technology and applications	1.87/4	46.67%

Table 46.5 Results by using Organizational BIM AP and the case study data

Category	BIM maturity levels	
Strategy	8/25	32%
BIM uses	4/10	40%
Process	3/10	30%
Information	4/15	27%
Infrastructure	8/15	53%
Personnel	10/25	40%

BIM QuickScan produces performance levels with respect to each area at the end of the self-assessment. As presented in Table 46.4, the company received ratings of 2.71, 2.4, 3.05, and 1.87 out of 4 points for Organization and Management, Mentality and Culture, Information Structure and Information Flow, and Technology and Applications, respectively.

Some of the questions of BIM QuickScan are not clear; hence, it was difficult for us to understand and answer these questions. For example, there is a question asking if the company works based on a specific structure. However, what is meant by the structure is not explained; hence, it was not possible for us to answer this question. Moreover, some of the questions are not in the scope of designers' tasks but it is not allowed to mark a question as not applicable. This creates conflicts since some of the questions are not clear and some of them are not applicable to all AEC/FM companies. For instance, there is a question to evaluate if the company linked BIM to geographical information systems. Although we know that the company has not done this in our case, this question is not applicable to a structural design company. Hence, it should have been possible to leave this question out of the BIM performance calculation. Available answer options for some of the questions of BIM QuickScan neither match the question nor self-explanatory. For example, one of the questions about measuring the employee motivation of companies has two answers as (A) No and (B) Yes, on average, always. Choice B is contradictory since it contains both of the words "on average" and "always". Some of the questions were hard to answer due to the nature of the Turkish AEC/FM industry. For example, BIM QuickScan includes a question asking whether companies have specific kind of contracts with their partners. This structural design company cannot prefer a specific kind of contract, since as a designer company they have to fulfill the request of general contractors.

Organizational BIM AP produces one final BIM maturity score for the company as well as scores for each area in terms of points and percentages. The BIM maturity score of the company is 37 points out of 100 which is equal to the sum of the scores of all BIM planning areas. As presented in Table 46.5, the company received 8, 4, 3, 4, 8, and 10 points for Strategy, BIM Uses, Process, Information, Infrastructure, and Personnel, respectively.

Although some of the measures of Organizational BIM AP are only applicable to specific type of organizations, it is not allowed to leave these elements as null. Even though, we did not have the primary data to give a rating for some of the measures, we chose the answers that fit best with the secondary data available. For example, Operational Uses are not in the scope of a structural designer's tasks. However, we selected the best level of the element that fits the company which is defined as record (as-built) models received by operations. Some of the obtained results may contain conflicts, since elements of Organizational BIM AP are not customized with respect to the organization type. For some of the measures, terms used within the answers to define the levels of maturity are not self-explanatory. For example, high level, integrated, and defined are the consecutive definitions of maturity levels for BIM processes.

During the comparison of the models, it is identified that one category of BIM-CAREM contains questions/elements from multiple categories of the BIM QuickScan or Organizational BIM AP. Thus, in order to compare the resulting BIM performances, we needed to recalculate the results based on the mapping of these elements. We were only able to compare the score of the BIM Skills of BIM-CAREM and the score of the Personnel of the Organizational BIM AP directly (without doing any recalculation), since these two categories have one to one relationship. The scores of the BIM Skills and the Personnel are 4/4 (see Table 46.3) and 10/25 (see Table 46.5), respectively. The resultant rating of BIM Skills is higher than the rating found for Personnel of the Organizational BIM AP, since elements of the Personnel are more detailed than the BIM attribute outcomes of the BIM Skills. For example, BIM Skills does not contain questions which asks how frequently companies give trainings to their employees and how many employees are given trainings. Organizational BIM AP also contains separate elements for training and education in the Personnel category. Besides, it was hard to compare the score found via BIM-CAREM and score calculated through BIM QuickScan/Organizational BIM AP, since most of the categories and their sub elements do not have one to one relationship.

46.4 Conclusions

In this study, we compared the metrics of BIM-CAREM with the questions/elements of the selected models from the literature, namely BIM QuickScan and Organizational BIM AP. One of the major problems of both of these models is that some of the questions/elements are not in the scope of designers tasks, which was our case study organization. Additionally, it is not allowed to select those measures as not applicable in the context of self-assessments, although answering unrelated measures can create errors in the final assessment results. In other words, both of these models do not allow customized assessment based on the organization type. On the other hand, since BIM-CAREM includes definitions of AEC/FM processes in BIM PRM, it allows users to perform assessments specific to organization types based on the processes they are involved in. BIM-CAREM has more detailed and specified questions for assessing BIM capability of different AEC/FM processes and has comparable assessment results to these capability models. Both of the evaluated models have self-assessment tools. BIM QuickScan has an online questionnaire and it is very easy to conduct a self-assessment. Organizational BIM AP has an excel-based tool and it is also easy to use. However, BIM-CAREM does not have a self-assessment tool. In order to eliminate this limitation, a web based assessment tool can be developed which may also allow collecting benchmark datasets with BIM-CAREM.

References

1. Edirisinghe, R.: Comparative analysis of international and national level BIM standardization efforts and BIM adoption. In: 32nd CIB W78 Conference (2015)
2. BSI: PAS 1192—2 Specification for information management for the capital/delivery phase of construction projects using building information modelling (2013)
3. NBIMS: National BIM Standard—United States ® Version 3, Scope (2015)
4. Yilmaz, G., Akcamete, A., Demirors, O.: A review on capability and maturity models of building information modelling. Lean Comput. Constr. **3**, 627–636 (2017)
5. NBIMS: National BIM Standard United States ® Version 3—Minimum BIM (2015)
6. IU Arhictect's Office: BIM Proficiency Matrix [Online]. Available: http://www.iu.edu/~vpcpf/consultant-contractor/standards/bim-standards.shtml (2009)
7. Succar, B.: Building Information Modelling Maturity Matrix. (2010)
8. Van Berlo, L., Dijkmans, T., Handriks, H., Spekkink, D., Pel, W.: BIM QuickScan: Benchmark of BIM Performance in the Netherlands, pp. 17–19 (2012)
9. BIM Supporters B.V.: BIM QuickScan Tool [Online]. Available: https://app.bimsupporters.com/quickscan/. Accessed on 04 Apr 2018
10. Kam, C., Senaratna, D., Xiao, Y., McKinney, B.: The VDC Scorecard: Evaluation of AEC Projects and Industry Trends (2013)
11. CIFE: VDC Scorecard [Online]. Available: https://vdcscorecard.stanford.edu/survey-input-forms. Accessed on 04 Apr 2018
12. PennState CIC: Organizational BIM Assessment Profile [Online]. Available: http://bim.psu.edu/resources/owner/bim_planning_guide_for_facility_owners-version_2.0.pdf (2012). Accessed on 27 Jun 2018
13. VICO Software: VICO BIM Scorecard Survey [Online]. Available: https://www.surveymonkey.com/r/9YCHVXC. Accessed on 25 Aug 2017
14. Liang, C., Lu, W., Rowlinson, S., Zhang, X.: Development of a multifunctional BIM maturity model. J. Constr. Eng. Manage. **142**(11), 06016003 (2016)
15. Yilmaz, G.: BIM-CAREM: A Reference Model for Building Information Modelling Capability Assessment [Online]. Available: http://lib.metu.edu.tr/metu-theses-collection-search (2017). Accessed on 28 Jun 2018
16. Wu, C., et al.: Overview of BIM maturity measurement tools. J. Inf. Technol. Constr. **22**, 34–62 (2017)
17. ISO/IEC: ISO/IEC 33003 Information technology—Process assessment—Requirements for process measurement frameworks (2015)
18. ISO/IEC: ISO/IEC 33004 Information technology—Process assessment—Requirements for process reference, process assessment and maturity models (2015)

Towards a BIM-Agile Method in Architectural Design Assessment of a Pedagogical Experiment

47

Henri-Jean Gless, Gilles Halin, and Damien Hanser

Abstract

This paper describes a scientific experiment carried out in the context of the AEC in France. This research is part of the digital transition in architecture, with a particular interest in BIM technology and how to integrate it into architectural design through social sciences. Indeed, the arrival of BIM technology raises both technical and human questions. The design work is changed, the amount of work is moved upstream, but above all we see new tools, new uses, and new practices without any project management method emerging. In other fields such as industry, software engineering and HMI design, we have seen the emergence of methods that focus more on the team and the user than on the process. We find Lean, continuous improvement, or agility, a family of methods that interests us here. Our research hypothesis is that inserting agile practices alongside current business practices will integrate and exploit BIM technology and other digital innovations. To do this, we identified what the problems were with BIM technology, and selected several agile practices highlighting communication, group cohesion and customer needs identification to address them. Thus, we carry out experiments in which we test, analyze and adapt these agile practices to architectural design. This paper then describes a pedagogical experiment conducted with Master 2 students at the École Nationale Supérieure d'Architecture of Nancy in France. In a workshop, the students had to carry out a BIM project, while they used the agile practices that we had adapted: the design matrix, the micro poker, and the stand-up meeting. In addition to these three practices, we took the opportunity to try agile overseeing using what we call a stand-up meeting. The objective is to validate the synergy of these practices while ensuring that they respond to our communication, group cohesion and customer needs integration issues. This experiment takes place over one week and will serve as a basis for us to prepare experiments in a professional context.

Keywords

Architectural design • Agile methods • Agile practices • BIM technology • Collaborative design • Intentions elicitation • Lean management • Project management • Social sciences

47.1 Introduction

This research takes place in the field of AEC industry in France where the digital adoption is underway with BIM technology still not properly implemented. Nowadays, for both the educational and the professional field this transition is often seen only through the technological prism and not through the social science approach.

As part of our research, we are developing so-called agile methods and collaborative practices to facilitate the adoption and the exploitation of BIM in architectural design. Agility is a term derived from the world of software engineering, and

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consists of human-centered methods and practices. In order to validate our hypotheses before testing them in the professional world, this paper describes an experiment with architecture students. Moreover, our hypothesis is that training students in new digital practices is an efficient way for changes to take place in the professional world.

During a workshop week called Design and Digital Manufacturing, the students put in groups must design a BIM architectural project before making a scale model 1/20 using 3D printers and laser cutters. They will apply three agile practices that we have adapted for architectural design: micro poker, design matrix and stand-up meeting. We have tested these practices individually. We want to show that they can improve communication in a collaborative working group, have a better group cohesion, and have a better integration of client needs. This experiment will allow to verify if these practices are compatible together. In order to ensure that the experiment is going well, we take the opportunity to insert another practice: the supervision of a BIM-agile coach. He ensures that the workshop runs smoothly, and deals with problems concerning the other practices.

We will focus in Sect. 47.2 on the current context of digital transition in France. Next, we will see in Sect. 47.3 how BIM technology disrupts work habits, and what locks are identified. Section 47.4 will focus on the practices proposed to address these blockages. Finally, Sect. 47.5 will concern the experimentation of these practices with our students.

47.2 A Sector in Transition Without Changes in Management

While the digital transition is taking place in the AEC industry, other sectors are adapting and creating innovative project management methods.

47.2.1 France at the Heart of Digital Change

The world of architecture, engineering and construction (AEC) in France, particularly in the field of architectural design, is currently going through an important period of change; digital practices and collaborative practices are changing and adapting while BIM technology is becoming both a regulatory requirement in public construction and a productivity requirement in complex projects. However, there is a certain inertia on the part of architects towards Building Information Modeling. This trend can be explained by the size of French architectural firms. Most of them are small (90% have 9 employees or fewer and 75% have 4 employees or fewer) [1]. Also because of the current socio-economic context, which favors a low level of investment in the medium and long term. Since each agency has its own method of doing architecture, they have already become involved in project management, and the arrival of a tool like BIM raises questions [2].

47.2.2 Emerging Project Management Practices

In the field of project management, methods are emerging from continuous improvement or Lean Production, as Lean Construction [3]. In order to improve the construction, it is necessary to ask the question of the place of the coordination in the whole process. According to Patrick MacLeamy's curve, BIM technology increases the amount of work upstream [4] and changes digital and collaborative practices, which can generate misunderstandings. We have identified communication, group cohesion, and customer needs satisfaction problems with the use of BIM technology. Results in a climate of mistrust between the actors of a project, and rigidifies coordination. In software engineering and HCI design fields, agile methods are being applied to answer similar issues [5].

47.3 BIM Technology Needs Agile Practices

The digital transition brings new technologies such as BIM, but for the latter, no framework is precisely described. There is a need for new management methods.

47.3.1 BIM Technology Brings Complexity

BIM is defined as a technology, which designates both a process and a design tool. However, it is actually a digital model in which designers will insert more or less information depending on the progress and complexity of the project. BIM stands for Building Information Model, Modeling, or Management. However, it only brings tools and uses (Model and Modeling) and no human coordination practices (Management) [6], which does not necessarily allow good exploitation, and therefore limits its integration with architects and agencies.

These new tools and uses change the way to do project management. The amount of design and modeling work is indeed shifted upstream of the design phase. By passing from a 2D design to a 3D (and more) design, the amount of work is also increased or moved upstream. This is also the case when we add semantic and enriched notions [7]. It becomes mandatory to think in more detail about object modeling.

By bringing more work and more complexity upstream, BIM technology brings more tasks and more decision-making processes and forces designers to bring more coordination earlier. These changes are transforming the collaborative process, with more information to be shared earlier among stakeholders. BIM poses the problem of the complexity but also creates a need for exchanges between the stakeholders.

47.3.2 A Need for Elicitation, Refinement and Evaluation

We conducted interviews with students and architectural design professionals in order to confirm our hypothesis about the exchanges. Our interlocutors are generally informed and aware of the BIM concept but remain concerned about its arrival. Moreover, we found that collective activities concerning BIM tasks are difficult activities, and more particularly their definition, their "owners", their transmission to other actors (with their initial meaning), or their estimated duration. We call that elicitation, refinement and evaluation activities [8].

Thus, we have oriented our research towards practices to improve collaboration and consequently exchanges within a group in order to solve these problems: the agile methods.

47.3.3 Agility as a Coordination Vector

Agile methods are specific management methods that involve the customer in the decision process and follow three other fundamental rules: team collaboration, continuous improvement and change acceptance [9].

Our hypothesis is that the insertion of agile practices into design activities (therefore the four basic rules will improve communication, group cohesion and customer integration) will improve the quality of the architectural project. Indeed, agile methods and practices focus on building trust between all the design actors (the customer including).

47.4 Agile Practices Identification and Adaptation

We have thus looked at the agile practices employed in the world of software engineering and the HCI design, and identified four of them. Three are practices used by the stakeholders themselves and one is a coaching practice. We experimented and adapted them to the architectural design.

47.4.1 Design Matrix: Writing Down Intentions

The design matrix is an online table that is filled out collaboratively. Inspired by Suh's matrices [10], we have created it to allow the actors of the collaboration to confront their architectural intentions. The programmatic elements of the project, referred to as the inputs, are found in rows; the needs or deliverables, referred to as outputs, are listed in columns.

This practice allows the actors to elicit collaboratively their intentions, and to ask themselves all the questions they have in mind about the project: the concept, the references, the keywords, etc.

Moreover, this practice provides a reflective framework for design, a concrete basis to help the less creative or comfortable actors with a pencil to still give their ideas (Fig. 47.1).

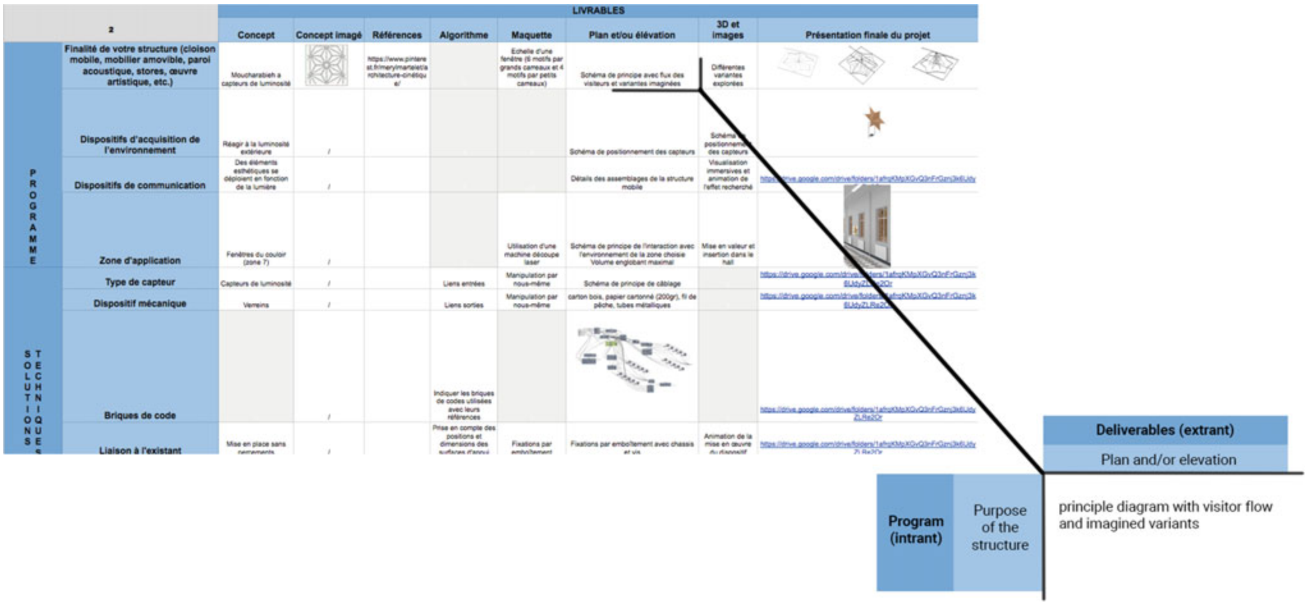

Fig. 47.1 Zoom on how to fill a design matrix with text (could be schemas, pictures or URL)

47.4.2 Micro Poker: Put Everybody on the Same Page

Micro poker is an agile practice that we have adapted from planning poker [8, 11]. It is a deck of cards, and each player has four cards. There are several scales of values such as numbers (1, 20, 80 and 100) or color (green, yellow, orange or red) or size (S, M, L and XL). In order to properly identify a design task, players ask questions, and all of them answering at the same time by choosing a card.

Once everyone has played, the players with the furthest cards begin to debate their choice. Once everyone has spoken, the group must converge towards a compromise. Then start another round.

This practice allows players to express themselves and elicit their thoughts, while avoiding the phenomenon of the "first speaker". This phenomenon is the fact that, during a debate, the protagonists set their arguments against those of the person who spoke first (Fig. 47.2).

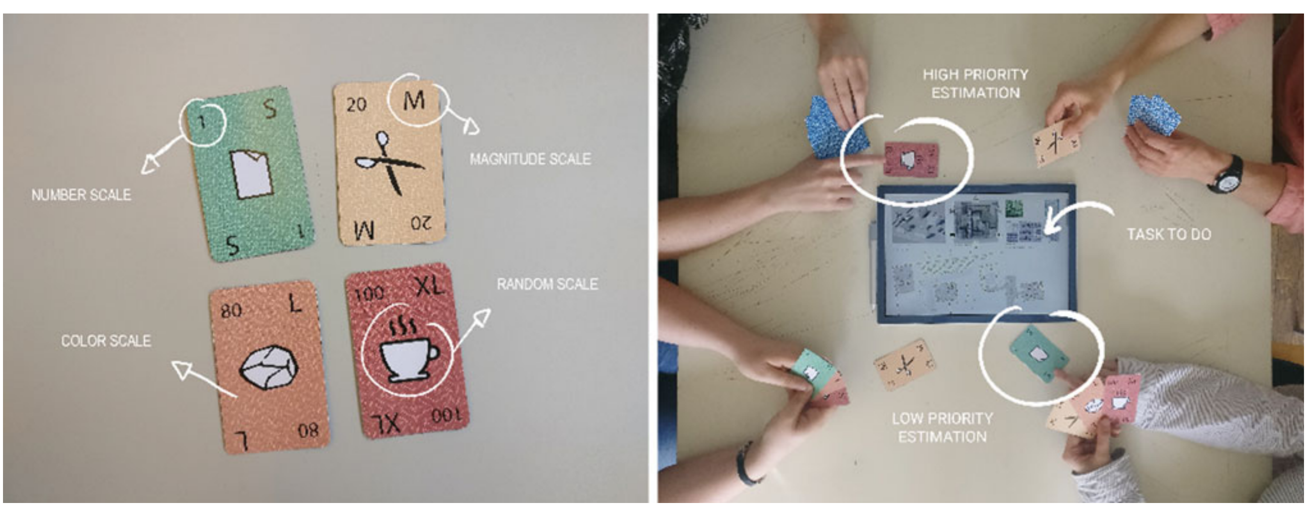

Fig. 47.2 A set of Micro Poker cards (left) and four players during a round (right)

This is an example of an exchange sequence:

Actor 1: How long does it take to place the point cloud in the 3D model we scanned yesterday? We use S, M, L or XL. (everybody chooses a card, and reveals it at the same time; actor 1 and actor 2 with extreme card start talking).

– Actor 1: I have put a S card because it is not difficult to import a cloud point in the software.
– Actor 2: I do not agree! I have put a XL card because by experience, there is always something that goes wrong, and we need to clean the point cloud before import it.
– Actor 1: OK I have not thought about that.
– Actor 3: And we need to finish the ground modeling before that.
– Actor 2: Right! OK, I will clean the cloud, during this time, can you finish the ground?
– Actor 1: I will help him, I am comfortable with that. So, for the next round: how long does it take to finish the ground? (*Here starts a new round*) [8].

47.4.3 Stand-up Meeting: Taking Stock

The stand-up meeting is an agile practice that consists of making a short daily meeting among the actors of the collaboration [11]. These actors stand and talk about what they did yesterday, what they are going to do today, and what do they need if they have problems.

This practice allows to know what other actors do and to develop cohesion and a shared knowledge of the project. People remain standing in order to stay focused away from their workstations, and also to minimize the comfort and therefore the duration of the meeting. They want to get back to work.

The goal is to have a quick global vision of the progress and the problems encountered. An actor who is above the project often leads this practice in order to bring objectivity and help. This practice did not need much adaptation: a graphic document seems, however, relevant in an architectural design context. Indeed, it allows to have what is called deliverables, kind of design milestones reorienting the work and thus to integrate the customer's needs (Fig. 47.3).

47.4.4 A BIM-Agile Coach to Oversee the Workshop

Experimentation here consists of knowing if they are compatible and beneficial to the use of BIM. The students have already experienced the different practices independently of each other but can still ask themselves some questions. One of the practices we had previously identified that did not require students' participation is the BIM-agile coach or coordination facilitator. This person knows perfectly the three other practices, as well as the project that the students must carry out, and supervises them in order to answer their questions about the project, technical issues or coordination.

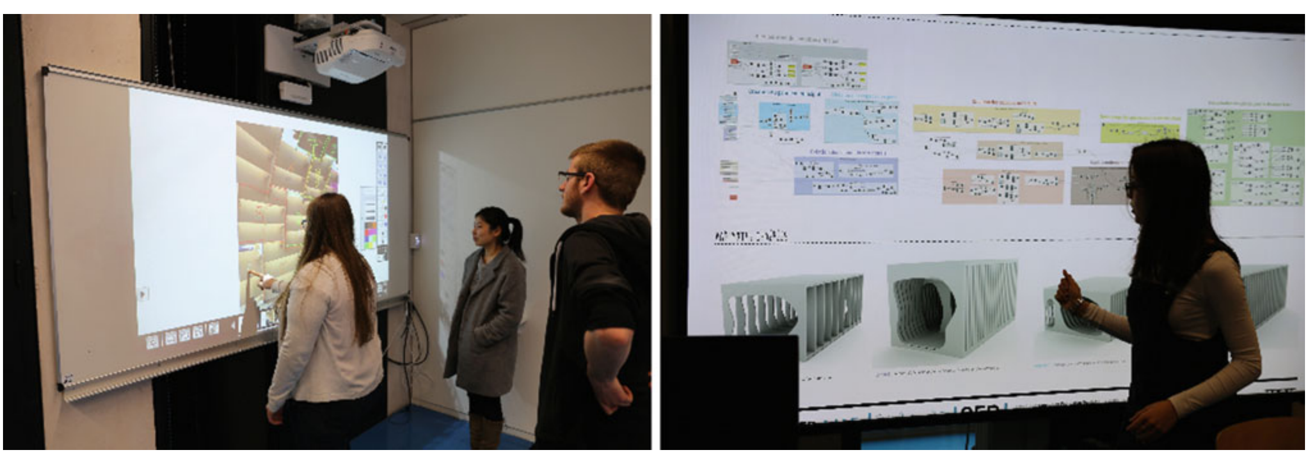

Fig. 47.3 Examples of two stand-up meetings with graphic supports. An engineer showing her assembling (left); an architect showing variants of its algorithm (right)

This practice comes from the scrum method [11] where we find a scrum master and a product owner. The first one is in charge of the well application of the method, and the second one represents the customer needs and views about the project. In our pedagogical context, we adapted them both in order to merge into a BIM-agile coach.

47.5 The Four Practices in Experimentation

In order to validate their semester, the 20 students from the Master 2 AME[1] must make a workshop called Design and Digital Manufacturing. They can apply everything they have learned during the year, about BIM, project management and design.

47.5.1 Design and Digital Manufacturing Workshop

Students experimented in February during the Design and Digital Manufacturing workshop our agile practices. The students' work topic consisted of the realization of an architectural object of their choice, related to mobile micro architecture. Students came from different curricula, so each group contained at least an architect, an engineer and a designer. The topic and the composition of the groups were sent to them beforehand so that they could appropriate it during the weekend. They already have been introduced to agility with a course, and with some exercises.

We distributed a set of micro poker to each student, and they could use it when they want as a decision-making tool throughout the week, as well the design matrix. The stand-up meeting was held every morning. The agile coach was there during the whole week to provide support.

In order to measure the benefits of these agile practices, we were interested in the students' use of our tools or simply whether they were using them during the whole week; the students also received at the end of the week a survey so that they can give their opinion on agility.

47.5.2 A Protocol for One Semester

Before conducting the experiment, we gave courses and exercises about agility and project management to our students.

We followed this protocol:

- Theoretical phase: opening course on agility and project management followed by an explanation of the three agile practices;
- Practical phase: one exercise per practice;
- Practical phase: a semester long BIM collaborative project studio;
- Data gathering: students do a report about the previous collaboration exercise, with comments on practices;
- Practical phase: the Design and Digital Manufacturing workshop;
- Data gathering: recordings and observations during the DDM and anonymous online survey about agility after it;
- Data analysis: bias sort and practices improvement.

The theoretical phase allows students to understand project management by studying its history and to realize that there are important changes when adopting digital technologies. It is also a phase allowing an introduction to agile methods and practices.

The first practical phases consist of exercises where we present our agile practices. The second practical phase is a collaborative BIM project where they are free to apply the practices they wish. Finally, they end the semester with the MDD workshop where we ask them to implement our practices.

The first data gathering phase mainly consists to organize an oral presentation and to offer students agile feedback; this prepares the DDM workshop week. The second one is doing recordings and distributing an anonymous survey that gives us qualitative feedback.

[1]AME (Architecture, Modeling and Environment) is a Master 2 course from the École Nationale Supérieure d'Architecture (National School of Architecture) of Nancy, France.

Finally, the data analysis phase consists of a sorting of the data previously collected, in order to eliminate misunderstanding biases of the subject, or irrelevant answers of the survey.

47.5.3 Observations During the Workshop

The BIM-agile coach could observe how the students used the practices to experiment in addition to his support work. We made the following observations:

- Design matrix: it is used at the beginning of the workshop to allow students to write and draw the ideas they have. On the other hand, it is used less and less as the week progresses.
- Micro poker: students tend to use poker not as an elicitation and refinement tool, but as a voting system.
- Stand-up meeting: students were reluctant to use it at the beginning, thinking they didn't need it. On the 2nd day, they asked for it in order to take stock and "officially" make their choices.
- BIM-agile coach: this made it possible to quickly solve the problems of timetable, interpretation of the subject and techniques.

We realized that tools can be used less as time goes on. This is normal: no more need for decision support tools when the project is advanced and only production tasks remain to be carried out.

47.5.4 The Survey Results

Two weeks after the intensive workshop, we distributed a survey to students to gather their opinions on the practices used and agility in general. The results are rather positive in the sense that out of 20 people, there is never less than 60% satisfaction and never more than 15% bad criticism on agility (Fig. 47.4).

More specifically, 65% of students found the frequency of one stand-up meeting per day appropriate, while 10% found it too low and 10% too high. The same proportion of students are satisfied with the practice's contribution to their organization. A large proportion, 75% of the 20 students, thinks that agility was useful in carrying out their project. However, only 60% or 15 points less plan to reuse agile practices in their future projects. One can qualify with the fact that no student ever plans not to reuse them.

Finally, a majority of students found that the three agile practices they used allowed them to have a better group cohesion, a better communication, as well as a rhythm of deliverables allowing them to stick to the needs of the statement (a virtual customer in a certain way).

47.6 Conclusion and Opening on Professional Experiments

The observations made during the workshop and the results of the survey allow us to say that the agile practices we have proposed have been beneficial for collaboration.

First of all, all three student practices were used, and the survey shows their willingness to apply agile practices again. The design matrix was not completed to the end, but as said, the tool was no longer pertinent after a while. Micro poker allowed students to make decisions quickly, and they even made it their own. For the record, they sometimes used it to decide what to eat. The stand-up meeting was the practice that really made it possible to complete such a complex project in such a short time. Having a regular cycle of deliverables and being able to take stock every day allowed them not to get lost in projects too ambitious or too far from the subject. Finally, the BIM-agile coach served on both sides: an interlocutor for them who solves problems and a "pressure" sensor for us.

To conclude, this experimentation has confirmed that agility can play a major role in the integration of BIM and new technologies into architectural design. We will then try our agile practices in a professional environment in order to continue our research.

Fig. 47.4 Some results of the student survey conducted after the workshop

References

1. Observatoire de la profession d'architectes, Archigraphie, p. 48. https://www.architectes.org/sites/default/files/atoms/files/archigraphie-coul-2016-web_0.pdf (2016). Last accessed 02 Apr 2018
2. Hochscheid, E. et al.: BIM Implementation in SMEs: an Experience of Cooperation between an Architect Agency and a Carpentry Firm. International Conference on Computing in Civil and Building Engineering, 6–8 July 2016, Osaka, Japan (2016)
3. Dupin, P.: Le LEAN appliqué à la construction: Comment optimiser la gestion de projet et réduire coûts et délais dans le bâtiment?, 1st edn. Eyrolles, Paris (2014)
4. Kensek, K., et al.: Manuel BIM: Théories et Applications. Eyrolles (2015)
5. Womack, J., Jones, D.: Lean Thinking: Banish Waste and Create Wealth in Your Corporation, 2nd edn. Free Press, New York (2003)
6. Zignale, D., et al.: Modelling practices and usages to improve adaptation of groupware-tool services: Application in the AEC sector. Europia.13: 13th International Conference on Advances in Design Sciences and Technology. Roma, Italy (2011)
7. Halin, G., Gallas, M.: Une approche pédagogique par les modèles pour la sensibilisation au concept de BIM (Maquette Numérique) SCAN'16, 7-9 September 2016, Toulouse, France (2016)
8. Gless, H.-J., et al.: BIM-agile practices experiments in architectural design. In: Luo, Y. (ed.) Cooperative Design, Visualization, and Engineering. CDVE 2017. Lecture Notes in Computer Science, vol. 10451, pp. 135–142. Springer, Cham (2017)
9. Beck, K. et al.: Manifesto for Agile Software Development. http://agilemanifesto.org (2001)
10. Suh, N.: Axiomatic Design: Advances and Applications. Oxford University Press, Oxford (2001)
11. Kniberg, H.: Scrum and Xp from the Trenches: How We Do Scrum, 2nd edn. Lulu Press, Morrisville (2015)

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48 A Generalized Adaptive Framework for Automating Design Review Process: Technical Principles

Nawari O. Nawari

Abstract

Design review is the process of evaluating a design against its requirements to verify the performance of the design and identify issues before construction takes place. The cited methods for automating the design review process are either based on proprietary, domain-specific or hard-coded rule-based representations, which may be successful in their particular implementations, but they have the drawbacks of being costly to sustain, inflexible to change, lack generalized framework of rules and regulations modeling that can adapt to various engineering design realms, and thus don't support an open neutral standard. They are often referred to as 'Black Box' approaches. This study proposes a new comprehensive framework that minimizes the shortcomings of the cited methods. Building regulations for example, are legal documents written and authorized by people to be interpreted and applied by professionals. They are barely precise as formal logic. Engineers can read those documents and translate them into scientific notations and software applications. They can extract any information they need, reason about it, and apply it at various levels of precision. How these extraction and application are carried out is a critical component of automating design review process. The primary project goal is to address this issue by focusing on the development of a Generalized Adaptive Framework (GAF) for an open standard [based on Industry Foundation Classes (IFC)] that enables automating the design review processes to attain design efficiency and cost-effectiveness. The objectives of this paper include: (a) the conceptual and theoretical development of a framework that is adaptive to the target domain and supports an open standard for transforming the written design regulations and rules into a computable model, and (b) defining the different modules needed for the automation of the design review process.

Keywords

Design review • BIM • IFC • Generalized adaptive framework • GAF • Automation of design review

48.1 Introduction

Design review is the process of evaluating a design against its requirements to verify the performance of the design and identify issues before construction takes place. Design requirements typically take the form of written texts, tables, and equations. These rules, in general, have lawful status. However, the reasoning and analytic ability of the human brain is unlike algorithms implemented in computer systems. Thus, the automation of this process poses a real challenge to the engineering domains. For example, how can the interpretation of these rules in a computer interpretable format be performed, in a manner that the implementation can be validated as consistent with the written design requirements?

One of the first effort to automate design compliance is demonstrated by the work of Fenv [4], when he investigated the application of decision tables to represent the AISC (American Institute of Steel Construction) standard specifications. He made the remark that decision tables, If-Then-novel programming, and program documentation technique, could be

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utilized to represent design standard provisions in a precise and unambiguous form. The concept was set to practical application in the [2] AISC Specification. It was described as a set of interrelated decision tables. Later, other researchers tried to build on Fenv work such as Lopez et al., who implemented the SICAD (Standards Interface for Computer Aided Design system [7, 8]. The SICAD system was a software prototype developed to demonstrate the checking of designed components as described in application program databases for conformance with design standards. The SICAD concepts were in production use in the AASHTO Bridge Design System [1].

Other recent research efforts have proposed to manually extract and translate written regulatory rules directly into computer code [10, 11]. In such approach, formalized regulatory information in the form of codified rules is then accessed internally by the software code of the compliance examination application. Further recent efforts on automating design review process are focused more on the concept of regulatory text mining and semantic web approach to creating a computable representation [5, 13, 16]. Other investigations are centered chiefly on the studies of automated or semi-automated extraction of information from regulatory texts into rules using Artificial Intelligence (AI) and Natural Language Processing (NLP) [15–18]. There are also some research efforts that target specific domains and are bounded by the particular area of computerized code compliance verification system [6, 9].

48.2 Statement of Contribution

The current methods for automated rules compliance auditing are either based on proprietary, domain-specific or hard-coded rule-based representations, which may be successful in their particular implementations, but they have numerous disadvantages. These methods are costly to maintain, inflexible to change, lack a generalized framework of rules and regulations modeling that can adapt to various domains, and thus don't support an open neutral standard. They are often referred to as 'Black Box' or 'Gray Box' approaches.

The proposed GAF for Automated Design Review (ADR) process involves the development of the computable representation of code regulations and the mechanisms for exchanging data between the different components of the framework and the Building Information Model (BIM) data. This paper focuses on the basic principles of the GAF. This includes the general concepts and the interpretation process where the semantic structure of the building codes regulations is manipulated and transformed into object rules or parametric models using Transformation Reasoning Algorithm (TRA) and the development of Model View Definition (MVD) that would lead to Industry Foundation Classes (IFC) data schema. This requires the development of taxonomy, knowledge conceptualization, modification, integration, and decomposition of the design regulations and rules.

48.3 Goals and Objectives

The project primary goal is to address the issue of ADR process by concentrating on the development of a Generalized Adaptive Framework (GAF) for an open standard [based on Industry Foundation Classes (IFC)] that establishes the foundation for automating building design review processes.

The objectives of this research include the theoretical development of a framework that is adaptive to the target domain and supports an open standard for transmuting the written regulations and rules into a computable model, defining the different components needed for the automation of the design review process, and creating an algorithm for the data exchanges between the components of the framework to execute the virtual review process of a building design.

48.4 Methodology

48.4.1 Theoretical Framework

The GAF for ADR process involves the development of a computable representation of building regulations and the mechanisms for exchanging information between regulations and the Building Information Model (BIM) data. Figure 48.1 delineates an overview of the components and phases of the proposed framework. An overview of these main phases is given below:

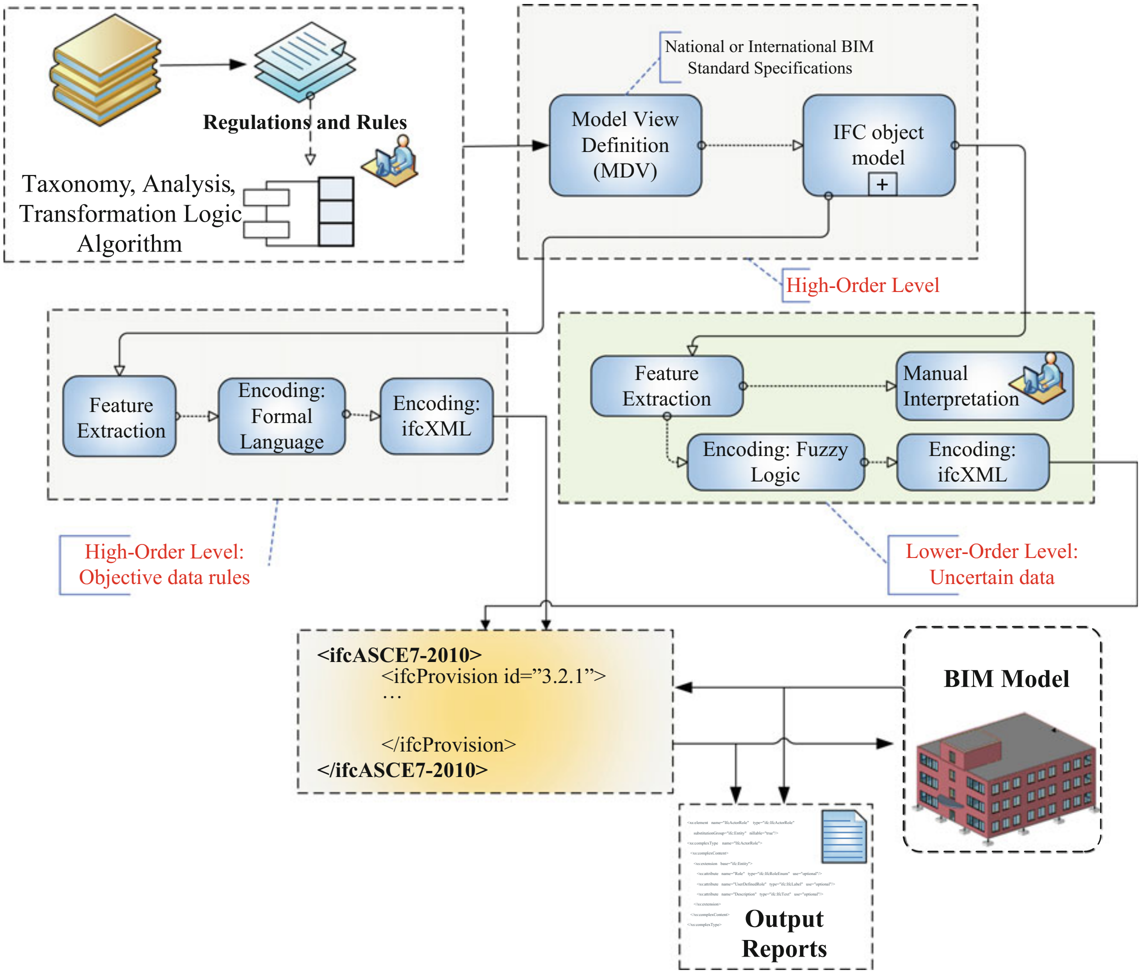

Fig. 48.1 The generalized adaptive framework (GAF) for automated buildings design review

(A) High-Order Level I: Taxonomy formation, knowledge conceptualization, modification, integration, and decomposition of the design regulations and rules. This encompasses data analysis, partitioning and classification of regulatory text into broad categories. This is shown in the first step of Fig. 48.1. This phase is referred to as Transformation Reasoning Algorithm (TRA).

(B) High-Order Level II: Requires the Development Model View Definition (MVD), leading to Industry Foundation Classes (IFC) schema of the information obtained from phase A. The final data format is ifcXML representation. IfcXML is defined as the XML equivalent to the EXPRESS based specification of the IFC data model.

(C) Higher-order level III: The development feature extraction algorithm for all objective data (unambiguous data) leading to full translation into the object-based model. This extraction and transformation will lead to ifcXML data object model (see Fig. 48.1).

(D) Lower-order level: Necessitates feature extraction of uncertain data, then employing an algorithm for partial translation using fuzzy logic and approximate reasoning methods. Fuzzy logic provides a means of expressing linguistic rules in such a form that they can be combined into a coherent reasoning model. Such a model consists of three main parts: (i) fuzzification, (ii) inference engine (fuzzy rule base), and (iii) defuzzification (the process of transforming the aggregation result into a crisp output). The resulting data model from this phase is projected to be in ifcXML.

(E) The execution phase, which carries out the communications between the different layers of development. This encompasses the design of an algorithm linking the data from (B), (C), (D) and the BIM model. This phase will result in generating reports of the ADR outputs.

This paper centers primarily on the TRA. Subsequent publications will address the other phases of the GAF along with the criteria used to evaluate this part of the framework comprise interpretation accuracy, dealing with complexity, and the degree of completeness.

48.4.2 Transformation Reasoning Algorithm (TRA)

The TRA introduces the taxonomy for the building regulations knowledge followed by conceptualization process. Subsequently, knowledge created will be transformed into a new formalized form to deduce various facts to carry out automated reasoning. For example, building regulation or provision X_i will be transformed into a concept Y_i using TRA principles. TRA taxonomy defines the following major concepts:

Content (C_i)
Provisory (P_i)
Dependent (D_i)
Ambiguous (A_i)

Contents ($C_i \ldots C_n$) are the sections of the building codes and regulations that cannot be transformed into object rules. These clauses are usually devoted for definitions, such as the definition of types of loads, firewall, fire rate, smoke evacuation, high-rise building etc. For instance, the live load is defined by the ASCE7-10 standard as: "*A load produced by the use and occupancy of the building or other structure that does not include construction or environmental loads, such as wind load, snow load, rain load, earthquake load, flood load, or dead load*".

Provisory ($P_i \ldots P_n$) are clauses of the regulations that can be transformed from the textual format into a set of object rules. Examples of such clauses are prevalent and typical structures include rules with specific values such as those given in tables or equations in the building codes and standards.

Dependent ($D_i \ldots D_n$) clauses specify that one clause is reliant on one or more other provisions. This means that some requirements are only appropriate for a specific condition when other clauses are satisfied. These clauses generally contain provisory clauses ($P_i \ldots P_n$) and are often challenging to transform into sets of immediate object rules. These sections quite often may require manual checking for compliance. For instance, in Florida Building Code [3], section 503.1 regarding building height and area, states that "*The building height and area shall not exceed the limits specified in Table 503 based on the type of construction as determined by Section 602 and the occupancies as determined by Section 302 except as modified hereafter. Each portion of a build separated by one or more firewalls complying with Section 706 shall be considered to be a separate building.*"

Ambiguous ($A_i \ldots A_n$) clauses are the vague or inexact provisions that would need an expert judgment to be evaluated. They usually include words such as: approximately, about, relatively, close to, far from, maybe, etc. An example of such provision is the footnote of the design lateral soil pressure for the clause given in ASCE 7–10: "*For* ***relatively*** *rigid walls, as when braced by floors, the design lateral soil load shall be increased for sand and gravel type soils to 60 psf* (9.43 kPa) *per foot (meter) of depth. Basement walls extending not more than* 8 ft (2.44 m) *below grade and supporting* ***light*** *floor systems are not considered as being* ***relatively*** *rigid walls*." This concept covers all regulations that are not capable of being computerized and some of them may have to be rewritten to enable implementation in automated code compliance auditing environment. Interpretation and revising both must adhere to understanding terms from both the legal and construction perspectives.

These concepts can then be modified, integrated or decomposed to enable computable representation of building regulations and standards. Knowledge concepts X_i can be transformed or combined with another concept into Y_i and then Y_i can be transmuted into Z_i to enable efficient computable representation. Thus, the TRA is defined as the conceptualization of knowledge representation by mapping building code and regulations into sets of object rules. Figure 48.2 is a pictorial description of the TRA for building regulations.

Building regulations will be classified using the taxonomy defined earlier and can also be translated into conceptual representations that closely approximate the meaning of the building code provision. These figurative structures can then be transformed and manipulated to deduce various facts and rules to carry out automatic compliance validation.

The TRA is based partially on first-order logic calculus. For example, the building code provision that says, "only Professional Engineer(PE) must approve structural design" can be stated as following using TLA:

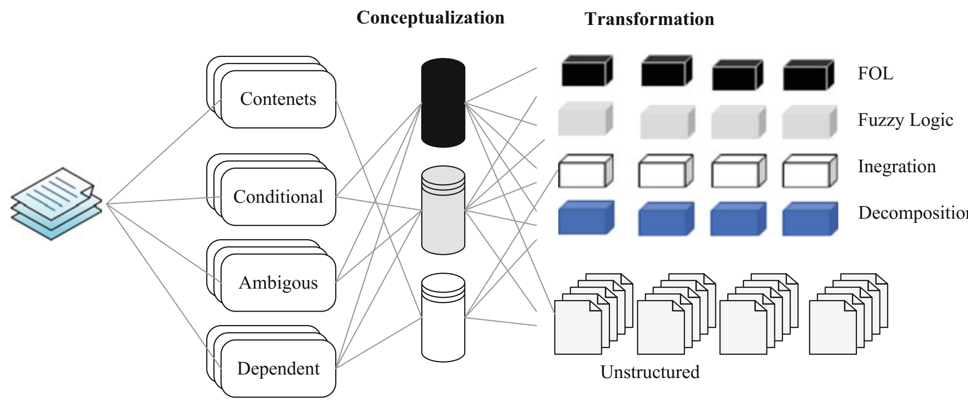

Fig. 48.2 The transformation reasoning algorithm (TRA)

Fig. 48.3 **a** Section 48.304 of Florida building code—residential [3]. **b** Florida building code—residential [3]

(a)

SECTION R304
MINIMUM ROOM AREAS

R304.1 Minimum area.
Habitable rooms shall have a floor area of not less than 70 square feet (6.5 m^2).
Exception: Kitchens.
R304.2 Minimum dimensions.
Habitable rooms shall be not less than 7 feet (2134 mm) in any horizontal dimension.
Exception: Kitchens.
R304.3 Height effect on room area.
Portions of a room with a sloping ceiling measuring less than 5 feet (1524 mm) or a furred ceiling measuring less than 7 feet (2134 mm) from the finished floor to the finished ceiling shall not be considered as contributing to the minimum required habitable area for that room.

(b)

SECTION R305
CEILING HEIGHT

R305.1 Minimum height.

Habitable space, hallways and portions of *basements* containing these spaces shall have a ceiling height of not less than 7 feet (2134 mm). Bathrooms, toilet rooms and laundry rooms shall have a ceiling height of not less than 6 feet 8 inches (2032 mm).

Exceptions:

1. For rooms with sloped ceilings, the required floor area of the room shall have a ceiling height of not less than 5 feet (1524 mm) and not less than 50 percent of the required floor area shall have a ceiling height of not less than 7 feet (2134 mm).
2. The ceiling height above bathroom and toilet room fixtures shall be such that the fixture is capable of being used for its intended purpose. A shower or tub equipped with a showerhead shall have a ceiling height of not less than 6 feet 8 inches (2032 mm) above an area of not less than 30 inches (762 mm) by 30 inches (762 mm) at the showerhead.
3. Beams, girders, ducts or other obstructions in *basements* containing *habitable space* shall be permitted to project to within 6 feet 4 inches (1931 mm) of the finished floor.

R305.1.1 Basements.

Portions of *basements* that do not contain *habitable space* or hallways shall have a ceiling height of not less than 6 feet 8 inches (2032 mm).

Exception: At beams, girders, ducts or other obstructions, the ceiling height shall be not less than 6 feet 4 inches (1931 mm) from the finished floor.

Table 48.1 Syntax of transformation reasoning algorithm (TRA)

Symbol	Definition
:: =	Is defined as
∧	Conjunction
∨	Disjunction
⊂	Subset of
¬	Negation
∀	Universal Quantifier
∃	Existential Quantifier
∈	Belongs to
→	Implication
↔	Biconditional
⇒	Transform into
Constant	String starting with an uppercase letter
Variable	String starting with a lowercase letter
Pred (arg1, arg2, …)	Predicate
Fun (arg1, arg2, …)	Function
Pred1 (arg1, arg2, …) ∧ Pred2 (arg1, arg2, …) ∨ …	Rule

$$Prov(PE) \in Conditional; \forall \mathrm{x}(PE(\mathrm{x}) \rightarrow Permitted(\mathrm{x}, \text{approve design}))$$

$$\forall \mathrm{x}\,(\neg PE(\mathrm{x})\,\forall \mathrm{x}\,\neg\, Permitted(\mathrm{x}, \text{ approve design}))$$

This TRA algorithm can be illustrated further by considering Florida Building Code—Residential 2017 [3]. Figure 48.3 depicts various section from the [3]-Residential (Table 48.1).

The provision shown in Fig. 48.3a can be transformed into computable representation using the TRA as follows:

Let REG_i = "Section R304"; Where i varies from 1 to n number of code provisions. Then we have

$$REG_i \in \mathrm{P_i} \Rightarrow \mathrm{Y_i} \Rightarrow \mathrm{X_i} \tag{48.1}$$

where,

The subscript i stands for the counts of the code sections being processed and varies from 1 to n sections.

P_i designates that this is a provisory clause, and describes the minimum room area (Y_i) which is given by X_i that expresses the various Rules describing Y_i:

$$\mathrm{X_i} = \{\mathrm{R_1}, \mathrm{R_2}, \ldots, \mathrm{R_m}\} \tag{48.2}$$

where, R_1, R_2, … R_m are the rules defining X_i.

$$\text{Let}\, \mathrm{Z_{1j}} = \left\{\mathrm{z_{11}} \ldots \mathrm{z_{1q}}\right\} \tag{48.3}$$

$$\mathrm{z} = \text{IfcSpace}; \mathrm{z_{11}} = \text{``R304.1''}; \text{and}; \mathrm{z_{12}} ::= \text{Floor area} > \; = 70\,\text{ft}^2\left(6.5\text{m}^2\right) \tag{48.4}$$

$$R_2{:}\forall\,\mathrm{z}\,(REG_i(\mathrm{z})) \rightarrow Minimum\ Area\left(\mathrm{z}, \mathrm{Z_{1j}}\right) \wedge \neg\, Space\ Name(z, KITCHEN) \tag{48.5}$$

$$\mathrm{Z_{2j}} = \left\{\mathrm{z_{21}} \ldots \mathrm{z_{2q}}\right\} \tag{48.6}$$

$$\mathrm{z_{21}} = \text{``R304.2''}; \text{ and}\, \mathrm{z_{22}} ::= \text{least horizontal dimension of any habitable room} > \; = 7\,\text{ft}(2.134\,\text{m})$$

$$R_3{:}\forall\,\mathrm{z}\,(REG_i(\mathrm{z}) \rightarrow Minimum\ Dimension\left(\mathrm{z}, \mathrm{Z_{2j}}\right) \wedge \neg\, Space\ Name(z, KITCHEN) \tag{48.7}$$

$$\mathrm{Z_{3j}} = \left\{\mathrm{z_{31}} \ldots \mathrm{z_{3q}}\right\} \tag{48.8}$$

$Z_{31} =$ "R304.3″; z_{32} ::= Ceiling height > 5 ft for sloped ceiling; and z_{33} ::= Ceiling height > 7 ft for furred ceiling

$$R_4{:}\forall z(REG_i(z) \rightarrow \textit{Ceiling Height Limitation}(z, Z_{3j})) \tag{48.9}$$

$$X_i = \{R_1 \wedge R_2 \wedge R_3 \wedge R_4\} \tag{48.10}$$

Equation 48.10 represents the knowledge transformation process to generate a computable model for the code specifications expressed in FBC 2017 [3] Residential, section R304. This knowledge representation can then be mapped into IFC schema as given by [12].

As a further example, consider section R305 in Fig. 48.3b. In this example, the variables used above will have the following values:

REG_2 = "Section R305"; then we have

$$REG_2 \in (P_2) \Rightarrow Y_2 \Rightarrow X_2 \tag{48.11}$$

where,

P_2 designates that this is a provisory clause, and describes the minimum ceiling height (Y_2) which is given by X_2 that expresses the various Rules describing Y_2:

$$X_2 = \{R_1, R_2, \ldots, R_m\} \tag{48.12}$$

where, R_1, R_2, …, R_m are the rules defining X_i.

$$\text{Let } Z_{1j} = \{z_{21}, \ldots, z_{2q}\} \tag{48.13}$$

$$z = \text{IfcSpace}; z_{11} = \text{``R305.1''} \tag{48.14}$$

$$z_{12} ::= \geq 7\,\text{ft}; z_{13} ::= \geq 6.667\,\text{ft}; z_{14} ::= \geq 6.333\,\text{ft}; z_{15} \geq 5\,\text{ft} \tag{48.15}$$

$$R_2{:}\forall z\,(REG_2(z) \rightarrow \textit{Ceiling Height}(z, z_{12}) \wedge \textit{Habitable Space}(z) \wedge \neg \textit{Space Name}(z, \textit{BATHROOM}) \wedge \neg \textit{Space Name}(z, \textit{TOILETROOM}) \wedge \neg \textit{Space Name}(z, \textit{LAUNDRYROOM}) \wedge \neg \textit{Sloped Ceiling}(z) \tag{48.16}$$

$$R_3{:}\forall z\,(REG_2(z) \rightarrow \textit{Ceiling Height}(z, z_{13}) \wedge \textit{Habitable Space}(z) \wedge (\textit{Space Name}(z, \textit{BATHROOM}) \vee \textit{Space Name}(z, \textit{TOILETROOM}) \vee \textit{Space Name}(z, \textit{LAUNDRYROOM})) \wedge \neg \textit{Sloped Ceiling}(z) \tag{48.17}$$

$$A = \textit{Floor Area}(z); z_{16} ::= \geq 0.5 * A \tag{48.18}$$

$$R_4{:}\forall z\,(REG_2(z) \rightarrow \textit{Ceiling Height}(z, z_{15}) \wedge \textit{Sloped Ceiling}(z, z_{16}) \tag{48.19}$$

$$\text{Let } Z_{2j} = \{z_{21}, \ldots, z_{2q}\} \tag{48.20}$$

$$z = \text{IfcSpace}; z_{21} = \text{``R305.1.1''} \tag{48.21}$$

$$z_{23} ::= \geq 6.667\,\text{ft}; z_{24} ::= \geq 6.333\,\text{ft}; z_{25} = \text{IfcBeam}; z_{26} = \text{IfcDuct}; \tag{48.22}$$

$$R_5{:}\forall z\,(REG_2(z) \rightarrow \textit{Ceiling Height}(z, z_{23}) \wedge \neg (\textit{At Beam Elevation}(z, z_{25}) \vee \textit{At Duct Elevations}(z, z_{26})) \wedge \neg \textit{Habitable Space}(z) \tag{48.23}$$

$$R_6{:}\forall z\,(REG_2(z) \rightarrow \textit{Ceiling Height}(z, z_{24}) \wedge (\textit{At Beam Elevation}(z, z_{25}) \vee \textit{At Duct Elevations}(z, z_{26}) \tag{48.24}$$

$$X_2 = \{R_1 \wedge R_2 \wedge R_3 \wedge R_4 \wedge R_5 \wedge R_6\} \tag{48.25}$$

An example of inexact code provision can be seen in section R322.1 of [3]-Residential (Fig. 48.4). In this provision, the regulations states: "*Buildings and structures constructed in whole or in part in flood hazard areas, including A or V Zones and Coastal A Zones, as established in Table R301.2(1), and substantial improvement and restoration of substantial damage of buildings and structures in flood hazard areas, shall be designed and constructed in accordance with the*

Fig. 48.4 Part of Florida building code—residential [3]

> **SECTION R322**
> **FLOOD-RESISTANT CONSTRUCTION**
>
> **R322.1General.**
> Buildings and structures constructed in whole or in part in flood hazard areas, including A or V Zones and Coastal A Zones, as established in Table R301.2(1), and substantial improvement and restoration of substantial damage of buildings and structures in flood hazard areas, shall be designed and constructed in accordance with the provisions contained in this section. Buildings and structures that are located in more than one flood hazard area shall comply with the provisions associated with the most restrictive flood hazard area. Buildings and structures located in whole or in part in identified floodways shall be designed and constructed in accordance with ASCE 24.

provisions contained in this section." The word substantial is never defined precisely. Using the TRA, then we have, REG_3 = "Section R322";

$$REG_3 \in (C_1 \wedge A_1) \Rightarrow Y_3 \Rightarrow X_3 \tag{48.25}$$

$(C_1 \wedge A_1)$ designates that this is a content clause with ambiguous statements describing flood resistance construction (Y_3) which is given by X_3 that defines the various conditions unfolding Y_3.

$$X_3 = \{R_1, R_2, \ldots, R_m\} \tag{48.26}$$

where, R_1, R_2, …, R_m are the rules defining X_3.

$$\text{Let } Z_{3j} = \left\{z_{31}, \ldots, z_{3q}\right\} \tag{48.27}$$

z = IfcBuilding; z_{31} = "[3]—R322"; z_{32} = "ASCE 24"

$$R_1{:}\forall z\,(\textit{In Flood Zone}(z) \rightarrow \textit{Required Provision}(z, z_{31})) \tag{48.28}$$

$$R_2{:}\forall z\,(\textit{In Flood Ways}(z) \rightarrow \textit{Required Provision}(z, z_{32})) \tag{48.29}$$

As for the conceptualization of the term "substantial damage", a fuzzy logic and predicates will be utilized to transform concept into a rule representation. A fuzzy set is defined as [14]: ***A*** is a fuzzy subset of the universe of discourse ***U***, is characterized by a membership function $\boldsymbol{\mu}_{\boldsymbol{A}:}$ *U* ➔ *[0…1]* which associates with each element ***u*** of ***U*** a number $\boldsymbol{\mu}_{\boldsymbol{A}}$ *(u)* in the interval [0,1]. This definition can be employed to define fuzzy predicate (first-order predicate.) The truth-value of any proposition can be evaluated as the degree of membership of the responding fuzzy relation. Thus, a fuzzy predicate can be considered as the membership function of a fuzzy relation over individual variables' universe of discourse. Each fuzzy predicate represents a concept in the TRA.

For example, the building damage stated in section R322 can be represented as a fuzzy variable having values depicted in Fig. 48.5. These include small damage, medium damage and substantial damage. These definitions need to be determined from experience or local guidelines.

Now, let z_{32} = a fuzzy variable defined by

$$\left.\begin{aligned} \boldsymbol{\mu}_{\boldsymbol{A}}(u) &= 0 && 25\% <= u> = 0 \\ &= (1/15)u - 25/15 && 25\% < u> = 0 \\ &= 1 && u > 40 \end{aligned}\right\} \tag{48.30}$$

where, $0 \leq \mu_A(u) \leq 1$

Now, section R322 of [3]-Residential is transformed into the following rule:

$$R_3{:}\forall z\,(\textit{In Flood Zone}(z) \wedge \textit{Damage}(z, z_{32}) \rightarrow \textit{Required Provision}(z, z_{31})) \tag{48.31}$$

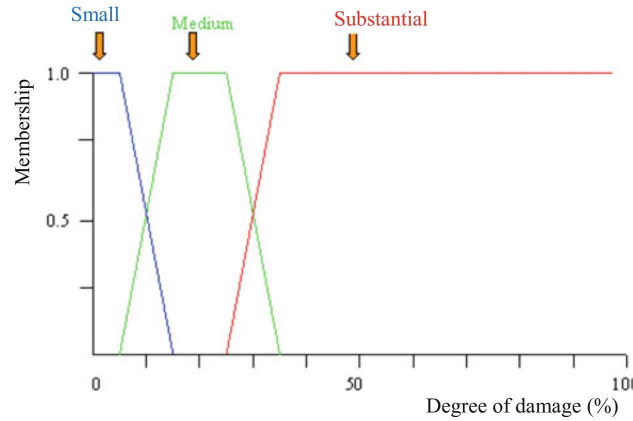

Fig. 48.5 The concept of fuzzy transformation of building damages

Building codes do have quite often such imprecise terms to describe specific conditions. Future research will study these terms and their transformation using fuzzy predicates.

48.5 Conclusions

The current design review process lacks a generalized framework of rules and regulations modeling that can adjust to several engineering design domains and support an open neutral standard for automating the review process. This paper proposes a framework that is adaptive to the target domain and endorses a neutral standard for transforming the written design regulations and rules into a computable model to enable ADR process. The paper outlines and defines the different components of the proposed framework and their relationships. This paper centers on the higher order level I of the framework which is denoted by the Transformation Reasoning Algorithm (TRA). The TRA introduces the taxonomy for the building regulations knowledge along with the conceptualization and transformation processes. Subsequently, knowledge created is a new formalized object representation that model objective and ambiguous building regulations and can deduce various facts to carry out automated reasoning. This approach minimizes the shortcomings of the cited methods by transforming objective and vague data of building code into a concise formal representation that can be mapped into IFC data schema. Future studies will investigate the other levels of the GAF and how they would influence the broader impacts of this research project. These impacts include the enormous benefits to the AEC industry depicted in the consistency of the interpretation of regulatory provisions, the ability to self-check required aspects before bidding, saving time and resources during design review, optimum design, the quicker turnaround in feedback, and faster approvals for construction permits by building authorities.

References

1. AASHTO: AASHTO Guide for Design of Pavement Structures, 4th edn. American Association of State Highway and Transportation Officials, Washington, DC (1998)
2. AISC (American Institute of Steel Construction): Specification for the Design, Fabrication and Erection of Structural Steel for Building (1969)
3. FBC: Florida Building Code, 6th edn. International Code Council (ICC), Washington, DC (2017)
4. Fenves, S.J.: Tabular decision logic for structural design. J. Struct. Eng, ASCE **9–92**, 473–490 (1966)
5. Kiyavitskaya, N., Zeni, N., Mich, L., Cordy, J.R., Mylopoulos, J.: Text mining through semi automatic semantic annotation. In: Proc. of PAKM'06, vol 4333 LNCS, pp 143–154. Springer-Verlag (2006)
6. Lee, J.: Building environment rule and analysis (BERA) language. PhD Thesis, Georgia Institute of Technology (2011)
7. Lopez, L.A., Elam, S., Reed, K.: Software concept for checking engineering designs for conformance with codes and standards. Eng. Comput. **5**, 63–78 (1989)
8. Lopez, L.A., Wright, R.N.: Mapping Principles for the Standards interface for Computer Aided Design, NBSIR 85-3115. National Bureau of Standards, Gaithersburg, MD (1985)
9. Mazairac, W., Beetz, J.: BIMQL—An open query language for building information models. Adv. Eng. Inform. **27**(2013), 444–456 (2013)
10. Nawari, N.: Automating codes conformance. J. Archit. Eng. ASCE **18**(4), 315–323, (2012a)
11. Nawari, N.O.: Automated code checking in BIM environment. In: Proceedings of the 14th International Conference on Computing in Civil and Building Engineering, Moscow, Russia, 27–29 June, (2012b)

12. Nawari, O.N.: Building information modeling: automated code checking and compliance processes, CRC Press, ISBN-10:1498785336. (2018)
13. Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., Van Campenhout, J.: A semantic rule checking environment for building performance checking. Autom. Constr. **20**(5), 506–518 (2011)
14. Zadeh, L.A.: Fuzzy sets. Information and control, vol. 8, pp. 338–353. (1965)
15. Zhang, J., El-Gohary, N.: Extraction of construction regulatory requirements from textual documents using natural language processing techniques. J. Comput. Civil Eng. ASCE **2012**, 453–460 (2012)
16. Zhang, J., El-Gohary, N.: Semantic NLP-Based information extraction from construction regulatory documents for automated compliance checking. J. Comput. Civil Eng. ASCE **30**, 04015014 (2013)
17. Zhang, J., El-Gohary, N.: Automated information transformation for automated regulatory compliance checking in construction. J. Comput. Civil Eng. ASCE **29**, B4015001 (2015)
18. Zhang, J., El-Gohary, N.: Semantic-based logic representation and reasoning for automated regulatory compliance checking. J. Comput. Civil Eng. ASCE **31**, 04016037 (2016)

49 An Integrated Simulation-Based Methodology for Considering Weather Effects on Formwork Removal Times

Robert Larsson

Abstract

This paper presents an integrated simulation-based methodology for considering the effects of weather on formwork removal times. An expert tool for estimating formwork removal times and weather data with high resolution are integrated into a discrete-event simulation model containing a process model of in situ concrete wall operations. In addition, operational measures (denoted as curing strategies) and their ability to shield concrete curing against various weather conditions are also studied. From the simulation results, it can be concluded that weather conditions and curing strategies may have a significant influence of construction duration. The proposed simulation-based approach facilitates systematic analysis of formwork removal times and curing strategies under various climatic conditions when planning concrete works.

Keywords

Productivity • Weather • Concrete curing • Formwork removal • Discrete-event simulation

49.1 Introduction

Efficient concrete construction require not only well planned and synchronized work tasks but also a predictable concrete curing process since it determines when formwork can be removed. Delayed formwork removal time causes disruptions for the whole construction cycle and lowers productivity. In addition, too early removal of formwork when concrete strength is not sufficient can lead to other serious effects, e.g. damages with potential future durability issues, or even structural collapse.

Weather conditions affect concrete strength development and by that, also the time when formwork can be removed. Accordingly, accurate predictions require good estimations of actual weather conditions considering natural variations both on short (daily or weekly) and long term (seasonal effects). This is important, not least when pouring concrete in regions with long periods of cold weather, as is typically the case in the Nordic Countries. Previous studies have focused on the effect of weather on productivity on project or work task level [1–4]. Moreover, studies that have limited the scope to the influence of weather on formwork productivity, e.g. [5, 6], have not explicitly considered the implications on formwork removal.

In the Nordic countries, special-purpose simulation tools are commonly used for prediction of concrete strength development. These simulation tools enable to predict formwork removal time for specific concrete types and external conditions. However, accounting for variable weather conditions in these tools is a relatively time-consuming work. Therefore, variations in weather conditions are normally neglected in order to make predictions manageable. Since weather conditions typically vary both on short and long term basis, such simplifications add uncertainty to the estimations. In addition, simulations of formwork removal times are not always properly integrated with tools for planning or analysis of the overall construction process. Lack of integration increases the risk of formwork removal that is poorly adjusted to the planned

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construction cycle and vice versa. Consequently, there is a need for an integrated solution which improves planning of concrete works by more accurately account for the effects of weather on formwork removal.

The aim of this research is to develop and demonstrate an integrated simulated-based methodology for considering effects on formwork removal time due to variations in weather conditions. Another aim is to study the efficiency in different operational measures employed in order to shield curing against varying climatic conditions which are typical for Sweden.

The proposed methodology combines discrete-event simulation (DES) and specific simulation tools for predictions of formwork removal times. DES is chosen since it offers powerful capabilities to model and study complex systems [7]. Various factors such as weather can be explicitly described and their relative effect on the model can be simulated in a highly controlled environment. Results from the expert-based simulation tool are integrated to the model to account for formwork removal. The model is then demonstrated by studying the effect of weather and curing strategies on the duration of concrete wall operations.

49.2 Research Approach

The research was divided into five steps; (1) Literature review of how weather influences concrete strength development; (2) Conducting two separate field studies to study and collect information about concrete wall operations, e.g. work sequence, productivity rates, and resource usage. Information about what measures that are typically used in order to shield curing against ambient climate was documented as well. These findings were used to formulate a set of different curing strategies. The field studies involved on-site visits and interviews with construction site managers; (3) Weather statistics were collected and analyzed for three geographical locations in Sweden representing different climatic zones; (4) An expert simulation tool was used to estimate formwork removal times as a function of different climatic conditions and curing strategies as were identified in step 2; (5) Based on knowledge gained from previous steps, a discrete-event simulation model was developed describing the workflow of concrete wall construction. A specific algorithm was developed to dynamically account for formwork removal times due to varying weather conditions. Finally, the model was applied to concrete wall operations to study the effect of weather on construction duration by accounting for different weather conditions and curing strategies.

49.3 Concrete Curing and Formwork Removal

49.3.1 Concrete Wall Construction

Construction of concrete walls is a common sub-process of reinforced concrete structures. It is characterized by several manual work tasks carried out in sequence repeated on a daily basis. Since formwork constitutes for a considerable amount of the cost of in situ concrete structures, formwork panels are reused. As a result, the time at which formwork panels can be removed becomes critical in order to keep up with the planned production cycle.

Removal of vertical formwork is determined by minimum value of concrete strength. In Sweden, general recommendation for minimum strength is 6 MPa. Removing formwork when concrete has not yet reached sufficient strength may have serious effects on safety. It may also cause issues related to damages to the structure with future durability issues. In this perspective, it is desirable to have a certain time margin (denoted as a time buffer) between the time when concrete has reached sufficient strength and the time at where formwork is actually removed. A small time buffer is positive for productivity reasons but increases risks related to safety and quality issues. On the other hand, a large time buffer indicates that measures employed to shield the curing process are too extensive. Ultimately, large time buffers may result in higher construction costs and unnecessary environmental impact. Accordingly, employment of measures to enable for "optimal" formwork removal must balance the needs of safety, quality and productivity.

49.3.2 Concrete Curing

The development of concrete strength is usually described as the hardening or curing process. This material-related process is crucial since it determines several critical aspects of a concrete structure both at early and later stages. The concrete strength is determined by the development of chemical reactions between cement and water (denoted as hydration).

The hydration process is influenced by several factors, e.g. cement type, chemical activation, and curing temperature [8]. It is well known that higher concrete curing temperatures result in higher short term strength compared to lower curing temperatures. As a result, the ambient climate becomes important since it strongly influence the curing temperature. Cold temperature and high winds reduce the concrete temperature which in turn slows down or even stops the hydration process.

Early strength development can be estimated using the maturity method [9]. The method is based on scientific findings that the concrete strength is directly related to the hydration temperature history of cement.

49.3.3 Measures to Shield Concrete Curing Against Cold Weather

In general, four types of measures (a to d) are typically employed to consider the effects of ambient climate. These types of measures can be used separately, but in most cases a combination of measures is used; (a) Concrete mix design: The type of cement (e.g. Portland cement CEM I or blended cement CEM II), water-to-cement ratio (w/c), and chemical additives influence the curing process; (b) Covering and isolation of concrete surfaces: Covering or isolation of concrete prevents that the curing process slows down or even stops due to rapidly heat losses to ambient climate; (c) Increased initial concrete temperature: Increasing the temperature of the concrete mix leaving the concrete batch plant is positive since it results in higher temperature at the construction site; (d) Use of heating system: Both external and internal heating system can be used. External systems temporarily increase the temperature at the concrete surface. Internal heating systems are embedded into the concrete structure, e.g. heating cables.

The use of both increased concrete temperature (c) and heating systems (d) requires isolation or coverage of concrete surface in order to be effective.

49.3.4 Simulation of Formwork Removal Times

Special-purpose simulation tools can be used for estimating strength development for different concrete structures, such as walls or slabs. In the Scandinavian countries, there exist different software tools, e.g. Hett11[1] or PPB[2]. The software tools simulate the dynamic change in concrete temperature as a result of hydration of cement and heat losses to the surrounding climate. It is possible to estimate the effects of different measures to shield the curing process against surrounding climate, e.g. isolation and heating of concrete. The software tools estimate concrete strength using temperature profiles and the maturity method.

In this research, the software tool PPB (version 1.2.2) was used. More details about the software's underlying temperature and maturity models can be found in [8]. Examples of simulation of strength development for a concrete wall exposed to varying climatic conditions are presented in Fig. 49.1. As shown, weather conditions influence the time when formwork can be removed, i.e. when concrete has reached a minimum of 6 MPa.

49.4 Discrete-Event Simulation Model

The model was developed using ExtendSim[3] (version 9) as the software platform. The structure of the DES-model is outlined in Fig. 49.2.

The model simulates the duration of concrete wall operations. Timing of work tasks, availability of resources, and status of weather are continuously updated during the simulation. Different type of information (project, weather, and formwork removal) are stored in databases and loaded into the model when needed as the simulation proceeds. During the run of the simulation, the model constantly updates current weather conditions and an algorithm dynamically accounts for the duration of curing based on current weather conditions and curing strategy (see Sect. 49.5.1).

The logical behavior of the algorithm is outlined in Fig. 49.3. When the concrete walls have been poured, current time is set to t0. Then, a forecast of weather is made for the next 12 h and the mean temperature and wind speed is calculated. Calculated mean weather parameters are then used to determine the duration of curing based on a predefined curing strategy.

[1]Hett11: www.cementa.se.
[2]PPB: Produktionsplanering betong, www.sbuf.se/ppb.
[3]www.extendsim.com.

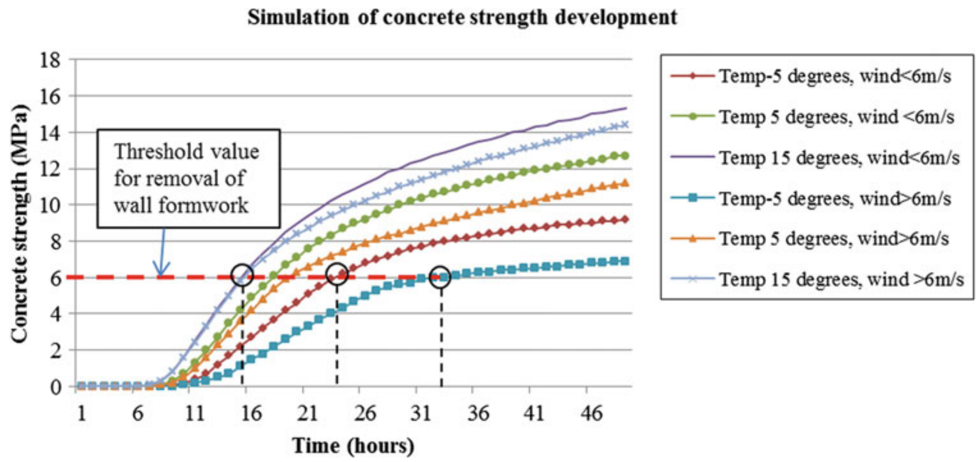

Fig. 49.1 Estimation of concrete strength and formwork removal times for climatic conditions

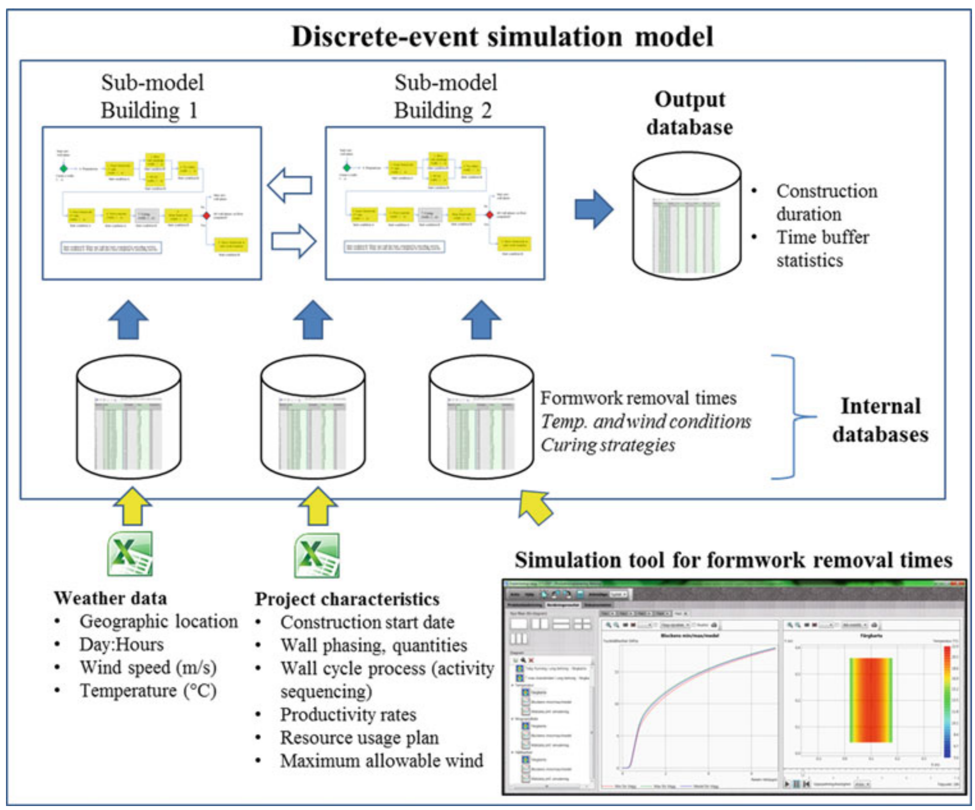

Fig. 49.2 Overview of discrete-event simulation model

The algorithm collects statistics for calculating buffer time as discussed in Sect. 49.3.1. The buffer time is defined as the difference in time between when formwork, at the earliest, can be removed and when formwork is actually removed.

49.5 Simulation Experiments

49.5.1 Construction Project, Curing Strategies and Weather Statistics

A project consisting of two six floor buildings were used as a reference for conducting experiments. Each floor was divided into four wall phases where each phase consisted of four wall segments. The buildings were erected simultaneously and the formwork system was moved between the two work locations during construction. The planned production cycle was set to

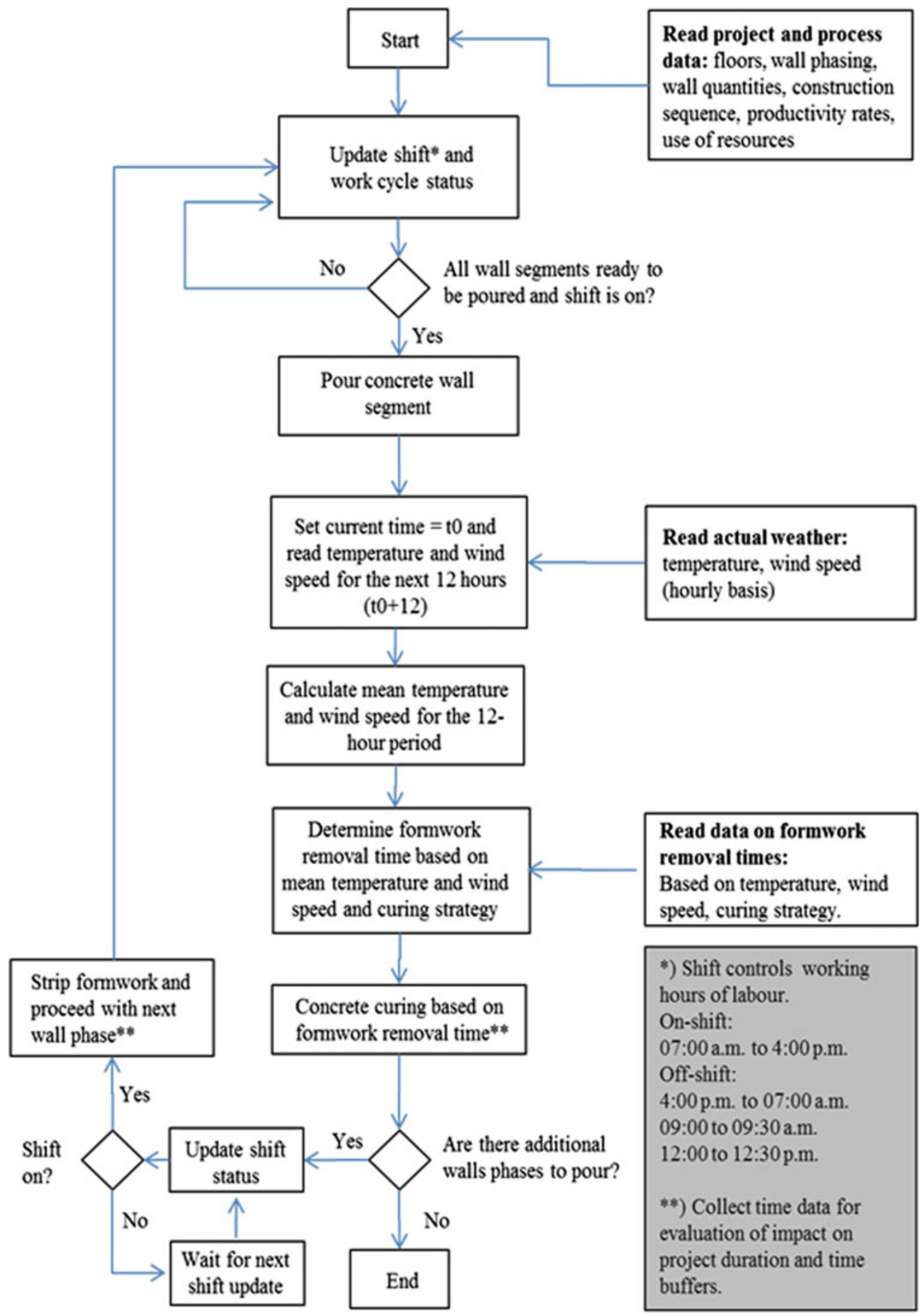

Fig. 49.3 Outline of the algorithm for estimating formwork removal time based on current weather and selected curing strategy

finish one wall phase per day resulting in a total duration of 48 days. Productivity rates and resource usage typical for concrete walls were obtained from site visits and discussions with site managers. To study the effect of different measures to shield the curing process against ambient climatic conditions, a set of different measures were identified involving concrete mix design, increased initial concrete temperature, isolation of formwork, and the use of embedded heating systems. These measures were either employed separately or in combination resulting in 12 different curing strategies (A–L), see Table 49.1.

The simulation tool PPB was used for estimating formwork removal times for the curing strategies A–L under varying weather conditions. The estimated formwork removal times were imported to the DES-model and used in the simulation experiments. Weather statistics for three geographical locations in Sweden (Malmö, Stockholm and Umeå) were collected. These locations were chosen since they represent three different climatic zones in Sweden. For Malmö and Stockholm, hourly

Table 49.1 Specification of measures employed for curing strategies A–L

Strategy	Concrete class	Cement (CEM II/A-V 52,5 N Portland-fly ash cement is used in all cases) content (kg/m^3)	Concrete temperature (°C)	Formwork isolation (30 mm)	Internal heating (3 × 40 W/m)
A	C25/30	300	15	No	No
B	C20/25	275	15	No	No
C	C28/35	330	15	No	No
D	C25/30	300	15	Yes	No
E	C25/30	300	20	Yes	No
F	C25/30	300	20	Yes	Yes
G	C20/25	275	15	Yes	No
H	C20/25	275	20	Yes	No
I	C20/25	275	20	Yes	Yes
J	C28/35	330	15	Yes	No
K	C28/35	330	20	Yes	No
L	C28/35	330	20	Yes	Yes

data for temperature, precipitation, and wind speed covering the period of 1997–2016 (20 years) were retrieved from official weather statistic databases (SMHI[4]). For Umeå, it was only possible to compile data for a 10 year period (2007–2016). The data sets were analyzed in order to identify a year which could be considered as a normal year. A normal year was defined as the year that had least annual mean deviation in precipitation, temperature and wind compared with mean values for the total period of 10 year (Umeå) or 20 years (Stockholm and Malmö).

49.5.2 Design of Experiments

The experiments focused on three variables, namely; (1) Geographical location (Malmö, Stockholm and Umeå); (2) Start of construction to consider the effect of different seasons: Winter (start date 1st January), Spring (start date 1st April), Autumn (start date 1st October); (3) Strategies for concrete curing according to Table 49.1.

49.5.3 Results

The effect on construction duration due to weather and curing strategies are given in Fig. 49.4. The results for Malmö, Stockholm, and Umeå are presented in the chart diagrams a, c, and e. In these diagrams, the y-axis shows the relative effect on construction duration. A value equals to one corresponds to an ideal scenario unaffected by variations in formwork removal, i.e. zero loss in productivity. A value higher than one indicates loss in productivity. In should be noted that values lower than one is not possible since it represents the best possible (ideal) situation.

Strategies A, B and C result in major productivity losses for all three locations (see chart diagrams a, c, and e in figure). Missing bars in the chart diagrams mean that the curing process is too slow to enable formwork removal. This occurs for example for strategy A and B in Umeå during winter and autumn. It is shown by diagrams that strategy A is not suitable for use in Umeå or Stockholm during any season. For Malmö, the strategy can be employed during spring and autumn but will then result in losses in the range of 10–15%. Lowering the concrete quality without any additional measures as was the case in strategy B is not recommended for any location or season. Increasing concrete quality (strategy C) is feasible for Malmö and Stockholm during spring and autumn. However, it is not adequate during winter since it will result in significant loss in productivity.

To study the extra time margin (time buffer), a time buffer index is introduced. This index is shown in diagram b, d, and f for Malmö, Stockholm, and Umeå respectively. The index represents the time between when formwork removal is possible

[4]SMHI, Swedish Meteorological and Hydrological Institute, www.smhi.se.

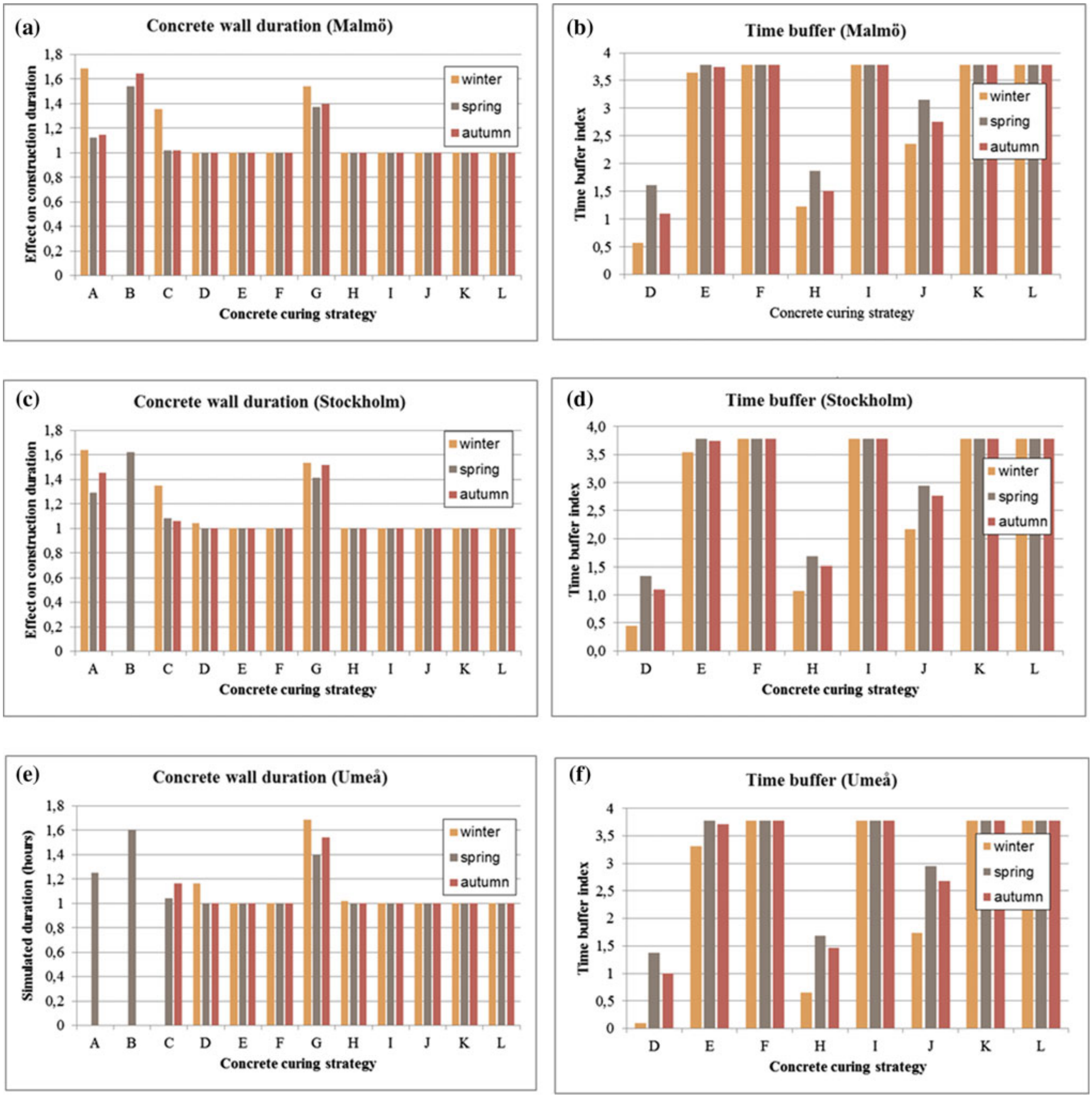

Fig. 49.4 Simulated effect on construction duration for various seasons and geographical locations (diagrams **a**, **c** and **e**). Diagrams **b**, **d** and **f** show corresponding time buffer index

(i.e. when concrete has reached at least 6 MPa in strength) and the time when removal of formwork actually begins. An index near zero means that the time buffer is non-existent. The higher the value of the index, the larger is the buffer. Strategies A, B, C, and G are not presented in the chart diagrams since these do not have any time buffers. Strategies F, I, K and L have the highest buffer index. The index values are also the same for all three places and seasons. This means that any further reduction in formwork removal is not possible without making other changes, e.g. using more rapid cement types. Strategy D has the lowest index followed by strategy H and then J. Note that the index is close to zero for strategy D during winter in Umeå indicating that there is no margin left.

49.6 Discussion

It was found that weather conditions may have significant influence on construction duration as a result of inappropriate employed operational measures to shield concrete curing. Consequently, decisions on what measures to employ are critical in order to avoid loss in productivity as well as increased safety risks and quality problems during construction. The findings also indicate that curing strategies involving more than one measure are very effective to enable for predictable formwork removal times. However, it was also shown that employing strategies combining four types of measures are unnecessarily extensive for all cases studied. The time buffer index can be useful in order to assess how well a measure is customized to effectively support a desired production cycle. It also reveals how large the margin is in cases of unexpected changes in weather. As such, the buffer index provides a measure of the robustness of the chosen measures. On the other hand, high buffer index indicates an overuse of project resources which may increase costs and environmental impact.

Previous studies reported, e.g. in [5, 6] have emphasized on the effects of weather on productivity in manual works tasks involved in construction of concrete structures. However, this paper indicates that also the influence of weather on concrete curing should be considered. In this respect, this paper provides new insights on how to integrate general discrete-simulation with expert simulation tools and weather data, in order to account for formwork removal.

The findings of this study are based on formwork removal times estimated for generic concrete wall types. However, to expand the applicability of the model also horizontal formwork used for concrete slabs should be included. It is believed that the proposed algorithm could be used to consider removal of horizontal formwork as well. It would also be interesting to include more weather types, e.g. unusual or extreme weather to study the effects of changing climatic conditions.

The findings of this study should be validated, e.g. by collecting data from ongoing projects. Measurements of concrete strength and weather variables would be of value in order to confirm assumptions made for estimating formwork removal times.

References

1. Koehn, E., Brown, G.: Climatic effects on construction. J. Const. Eng. Manage. **111**(2), 129 (1985)
2. Thomas, H.R., Riley, D.R., Sanvido, V.E.: Loss of labor productivity due to delivery methods and weather. J. Const. Eng. Manage. **125**(1), 39 (1999)
3. Ballesteros-Perez, P., del Campo-Hitschfeld, M.L., Gonzalez-Naranjo, M.A., Gonzalez-Cruz, M.C.: Climate and construction delays: case study in Chile. J. Eng. Constr. Architect. Manage. **22**(6), 596–621 (2015)
4. Jung, M., Park, M., Lee, H.-S., Kim, H.: Weather-delay simulation model based on vertical weather profile for high-rise building construction. J. Const. Eng. Manage. **142**(6), 04016007 (2016)
5. Moselhi, O., Khan, Z.: Analysis of labor productivity of formwork operations in building construction. Const. Innovation **10**(3), 286–303 (2010)
6. Marzouk, M., Hamdy, A.: Quantifying weather impact on formwork shuttering and removal operation using system dynamics. KSCE J. Civil Eng. **17**(4), 620–626 (2013)
7. AbouRizk, S., Halpin, D., Mohamed, Y., Hermann, U.: Research in modeling and simulation for improving construction engineering operations. J. Const. Eng. Manage. **137**(10), 843–852 (2011)
8. Fjellström, P.: Measurement and modelling of young concrete properties. Licentiate Thesis, ISBN 9174396439, Luleå University (2013)
9. Benaicha, M., Burtschell, Y., Alaoui, A.H.: Prediction of compressive strength at early age of concrete—application of maturity. J. Build. Eng. **6**, 119–125 (2016)

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50 Exploring Future Stakeholder Feedback on Performance-Based Design Across the Virtuality Continuum

Sooji Ha, Neda Mohammadi, L. Sena Soysal, John E. Taylor, Abigail Francisco, Sean Flanagan, and Semra Çomu Yapıcı

Abstract

Communication of building project designs to stakeholders is important for successful implementation, but it is often difficult to get feedback from the future occupants of buildings. Yet, there is a growing trend in development of visualization tools to enhance participation of the public by effectively providing building information to stakeholders. However, we lack research evaluating the effectiveness of different building model visualization tools, and their performance with gathering feedback from future building occupants. This study compares the effectiveness of three visualization tools—360° panorama, virtual reality and augmented reality applications—with eliciting feedback from future occupants of a Living Building Challenge project at the Georgia Tech campus compared to more conventional 2D visualizations. The effectiveness comparison was conducted across the seven performance categories defined by the Living Building certification program. The results indicated that the visualization tools had significant differences in communicating information in the Equity, Energy, Health and Happiness, Place, and Water performance areas. This study provides a quantitative perspective on the effectiveness of visualization technologies across the virtuality continuum, and has implications for pre-occupancy surveys by exploring new feedback mechanisms that encourage users to participate in building design.

Keywords

Visualization • Virtual reality • Augmented reality • Living building challenge • Occupant perception

50.1 Introduction

Occupant satisfaction, comfort and productivity are dependent on the decisions made in a building's design phase and may directly influence the desired sustainability and performance goals [1]. This is especially true for buildings that are designed to very high energy and performance standards, and their successful operation depends on effective interactions with future occupants [2]. However, during a building's design and construction there are rarely opportunities for future building occupants to give feedback on the design [1, 3]. Proactively engaging with future occupants is critical in ensuring that the building best serves people of diverse backgrounds while reducing the risk of costly fixes in the future [4]. This is crucial when a building is expected to achieve high performance goals (i.e., net-zero energy, net-zero water, or certain green building certification programs such as LEED, or the Living Building Challenge). To collect and incorporate this feedback, a proposed building's design must be communicated to future occupants in an effective way despite it being difficult to those not involved in the design process to understand a proposed building design or its operations [1, 3]. In addition, communications must appeal to heterogeneous populations to ensure the feedback loop is accessible and inclusive to a variety of

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audiences [5]. An increasing body of research, underlying the need to involve future users into the design process, emphasizes the effectiveness of visualization technologies in communicating design features and plans [6, 7]. However, research has shown that understanding the proposed building design in the pre-construction phase can be challenging for non-expert occupants [3, 8].

In this study, we explore the implications of offering various spatial design representations to future building occupants via a combination of traditional and emerging visualization technologies: 2-dimensional (2D) images, 360° panorama views, virtual reality (VR), and augmented reality (AR). We compare the effectiveness of these tools for information communication and engaging future occupants with respect to the performance areas the building aims to achieve. We have developed this series of visualizations to specifically represent "The Kendeda Building for Innovative and Sustainable Design"—hereafter referred to as KBISD—at the Georgia Institute of Technology (Georgia Tech) campus, being constructed in 2018. The building should be substantially completed in early 2019, with Living Building Challenge (LBC) 3.1 certification expected in 2020.

50.2 Visualization Across the Virtuality Continuum

The concept of the virtuality continuum was first introduced by Milgram and Kishino [9]. It represents the mixture of classes of objects presented in any particular display. The virtuality continuum spans from completely real to completely virtual environments, encompassing various degrees of segmented and virtual reality. The real environment defines environments of solely real objects, and the virtual environment consists solely of virtual objects. The mixed reality (MR) environment, represents an environment where real world and virtual world objects are presented together within a single display, meaning it is anywhere between the two ends of the virtuality continuum [9]. As a subset of MR, AR is a visualization method in which virtual objects are aligned with the real environment, and the viewer can interact with them in real time [10].

The traditional visualizations used in building design communication are 2D images and drawings. With the advancement of technology and computerized visualizations over the past several decades, there has been a clear shift from using 2D methods to using 3D visualizations [11]. Compared to 2D visualizations, the 3D visualizations are often considered to have more capability to enable communication between user groups [1, 12, 13]. Immersive 3D visualizations create the sensation of being "inside" the visualization and can result in greater spatial understanding for the users [14]. 360° panorama views allow viewers to "look around", thus providing a sense of telepresence [15]. They are currently widely used as virtual tours, with applications including various historical sites, universities, and museums [16]. In the virtuality continuum, 360° panorama based VR is an extension of computer graphics and VR [17]. Categorized as a desktop VR, this can enable interaction with a smartphone or tablet, allowing non-VR expert end-users to experience virtual environments using familiar devices [18]. While they provide better user control and can be viewed on standard monitors with no high bandwidth requirements [17], 360° panorama views may have limited attributes of immersion or interactivity compared to VR or AR.

VR is a more immersive visualization where head-referenced displays, such as head-mounted displays, are usually worn on a user's head, so that the user experiences complete immersion in the virtual environment [14]. On the other hand, AR can be displayed on a smartphone or tablet. AR has been shown to improve design perception of computer-aided design (CAD) images [19]. AR and VR can be used to enable collaborative construction processes and performance monitoring [20], that may better engage diverse stakeholders. In addition, visualization tools have been used as a participatory and end-user-centered communication tool [21]. Wergles and Muhar [22] compared user responses to visualizations versus on-site visits and found that visualizations were superior to real site visits, when designed to target certain views.

We have implemented a study that evaluates future occupants' responses to a building pursuing a rigorous green building standard, using visualization tools including 360° panorama views, AR, and VR, which are compared with responses to traditional 2D image visualizations. This study is designed as follows: First, we developed 360° panorama views, AR, and VR applications along with the traditional 2D images of the KBISD building. Second, we recruited participants from among the Georgia Tech campus community to engage in exploring the building using one of the developed visualization technologies. Lastly, we examined how effective each application performed at communicating the seven building performance areas (i.e., Petals) to future occupants.

50.3 Methods

50.3.1 Kendeda Building for Innovative and Sustainable Design at Georgia Tech

Living Building Certification (LBC) is a green building certification program and sustainable design framework. Considered as the world's most rigorous proven performance standard for buildings, it aims to create buildings that give more to nature than they take, with net positive energy and net zero water as the basis of the challenge. The LBC is comprised of seven performance areas, referred to as "Petals": beauty, equity, energy, health and happiness, material, place, and water. Each Petal is subdivided into a total of 20 imperatives that a project must meet to receive certification. The LBC requires each project to operate for at least 12 consecutive months prior to evaluation, and projects that have met all the assigned imperatives and proven performance during operation earn full program certification—the 'Living' status. The KBISD at Georgia Tech is expected to provide a fully functional building that integrates naturally into the Georgia Tech campus and provides highly flexible academic and community space, becoming the first Living Building in the southeast of the U.S.

50.3.2 Research Design and Hypotheses

For the purpose of this study, we developed four visualizations of the KBISD including a 360° panorama views application, AR application, VR application, and 2D images of the KBISD using the original Revit 3D models provided by the project architect. These were incorporated into the *Unity* 3D platform. The 360° panorama views were used to create the baseline visualization 2D images. The visualization design and experimental setup are described in the following paragraphs.

To develop the 360° panorama views, significant locations in the VR were identified and developed into panorama views. Next, 2D images of the building were generated by taking screen captures in all four directions of each panoramic location. The AR and 360° panorama view applications were installed on an iPad device. The Oculus head-mounted display and control devices were used to provide interactive and immersive user experiences.

Next, participants were recruited by word-of-mouth, distribution of flyers, and online communications to emailing lists to explore the virtual model of the KBISD building and respond to a survey questionnaire approved by the Georgia Tech Institutional Review Board (IRB #H17412). We set up VR experiment kiosks and provided virtual tours in multiple locations on campus, including the Student Center, the Undergraduate Learning Commons, and at an outdoor Earth Day event, in addition to a VR experiment station in our research laboratory. AR participants met at the physical location of the future building, and had a tour of the building site. The survey was designed to investigate how effectively each tool provides information regarding each of the seven Petals. First, we asked respondents about their familiarity with AR/VR technologies and green building certification programs. Next, we asked them to rate their impression of the KBISD, with a 7-point scale ["Inspiration", "Delight", "Interest", "Neutral", "Boredom", "Discomfort", and "Sadness"].

Following general familiarity questions, four questions for each Petal were included, designed to closely address the Petal descriptions suggested by the International Living Future Institute [23], making a total of 28 questions. Within these questions, we asked respondents to report to what degree they thought each Petal was achieved. For example, for the Health and Happiness Petal participants were asked, "To what extent do you agree or disagree with the following statements? (1) The design of the interior spaces nurtures a connection with nature, (2) The design of the exterior spaces nurtures a connection with nature, (3) The number of windows allows adequate access to sunlight in the building, and (4) The design of the Living Building promotes good indoor air quality". Responses were restricted to 6-point Likert scale format, with the following options: strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree, and this tool does not provide me enough information to form an opinion. The final response option (i.e., no opinion) aligns with the response option in [24]. "No opinion" responses versus other responses (i.e., opinion formed) were evaluated to test our hypotheses.

Finally, demographics questions were asked to compare the sample population to the broader Georgia Tech community population. This question included: affiliation/relationship with Georgia Tech, age, gender, ethnicity, and average hours spent on campus. At the end of the survey, participants could optionally complete an open-ended response about their overall participation experience.

To quantify tool effectiveness, the following hypothesis was tested:

Hypothesis. There is a significant difference in the distribution of opinion formation enabled about the [H1–7] Petal Performance Areas between 2D images, 360° panorama views, AR, and VR visualization tools [a–f].

Table 50.1 Hypothesis development across the seven petals

Hypothesis	
a. 360° panorama views > 2D images b. AR > 2D images c. AR > 360° panorama views	d. VR > 2D images e. VR > 360° panorama views f. VR > AR

To statistically test the seven hypotheses, a non-parametric the chi-square (χ^2) test (significance level $\alpha = 0.05$) was used, to detect if a difference exists between the visualization tools. Because the chi-square test does not specify which combination of categories contributes to statistical significance, if a statistically significant difference is detected for each hypothesis we move forward to conduct post hoc tests using the standardized residual method [25] to determine which combination of visualization tools contribute to statistical significance (i.e., when a standardized residual is greater than 2.0 in absolute value). To adjust for Type I error rate, we use modified significance levels of $\alpha = 0.0131$(*) and $\alpha = 0.068$ (**), corresponding to $\alpha = 0.1$ and $\alpha = 0.05$, respectively [26]. Table 50.1 details the hypotheses developed comparing the effectiveness of each combination of visualization tool for each Petal category.

50.4 Results

A total of 129 responses were collected for the analysis, with a distribution of 34, 38, 41, and 16 participants in 2D, 360° panorama views, AR and VR study groups, respectively. Representative of the Georgia Tech community population, the demographic makeup of survey respondents includes a gender distribution of 56.6% male and 43.4% female, ethnicity distribution of 33.6% Asian, 42.5% white, 11.5% black or African American, 4.4% Hispanic or Latino, 2.7% white–Asian interracial, and 5.3% no response or other. The age distribution was 63.7, 23, 7.1, 4.4, and 1.8% for ages between 18–24, 25–34, 35–44, 45–54, and 55–64, respectively. More than half (54.9%) of the respondents were undergraduate students, 15.9% were PhD students, and 11.5% were masters students. Staff made up 14.2% of the respondents, while 1.3% were faculty members of Georgia Tech. More than 70% of the respondents spent more than 8 h on campus, while less than 10% of the respondents spent less than 5 h on campus on a daily basis. A total of 56.6% were either “Not familiar at all” or “Slightly familiar” with green building certificate programs, and only 13.3% responded they were more than “Very familiar” with such programs.

Table 50.2 shows the results of chi-square test of independence in opinion formation for each Petal across the four visualization tools.

Results indicate that responses to opinion formation for the four visualization tools are independently distributed, meaning that a statistically significant difference exists in the distribution of opinion formation for about all but the Beauty and Material Petals, between 2D images, 360° panorama views, AR, and VR visualization tools. Therefore, the null hypotheses H2 (Equity), H3 (Energy), H4 (Health), H6 (Place), and H7 (Water) are rejected, allowing us to move forward to post hoc tests. Failing to reject the null hypotheses H1 (Beauty) and H5 (Material), we conclude that the four visualization tools do not differ in providing information that may enable opinion formation in these Petals.

The standardized residual test was performed on hypotheses H2 (Equity), H3 (Energy), H4 (Health), H6 (Place), and H7 (Water), to test hypotheses (a) through (f) to interpret which tool contributed to the statistically significant difference of the four groups. Table 50.3 shows the standard residuals of the contingency tables for each hypothesis. Positive *z*-score represents that the visualization tool contributed to respondents being able to form opinions with the information they were

Table 50.2 Hypothesis test results of all visualization tools using chi-square test

Hypothesis	χ^2	df	*p*-Value
H1. Beauty	0.341504	3	0.96220378
H2. Equity	16.9335	3	5.000E–04*
H3. Energy	14.87556	3	0.00209979*
H4. Health	23.7192	3	2.000E–04*
H5. Material	4.038094	3	0.25787421
H6. Place	16.90154	3	7.999E–04*
H7. Water	15.93878	3	0.00139986*

$^{*}p < 0.05$

Table 50.3 Standardized residuals and corresponding *p*-values for opinion formed responses

Hypothesis	2D *z*-Score *p*-Value	360° *z*-Score *p*-Value	AR *z*-Score *p*-Value	VR *z*-Score *p*-Value
H2. Equity	−1.97 0.049245	−2.37 0.017608	0.54 0.587492	3.8 0.000144‡
H3. Energy	−2.11 0.035206	1.94 0.052288	−2.67 0.007497‡	1.99 0.047091
H4. Health	−3.88 0.000103‡	2.04 0.041413	−1.94 0.051968	3.05 0.002254‡
H6. Place	−2.64 0.008202†	−0.72 0.469492	−1.01 0.313691	3.92 8.75889E–05‡
H7. Water	−1.44 0.150728	−2.88 0.00401‡	1.78 0.075115	2.92 0.003538187‡

$^{\dagger}p < 0.0131$, $^{\ddagger}p < 0.0068$

provided by the tool. A negative *z*-score indicates that the visualization tool contributed to respondents being unable to form opinions with the information they were provided, meaning the tool failed to communicate enough information to users to form an opinion about the Petal. 2D images showed negative *z*-scores with significance for the Health and Happiness and Place Petals. 360° panorama views had negative *z*-score with significance at the Water Petal. AR showed significant *z*-score at the Energy Petal, with a negative *z*-score. VR showed significant positive *z*-score for all four tested hypotheses.

As shown in Table 50.3, VR has significantly contributed to opinion formation of all tested Petals, except for Energy. On the other hand, 2D images contributed significantly to no opinion formation for the two Health and Happiness and Place Petals. In H2 (Equity), VR significantly contributed to opinion forming responses, allowing us to accept hypotheses (b), (d), (f), and conclude that VR is more effective than other three visualizations in assessing the Equity Petal. However, since no other visualization tool has a significant *z*-score, there is not enough evidence to accept (a), (c), and (e), and therefore we did not find a relationship across any of the tools.

In H3 (Energy), only hypothesis (f) is accepted at *p*-value of 0.0131 level, since AR significantly contributed to no opinion forming of respondents, which means AR performed the worst among the visualizations. VR and 2D visualizations showed significant results in the Health and Happiness Petal; VR significantly contributed to opinion responses in the Health and Happiness Petal, while 2D has contributed to no opinion responses. Therefore, we accept H4 (a), (b), (c), (d), and (f): 2D performs worse than all the other three visualizations, and VR performs better than all the other visualizations. However, the results do not provide statistical evidence that AR performed better than panorama views, therefore, H4 (e) is rejected. Similarly, the standardized residual method's results for the Place Petal allows us to accept H6 (a), (b), (c), (d), and (f) and reject (e). However, this conclusion is made at a less significant level, since the negative *z*-score of 2D is significant at a 0.0131 *p*-value. Interestingly, in the Water Petal, the panorama view performed significantly worse than the other three tools, while VR was also the most effective visualization. Therefore, we accept H7 (b), (d), and (f). H7 (e) is also accepted for AR since it performed better than the 360° panorama views.

Table 50.4 provides a summary of the hypothesis test results. Overall, we can conclude that VR is a more effective visualization tool than the other three in communicating performance-based building design for Equity, Health and Happiness, Place, and Water Petals. 2D images generally contributed to "no opinion" responses.

Table 50.4 Overall hypotheses testing results

Hypothesis	Four tools are different	360°>	AR>		VR>		
		2D	2D	360°	2D	360°	AR
H1. Beauty	✖						
H2. Equity	✔*				✔‡	✔‡	✔‡
H3. Energy	✔*						✔†
H4. Health	✔*	✔‡	✔‡		✔‡	✔‡	✔‡
H5. Material	✖						
H6. Place	✔*	✔†	✔†		✔†	✔‡	✔‡
H7. Water	✔*			✔‡	✔‡	✔‡	✔‡

$^{*}p < 0.05$, $^{\dagger}p < 0.0131$, $^{\ddagger}p < 0.0068$

50.5 Discussion

Our findings that VR enabled users to better form opinions about the design are supported by qualitative comments collected at the end of the survey. For example, one user who viewed the 2D building images said the "Building looks nice but the pictures allow no context for making informed judgements". Another user stated they, "Want to see what it'd actually look like". Response rates for "Neutral", "Boredom", and "Discomfort" were larger in 2D than other groups: 21% of 2D group respondents selected one or two of these impressions for the building, while other groups' percentage for such neutral and negative impressions were relatively low, having 11, 5, and 13% from 360° panorama views, VR and AR groups, respectively. In addition, users who viewed the building in VR provided more positive comments. One user stated, "This is a great idea for using VR to show the building". Another user said, "I loved it! Cool space, excited for its construction", and "I appreciated the rooftop garden/space". Although the panorama view did not show significant contributions to either opinion or no opinion responses, the general comments collected from the application provides some interpretation of its use: more comments were provided for this application, and many of them were simple, complimentary comments, perhaps indicating that participants felt more comfortable providing comments using the visualization. However, AR seems to be a less user-friendly and effective tool for visualizing Petals, with one user saying, "The iPad was a bit cumbersome" and another reporting that it "was not a great choice for conveying information about the building. You spend a lot of time looking at the iPad, and don't really get a feeling for the size and layout of the building".

This study can be improved by enhancing the visualization tools such that additional details about each Petal can be communicated to users. Especially those that are often relatively harder to intuitively experience. For example, simulating sunlight and air circulation inside the building (Health and Happiness), labels of materials (Materials), and visible water collection and cleaning mechanical systems (Water) may significantly improve the level of information provided to users.

This study provides qualitative and quantitative evaluations of the effectiveness of visualization technologies across the virtuality continuum, among the seven Petals of the KBISD at Georgia Tech. However, the LBC is just one example of the many sustainable rating systems for buildings of the future that aim to address challenges and complex performance measures such as energy efficiency and human wellbeing. This study can provide guidance for pre-occupancy surveys, leveraging in situ feedback mechanisms to encourage users to participate in a building's design through utilization of advanced visualization technologies, namely AR, VR, and 360° panorama views. This approach can also inform future sustainable and high-performance building studies on how to maximize engagement of stakeholders into the performance-based design phase of the project to ensure the building functions best serve those who will use it.

50.6 Conclusion

This study compared the effectiveness of four visualizations in communicating building design information to future building occupants, through a case study of a building seeking LBC certification at the Georgia Tech campus. Three interactive visualization tools along with 2D images were developed. After virtually exploring the building using these visualization tools, participants' ability to form an opinion about the building Petals (performance areas) was examined via a survey questionnaire and used to measure the visualization tools' ability to provide enough information about each Petal. The results indicate that the four visualization tools differ in communicating design information about all but the Beauty and Material Petals. In particular, VR was the most effective communication and visualization tool, except for in the case of the Energy Petal. On the other hand, 2D images failed to communicate enough information to users, relative to the other visualization tools. 360° panorama and AR did not seem to have consistent contributions to either opinion or no opinion responses. These findings can inform design and construction firms on the most impactful approaches to providing design visualizations to stakeholders.

References

1. Carvajal, A.: The use of visualization technologies for the integration of building end-user perspectives, a managerial approach. Computing in Civil Engineering (2005), pp. 1–11. American Society of Civil Engineers, Reston, VA (2005)
2. Kim, M.J., Oh, M.W., Kim, J.T.: A method for evaluating the performance of green buildings with a focus on user experience. Energy Build. **66**, 203–210 (2013)

3. Shen, W., Zhang, X., Shen, G.Q., Fernando, T.: The user pre-occupancy evaluation method in designer-client communication in early design stage: a case study. Autom. Constr. **32**, 112–124 (2013). https://doi.org/10.1016/j.autcon.2013.01.014
4. Shin, S., Jeong, S., Lee, J., Hong, S.W., Jung, S.: Pre-occupancy evaluation based on user behavior prediction in 3D virtual simulation. Autom. Constr. **74**, 55–65 (2017). https://doi.org/10.1016/j.autcon.2016.11.005
5. Yetim, F., Stevens, G., Draxler, S., Wulf, V.: Fostering continuous user participation by embedding a communication support tool in user interfaces. AIS Trans. Human-Comput. Interact. **3**, 1–25 (2011). https://doi.org/10.5121/ijfcst.2014.4403
6. Heydarian, A., Carneiro, J.P., Gerber, D., Becerik-Gerber, B., Hayes, T., Wood, W.: Immersive virtual environments versus physical built environments: a benchmarking study for building design and user-built environment explorations. Autom. Constr. **54**, 116–126 (2015). https://doi.org/10.1016/J.AUTCON.2015.03.020
7. Lee, S., Ha, M.: Customer interactive building information modeling for apartment unit design. Autom. Constr. **35**, 424–430 (2013). https://doi.org/10.1016/j.autcon.2013.05.026
8. Skov, M.B., Kjeldskov, J., Paay, J., Husted, N., Nørskov, J., Pedersen, K.: Designing on-site: facilitating participatory contextual architecture with mobile phones. Pervasive Mob. Comput. **9**, 216–227 (2013). https://doi.org/10.1016/j.pmcj.2012.05.004
9. Milgram, P., Kishino, F.: A taxonomy of mixed reality visual displays. IEICE Trans. Inf. Syst. **E77**, 1–15 (1994)
10. Hammad, A., Asce, M., Wang, H., Mudur, S.P.: Distributed augmented reality for visualizing collaborative construction tasks. J. Comput. Civ. Eng. **23**, 418–428 (2009). https://doi.org/10.1061/(ASCE)0887-3801
11. Herbert, G., Chen, X.: A comparison of usefulness of 2D and 3D representations of urban planning. Cartogr. Geogr. Inf. Sci. **42**, 22–32 (2015). https://doi.org/10.1080/15230406.2014.987694
12. Francisco, A., Truong, H., Khosrowpour, A., Taylor, J.E., Mohammadi, N.: Occupant perceptions of building information model-based energy visualizations in eco-feedback systems. Appl. Energy **221**, 220–228 (2018)
13. Koramaz, T.K., Gulersoy, N.Z.: Users' responses to 2D and 3D visualization techniques in urban conservation process. Proc. Int. Conf. Inf. Vis. **IV**, 543–548 (2011). https://doi.org/10.1109/IV.2011.22
14. Bowman, D.A., Ray, A.A., Gutierrez, M.S., Mauldon, M., Dove, J.E., Westman, E., Setareh, M.: Engineering in three dimensions: immersive virtual environments, interactivity, and 3D user interfaces for engineering applications. Geo Congress 2006, pp. 1–17. American Society of Civil Engineers, Reston, VA (2006)
15. Stirbu, V., Belimpasakis, P.: Experiences building a multi-display mobile application for exploring mirror worlds. In: 2011 Fifth International Conference on Next Generation Mobile Applications, Services and Technologies, IEEE, pp 1–6 (2011)
16. Guerra, P.J., Pinto, M.M., Beato, C.: European scientific journal. European Scientific Institute (2015)
17. Xiao, D.Y.: Experiencing the library in a panorama virtual reality environment. Libr. Hi. Tech. **18**, 177–184 (2000). https://doi.org/10.1108/07378830010333572
18. Fukuda, T., Sun, L., Resch, B.: Mobile Panorama-based virtual reality capability for on-site architectural and urban visualization. Proc. 37th Symp. Comput. Technol. Inf. Syst. Appl. **37**, 133–138 (2014)
19. Wang, X., Dunston, P.S.: Potential of augmented reality as an assistant viewer for computer-aided drawing. J. Comput. Civ. Eng. **20**, 437–441 (2006)
20. Lu, Y., Li, Y., Skibniewski, M., Wu, Z., Wang, R., Le, Y.: Information and communication technology applications in architecture, engineering, and construction organizations: A 15-year review. J. Manag. Eng. (2015). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000319
21. Al-Kodmany, K.: Visualization tools and methods for participatory planning and design. J. Urban Technol. ISSN **8**, 1–37 (2001)
22. Wergles, N., Muhar, A.: The role of computer visualization in the communication of urban design—a comparison of viewer responses to visualizations versus on-site visits. Landsc. Urban Plan. **91**, 171–182 (2009)
23. International Living Future Institute: Living building challenge 3.1: a visionary path to a regenerative future. Living Futur. Inst. **31**, 1–82 (2016)
24. Albaum, G.: The Likert scale revisited: an alternate version. J. Mark Res. Soc. **39**, 331–332 (1997)
25. Beasley, T.M., Schumacker, R.E.: Multiple regression approach to analyzing contingency tables: post hoc and planned comparison procedures. J. Exp. Educ. **64**, 79–93 (1995)
26. Šidák, Z.: Rectangular confidence regions for the means of multivariate normal distributions. J. Am. Stat. Assoc. **62**, 626–633 (1967). https://doi.org/10.1080/01621459.1967.10482935

51 A BIM Based Simulation Framework for Fire Evacuation Planning

Qi Sun and Yelda Turkan

Abstract

This study implements Building Information Modeling (BIM) for conducting a simulation design involving the technologies of Fire Dynamics Simulator (FDS) and Agent Based Modeling (ABM) to foresee the relationship between evacuators' mortality and building layout design. The goals of this paper are to investigate (1) how to predict the building's Available Safe Egress Time (ASET) by using FDS software; (2) how to reflect the evacuation behavior within an ABM simulation; (3) how would the Required Safe Egress Time (RSET) be impacted by the building properties, fire properties, and human behavior. By making a comparison between ASET and RSET, the optimized building layout design that reflects minimum RSET can be chosen. And finally, BIM serves as the environment to visualize the results of (1) the hazardous zones that reflected in the fire simulation; (2) the effective escape routes that are recommended by the evacuation scenario. These results can be used to improve fire safety management for both fire education and construction design. Following the results, this paper concludes with a description of challenges associated with building fire and agent-based evacuation simulations that would arise from developing a BIM-based framework for highly occupied building fires.

Keywords

Fire safety management • Building information modeling (BIM) • Fire dynamic simulator (FDS) • Agent-based modeling (ABM)

51.1 Introduction

51.1.1 Background and Motivation

Fire hazards pose threat to human life and property safety. The fire statistics report published in 2015 by the U.S. fire administration reveals that only in the United States, 129,800 of fires caused 3280 deaths and 15,700 injuries, which resulted in 14.3 billion dollars loss [1]. Even though the number of fire hazards, thus deaths, injuries and property damages due to fire hazards have decreased within the past decade, the numbers are still significantly high, and there is room to improve current fire safety management practice. More specifically, human behavior during a fire hazard should be further studied.

Therefore, this paper focuses on the issue of safe evacuation. Other than the physical building properties, evacuation safety not only depends on characteristics of fire, but also closely associates with characteristics of human behavior [2]. It would be unrealistic to study human behavior during a fire hazard. Computational tools are a better choice to simulate the fire growth and human behavior under such conditions. This study attempts to develop a Building Information Modeling (BIM) based platform for conducting fire simulations using Fire Dynamics Simulator (FDS) and Agent-Based Modeling (ABM).

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This paper is organized as follows. The next section introduces the related works on BIM, FDS, ABM and critical factors on the evacuation time in fires. Section 51.3 details the research methodology and implementation. The preliminary experimental results of a case study are described in Sect. 51.4. Finally, conclusions and recommendations for future work are provided in Sect. 51.5.

51.2 Literature Review

This section summarizes the existing literature related to emergency simulation technologies including BIM, FDS, ABM. Then, the critical factors that affect the evacuation time and life safety outcome in building fire scenarios including the physical properties of the building, the characteristics of fire, and human behaviors are identified.

51.2.1 Simulation Technologies

Building Information Modeling. BIM use in the construction industry has increased tremendously within the last decade as it helps contractors save time and money while improving project quality [3–6]. It is essential to apply BIM on fire simulations since building fires are directly associated with human safety and property security [4, 6]. In this case, Revit [8] is a 3D BIM tool that allows users to visualize better and communicate more effectively with simulation designs. First, Revit enables information sharing and linking with other software by importing/exporting commonly file formats, such as DWG and DXF. Second, Revit models contain not only the 3D data but also the object attributes that provide data integration or design analysis support. Besides, the perspective and orthographic 3D views in Revit allow users to better visualize and more effectively communicate with the models. The function of a walkthrough [7]—a defined path created as a series of perspective views—is to display building layouts and planned escape routes to assist with fire education goals during the post-construction phase.

Fire Dynamic Simulator. FDS is a computational tool developed by NIST for modeling fire-driven flow with predicting burning products [9]. To quickly and accurately work with FDS models, PyroSim [10] is a particular software that enables importing DXF/DWG files from Revit for helping with various fire simulation goals. Galea et al. [11], Shen et al. [12] reconstruct fires by PyroSim for post-accident investigation. Glasa et al. [13], Glasa et al. [14], and Wang et al. [15] use PyroSim as a tool to evaluate fire safety of existing buildings. Besides, Tingyong et al. [16] combine PyroSim and EVAC [17] to establish a continuous FDS&EVAC model for assisting in building fire evacuation, and they demonstrate that FDS is an accurate and comprehensive simulation tool in fire safety field.

Agent-Based Modeling. ABM is one of a class of microscope agents for simulating the interactions of autonomous agents with a view to assess their effects on the system as a whole [18]. It is more of a mindset than a technology and can be applied across a wide range of research areas, such as economics, military, biology [19–21]. Thus, an agent-based modeling simulation is a powerful technique to simulate and capture the emergent behavior in individuals [22–25]. This study uses AnyLogic [26], which is a professional ABM software, to conduct the evacuation simulation since: (1) it can be integrated with Revit-developed buildings and structures by importing DXF file; (2) it can represent pedestrians as agents with individual parameters and behaviors; (3) it can simultaneously reflect the agents' interactions and reactions with spectacular 3D graphic [27]. To carry out evacuation planning, the AnyLogic Pedestrian Library, which is designed as a crowd analysis tool, allows users to model, visualize, and analyze pedestrian movements in an emergency scenario [28].

51.2.2 Critical Factors Affecting the Evacuation Time

Building Physical Properties. The physical characteristics of a building are closely associated with human decision-making process and fire growth. Although International Building Code (IBC) offers regulations for typical types of buildings, each building has its own engineered and situational attributes that affect fire outcomes. The engineered attributes are generally associated with the perspectives of building design and the situational attributes that are typically the environmental effects on evacuation performance [2, 25]. The building layout affect familiarity and proximity for pedestrians when they make their egress route decision. The capacity of a building to support pedestrian density will result in frequent congestion during emergencies.

Human Behavior. The pedestrians' individual personalities will affect their evacuation performance. The perception of risk and reward defined as a psychological process of risk assessment related to the current event [29]. It drives people to make an assessment of egress route selection before evacuating. However, the factor of bounded rationality prevents people from making rational decisions in an emergency, which requires a clear mind and a longer decision-making process [25, 29]. Due to the human characteristic of herding behavior, the escape decision-making will be attracted by the instruction of someone who is familiar with the building layout [30]. Also, the escape route selection would be significantly driven by the factors of familiarity that results in choosing the same exit as the one they entered into [31]. Besides, with congestions happening, people will encounter with destructive actions, such as stampede, pushing, or trampling on others [25]. Due to these destructive actions, the counter-flow will be functional as the negative forward flow to negatively impact on the evacuation efficiency [32].

The Characteristics of Fire. During a fire hazard, the most threatening element is smoke, rather than fire, and can cause body pain or impaired vision [33]. According to the research results currently available in fire safety engineering analysis, the heat generated will begin to harm the human body when (1) its upper layer radiation strength reaches 180 °C and (2) the layer of direct contact reaches 60 °C [19, 33]. The smoke density will reduce movement speed (1) as a 0.9 coefficient when the lower air layer reaches 1.5 m and (2) as a 0.6 coefficient when the lower layer reaches 1.2 m [19, 22]. The toxicity concentration of CO will begin to harm humans when it reaches 2500 ppm [33]. Furthermore, humans will experience impaired visibility and mobility when the smoke density reaches above 85% [34]. Thus, when designing computational simulation framework, the FDS measurements of heat generated, toxicity concentration, and soot density should be considered as factors that impact pedestrian movement.

51.2.3 Related Works on Fire Evacuation Design

To date, several researchers have conducted indoor fire evacuation simulation that reflects true human reactions. One of the pioneering studies in this domain was the grid simulation system that divided a simulated room into hundreds of grids [35], however human behavior simulation was limited by the computational abilities of that time. More than a decade later, Shi et al. [19], Peizhong et al. [20], Joo et al. [21] and Tang and Ren [22] successfully combined the ideas of the grid system and agent-based system that involved the impact of human evacuation behavior. However, none of them considered a delayed evacuation caused by building properties, such as the sensitivity of alarm system. Galea et al. [10] and Chaturvedi et al. [23] combined building properties and human properties together using the fluid and particle systems. However, they failed to consider fire effects. Abolghasemzadeh [24] used the matrix-based system to investigate the effect of building design on fire evacuation. Nonetheless, the matrix system is not a good choice for a crowded scenario, as the system struggles to simulate the effect of counter-flow.

By analyzing the current developments and limitations on fire evacuation simulation design, it is important to include all influential factors mentioned above to improve the accuracy of simulation outcomes. In this study, the movement of agents is based on the influence of human behavior (both individual and social behavior patterns), fire condition (temperature, toxicity, and smoke density), and building properties (alarm system, material thermal properties, and building layout). Moreover, this study develops a "re-decision model" for testing the effect of pedestrians who are impatient about queuing toward crowded exits. Besides, the effect of counter-flow will have an impact on agents' movement speed as a 0.81 coefficient of speed deduction [32], which refers to the destructive actions performed in counter-flow dynamics. To determine the effectiveness of building design, the number of exits, pathway width, and building capacity is adjusted to assist in optimizing the fire evacuation planning.

51.3 Research Methodology and Implementation

Revit software is used to established the architectural BIM model. BIM's interoperability function enables users to import the model into other software to conduct both the fire and evacuation simulations. PyroSim can be used to test the building's fire resistance and indicate the Available Safe Egress Time (ASET). The evacuation simulation is based on human physical limitation in fires to predict the Required Safe Egress Time (REST) by using AnyLogic.

To validate the designed simulation framework, the data collected from the Station Nightclub Fire, which occurred on the night of February 20th, 2003, in West Warwick, Rhode Island is used [36]. It was the fourth-deadliest nightclub fire in US history and killed 100 people, injured 230, and only 132 escaped uninjured [36].

51.3.1 Fire Simulation Design

Figure 51.1 shows the procedures of how to develop a fire simulation through PyroSim. The Revit model is first export as DWG file then resampled into the pre-defined 3D cubic mesh in PyroSim. The 2D drawings and material information for establishing the models are mainly obtained from the fire investigation report [36]. With an increased resolution of the mesh, a higher accuracy of the simulation can be obtained. However, reducing the mesh size as a factor of 2 will result in about a factor of 16 more computation time [29]. To balance the computation time and accuracy, 0.25 m length cubic mesh cells are used in this case. Moreover, nylon carpet, wood panels, and foam insulation account for the majority of fuel material that results in a quick fire spread [36]. These materials' thermal properties are referenced to the ASTM E84 [37]. Besides, the fire reaction is defined by creating the ignitor with 45 kW/m^2 Net Heat Flux, which is known as the heat energy transferred per surface unit area [9]. To measure and monitor the dynamic fire growth, the device system is composed by three types of devices (detectors of smoke, heat, and soot) and three layers of 2D slices (1.5, 2.0 and 2.5 m), which can reflect the changes of fire conditions in different heights. And finally, the outputs results of temperature, visibility and toxicity density will be visualized as time history plots in PyroSim, and the burning animation can be displayed in Smokeview [29]. The Available Safe Egress Time (ASET) represents the time before people begin to get hurt during the fire growth period.

51.3.2 Evacuation Simulation Design

The designed evacuation simulation in this study consist of four periods: the pre-alarm period, alarm period, pre-evacuation period, and evacuation period (Fig. 51.2). Fire ignition is defined in the model as the start time of 0 s. The pre-alarm period is the time necessary to receive a fire signal, which depends on the location of fire cues and the sensitivity of the alarm system. After the fire ignites, the agents' evacuation is delayed 0–60 s due to the time needed for the signal to be received and the risk assessed. In this design, 2% of agents are assumed as club officers who are familiar with the effective egress routes. And they will affect the movement direction of nearby agents. However, people may not be able to search for guided routes caused by the factor of bounded rationality. Unleaded agents will move to the main entrance initially due to the function of familiarity. The typical capacity of doorways allows 60 people per minute [34], thus the incapable doorway would be jammed and require people to queue for sheltering. As for the people who are impatience to wait longer than 30 s, they will make a re-decision of route selection. During the evacuation period, the default speed of agents is defined as adults' average walking speed of 1.25 ± 0.3 m/s [35]. By considering the influence of smoke density, their speeds will reduce to

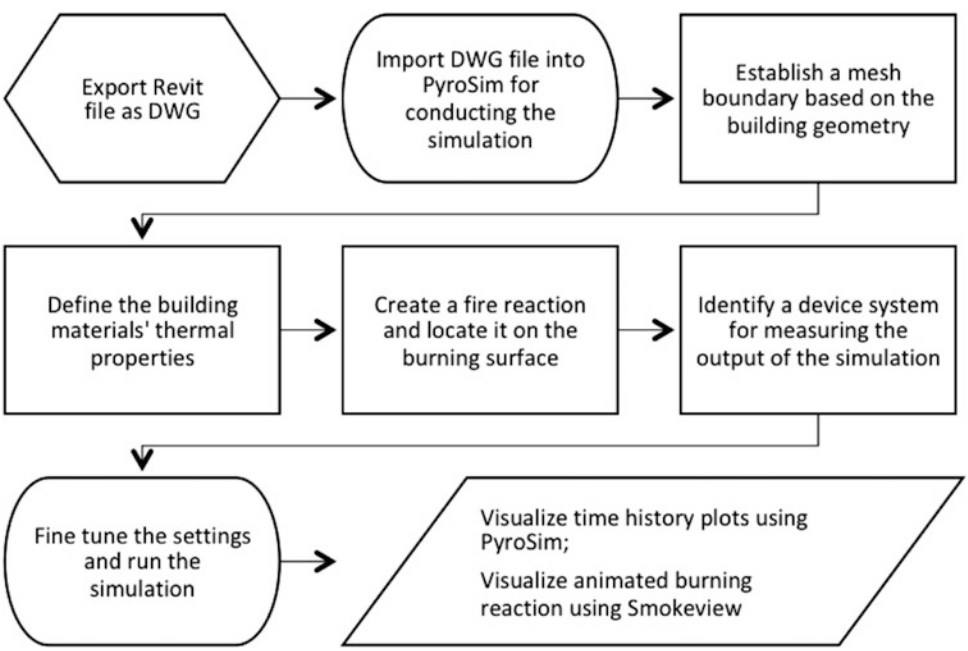

Fig. 51.1 Fire simulation design flowchart

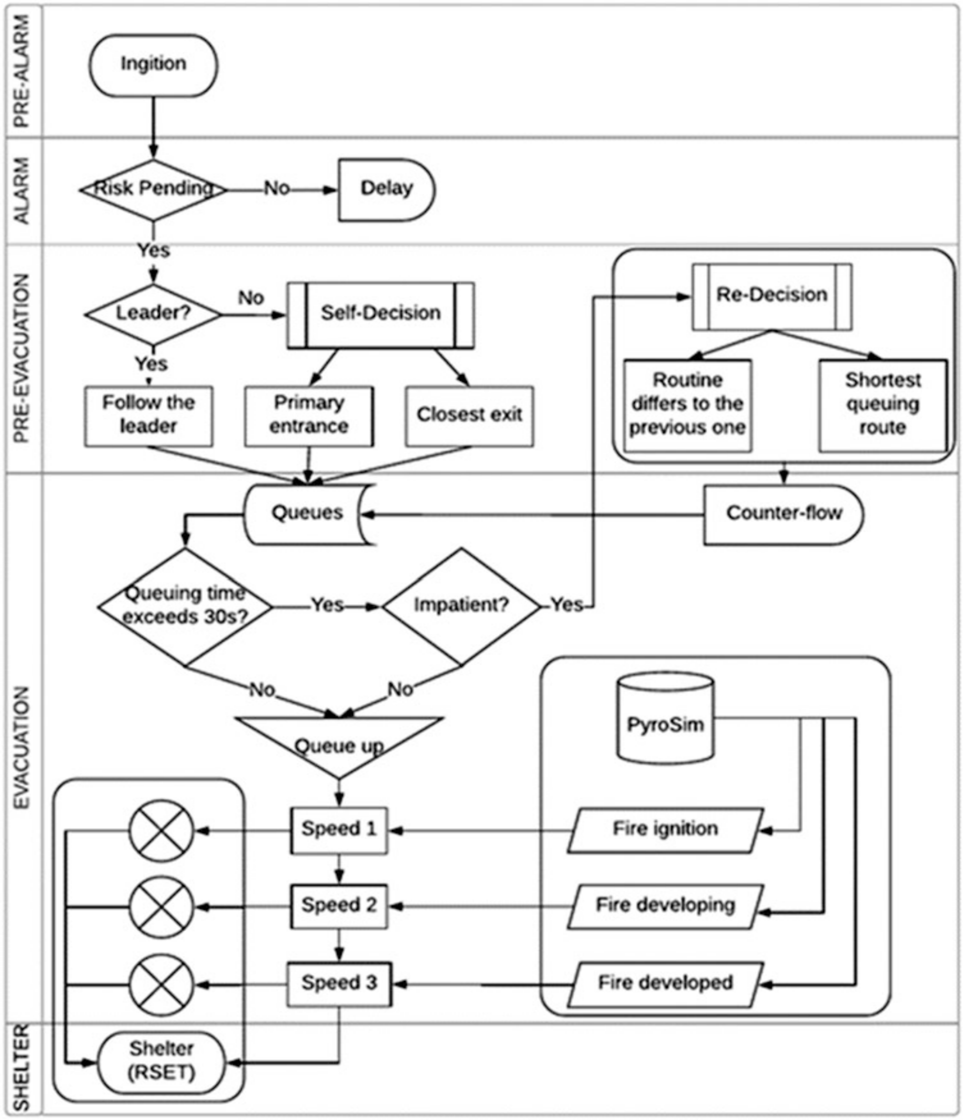

Fig. 51.2 Evacuation system flowchart

1.125 ± 0.27 m/s during the fire developing stage, and then reduce to 0.75 ± 0.18 m/s while the fire is fully developed. In the end, the time needed for sheltering all agents is used to represent the Required Safe Egress Time (REST).

51.4 Preliminary Results

51.4.1 Simulation Results

The fire simulation timeline approximately corresponds to the real accident timeline (Fig. 51.3). The smoke layer reaches 1.5 m at 180 s and reaches 1.2 m at 300 s, thus the agents' walking speed should deduct 10 and 40% respectively. Besides, the smoke density reaches 85% at 380 s, which happened earlier than other human physical limitations in fires. As a result, the ASET for uninjured, injured and severely injured escape are 180, 300, and 380 s respectively. Based on the evacuation simulation outputs: (1) 127 agents escaped uninjured; (2) 215 agents escaped with injuries; (3) 370 agents escaped with severe injuries and 92 died; (4) the RSET for all agents escaped without losing lives is 510 s. The numbers of sheltered

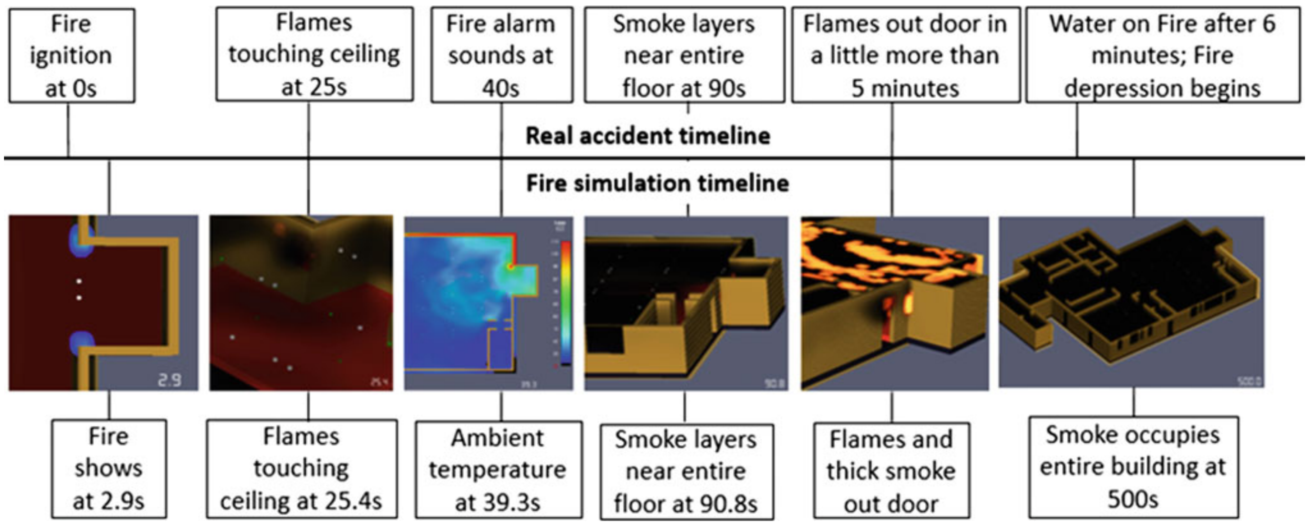

Fig. 51.3 Comparing timelines (ceilings are hided for better visualization)

Table 51.1 Suggested building designs for fire safety

Exits' number	Doorways' width (m)	Occupants' capacity	RSET	ASET	RSET $\leq$ ASET?
4	1	323	380	380	Yes
8	1	462	378	380	Yes
4	4	462	369	380	Yes

agents correspond to the accident records of injuries and deaths, which validates the accuracy of the evacuation simulation design.

Statistical Analysis. A statistical t-test is applied to investigate the relationship between RSET and building layout design. All of the simulations are assumed to be independent and normally distributed. As a result, with a 95% confidence level, small *p*-values (<0.01) significantly suggest a linear relationship between RSET and those three factors. The estimated model equation can be written as:

$$\text{RSET} = 265.60 - 32.78a - 46.78b + 0.93c \quad (51.1)$$

where factor a is the exit number, factor b is the doorway width, and factor c is the occupant capacity. This equation can be used to predict RSET for different building designs.

51.4.2 Application of Simulation Results

Acceptable building layout designs are defined by a smaller RSET number compared to ASET. Using Eq. 51.1, there are several building design suggestions that changes one variable only compared to the original building design (4 exits, 1 m doorway width, 462 occupant capacity) (Table 51.1). In order to achieve the maximized building utilization without human death, the optimal building design would be to keep the original layout design but lower the occupant capacity to 323.

Visualized through BIM. The Smokeview in PyroSim suggests that the dancing and stage area account for the fastest burn rate. One possible explanation for this is that the building uses non-fire retardant foam as wall insulation and the nylon carpet speeds up the spread of flames. The pedestrian density flow shown in AnyLogic indicates that the agents crowd and congest the main entrance while evacuating. This is caused by the fact that most pedestrians are not aware of the side-door exits and instead select the main entrance door as their egress selection. Thus, based on the simulation outputs, the stage area should be marked as the fire hazard zone, which needs to be improved and fireproofed. The side exits should also be more clearly represented as recommended egress options. Finally, 3D-BIM will serve as the environment to visualize these results.

51.5 Conclusions and Future Work

This paper proposed a comprehensive BIM-based simulation design that combines FDS and ABM to improve building fire safety management. By analyzing the simulation results shown in the case study, we verified the reliabilities of (1) simulating the fire growth by FDS tool; (2) involving the characteristics of the building properties, fire conditions, and human behaviors into the Agent-based evacuation design; (3) using a linear regression model to optimize the building design. In the end, 3D BIM served as the environment to visualize the results of (1) the hazardous zones that reflected in the fire simulation; (2) the effective escape routes that are recommended by the evacuation simulation.

Besides, this study leaves room to improve the simulation design: (1) it is recommended to test the effect of different ignition locations on the fire growth rate since the ignition location of a fire is hard to predict in real life; (2) in more complex building systems, a time-controlled device must be implemented in the fire simulation process, such as a sprinkler system being triggered at a specific time; (3) multi-story building structures should be studied to conduct more complex fire evacuation planning; (4) to assist in fire safety management through the entire construction life cycle, it is feasible to develop and apply the framework design on construction phase and maintenance phase, such as assisting in fire safety assessment of the construction site and fire safety equipment maintenance.

References

1. FEMA: Trends in fires, deaths, injuries and dollar loss. Report, US Fire Administration, Emmitsburg, MD (2016)
2. Kobes, M., Helsloot, I., Vries, B., Post, J.G.: Building safety and human behavior in fire: a literature review. Fire Saf. **45**(1), 1–11 (2010)
3. Lee, G., Sacks, R., Eastman, C.: Specifying parametric building object behavior (BOB) for a building information modeling system. Autom. Constr. **15**(6), 758–776 (2006)
4. Wang, S., Schyndel, M.V., Wainer, G., Rajus, V.S., Woodbury, R.: DEVS-based building information modeling and simulation for emergency evacuation. In: Proceedings of the 2012 Winter Simulation Conference (WSC) (2012)
5. Young, W.N., Jones, A.S., Bernstein, M.H., Gudgel, J.E.: The Business Value of BIM. SmartMarket Report: Design and Construction Intelligence. McGraw-Hill Construction, New York (2009)
6. Boukerche, A., Zhang, M., Pazzi, R.W.: An adaptive virtual simulation and real-time emergency response system. In: 2009 IEEE International Conference on Virtual Environments, Human-Computer Interfaces and Measurements Systems (2009)
7. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd edn. Wiley, Hoboken, NJ (2011)
8. Revit Software, Autodesk Inc
9. NIST Website: Fire dynamics. https://www.nist.gov/<front>/fire-dynamics. Last accessed 28 Mar 2018
10. PyroSim. Software. Thunderhead Engineering Consultants, Inc
11. Galea, E., Wang, Z., Veeraswamy, A., Jia, F., Lawrence, P., Ewer, J.: Coupled fire/evacuation analysis of the station nightclub fire. Fire Saf. Sci. **9**, 465–476 (2008)
12. Shen, T., Huang, Y., Chien, S.: Using fire dynamic simulation (FDS) to reconstruct an arson fire scene. Build. Environ. **43**(6), 1036–1045 (2008)
13. Glasa, J., Valasek, L., Weisenpacher, P., Halada, L.: Use of PyroSim for simulation of cinema fire. Int. J. Recent Trends Eng. Technol. **7**(2), 51–56 (2012)
14. Glasa, J., Valasek, L., Weisenpacher, P., Halada, L.: Cinema fire modelling by FDS. J. Phy. Conf. Ser. **410**(1), 012013 (2013)
15. Wang, T., Du, M.H., Tang, Y.F., Zhang, Q.: An analysis on the fire model and the safety evacuation based on BIM. Adv. Mater. Res. **1065**, 2386–2389 (2014)
16. Tingyong, F., Jun, X., Jufen, Y., Bangben, W.: Study of building fire evacuation based on continuous model of FDS & EVAC. In: 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring (2011)
17. EVAC. Software. AFMG Technologies GmbH
18. Grimm, V., Railsback, S.F.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Princeton University Press, Princeton (2005). ISBN 978-0-691-09666-7
19. Shi, J., Ren, A., Chen, C.: Agent-based evacuation model of large public buildings under fire conditions. Autom. Constr. **18**(3), 338–347 (2009)
20. Peizhong, Y., Xin, W., Tao, L.: Agent-based simulation of fire emergency evacuation with fire and human interaction model. Saf. Sci. **50**(4), 1171 (2011)
21. Joo, J., Kim, N., Wysk, R., Rothrock, L., Son, Y., Oh, Y., Lee, S.: Agent-based simulation of affordable-based human behaviors in emergency evacuation. Simul. Model. Pract. Theory **32**, 99–115 (2013)
22. Tang, F., Ren, A.: Agent-based evacuation model incorporating fire scene and building geometry. Tsinghua Sci. Technol. **13**(5), 708–714 (2008)
23. Chaturvedi, A., Mellema, A., Filatyev, S., Gore, J.: DDDAS for fire and agent evacuation modeling of the Rhode Island Nightclub Fire. In: Computational Science—ICCS 2006 Lecture Notes in Computer Science, pp. 433–439 (2006)
24. Abolghasemzadeh, P.: A comprehensive method for environmentally sensitive and behavioral microscopic egress analysis in case of fire in buildings. Saf. Sci. **59**, 1–9 (2013)

25. Pan, X., Han, C.S., Dauber, K., Law, K.H.: A multi-agent based framework for the simulation of human and social behaviors during emergency evacuations. AI Soc. **22**(2), 113–132 (2007)
26. AnyLogic. Software. The AnyLogic Company
27. AnyLogic Website: Features. https://www.anylogic.com/features/. Last accessed 25 Apr 2018
28. AnyLogic Website: Pedestrian Library. https://www.anylogic.com/resources/libraries/pedestrian-library/. Last accessed 25 Apr 2018
29. Kinateder, M.T., Kuligowski, E.D., Reneke, P.A., Peacock, R.D.: Risk perception in fire evacuation behavior revisited: definitions, related concepts, and empirical evidence. Fire Sci. Rev. **4**(1), 1 (2015)
30. Johnson, N.R., Feinberg, W.E.: The impact of exit instructions and number of exits in fire emergencies: a computer simulation investigation. J. Environ. Psychol. **17**(2), 123–133 (1997)
31. Proulx, G., Reid, I.M.: Occupant behavior and evacuation during the Chicago Cook county administration building fire. J. Fire. Prot. Eng. **16**(4), 283–309 (2006)
32. Heliövaara, S., Korhonen, T., Hostikka, S., Ehtamo, H.: Counter flow model for agent-based simulation of crowd dynamics. Build. Environ. **48**, 89–100 (2012)
33. Kuligowski, E.D.: Human Behavior in Fire. SFPE Handbook of Fire Protection Engineering, pp. 2070–2114. Springer, New York (2016)
34. Zhong, M., Shi, C., Tu, X., Fu, T., He, L.: Study of the human evacuation simulation of metro fire safety analysis in China. J. Loss Prev. Process Ind. **21**(3), 287–298 (2008)
35. Johnson, N.R., Feinberg, W.E.: The impact of exit instructions and number of exits in fire emergencies: a computer simulation investigation. J. Environ. Psychol. **17**(2), 123–133 (1997)
36. Grosshandler, W.L., Bryner, N.P., Madrzykowski, D., Kuntz, K.: Report of the technical investigation of The Station nightclub fire. Gaithersburg, MD: U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology. NIST NCSTAR 2, vol. I (2005)
37. ASTM E84: Standard Test Method for Surface Burning Characteristics of Building Materials, 6th edn, pp. 1000–1018. ASTM Fire Standards, American Society for Testing and Materials, West Conhohocken, PA (2007)

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52 Where Do We Look? An Eye-Tracking Study of Architectural Features in Building Design

Zhengbo Zou and Semiha Ergan

Abstract

Built environment plays an essential role in shaping the physical, physiological, and psychological human well-being given the fact that we spend more than ¾ of our times indoors. Various studies that investigated the impact of architecture on human health and well-being provided evidences on the influence of architecture with faster recovery in hospitals, better learning in schools, and more productivity in offices under variant configurations of architectural design features. This paper studied the impact of architectural design features (e.g., presence/size of windows, level of natural light and nature view) on human experience in buildings using a mobile eye-tracking solution to capture the subjects' attention toward various design features. The subjects were exposed to two distinct virtual environments designed with polarizing features, and were instructed to conduct a series of navigational and informational tasks. The eye-tracking results showed that subjects were more focused and had higher attention level in the positively configured virtual environment. The result of the informational task, where the subjects were asked to recall an array of words they just saw in the virtual environment, showed that subjects performed better (i.e., recalled more words) and experienced positive recall (i.e., recalled more positive words) in the positively configured environment.

Keywords

Eye-Tracking • Architectural design • Virtual reality • Human experience

52.1 Introduction

Architectural design could influence health and well-being of residents, since people spend most of their time inside of buildings [1]. Poorly designed buildings could cause physical and psychological discomfort for the occupants, such as Sick Building Syndrome (SBS), where the occupants experience sickness and discomfort that appear to be linked to the time spent in buildings [2]. As a result, fully understanding if certain architectural design features, such as (1) the presence of windows, (2) size of windows, (3) presence of natural light, and (4) presence of nature views, have any effects on human experience in buildings is a challenging task in architectural design. It is well known that these features could influence human emotions [3], hence impacting human health, well-being, and productivity [4, 5]. Previous studies on architectural design features' impact on humans mostly focused on surveying occupants after the construction is complete [6]. These survey studies were time-consuming and prone to errors introduced by the subjective feelings and demographics of the surveyed. As a result, there is still a need to objectively quantify the building design features' impact on human experience.

Previous research on quantifying the relationship between architectural design features and human emotions used Body Sensor Networks (BSN) as a data collection platform to record the subjects' physiological metrics (i.e., heart rate, facial

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muscle movement, and skin conductance) [7]. The results showed that environments with different architectural design features could cause statistical significant differences in BSN data [7]. However, the causal relationship of design features and human emotions is still inconclusive [8, 9].

As a result, it is essential to pinpoint the architectural design features that are causing the variance of human experience in architectural spaces, and eye-tracking technology is well suited for this purpose. Eye-trackers are devices that measure eye movement, which reflects the visual attention and gaze patterns of users [10]. Eye movement and gaze patterns have been related to attention and cognition, which are quantifiable links to the subjects' brain activities (e.g., scene awareness, perception of environment) [11, 12]. As a result, by measuring the visual stimuli and the subjects' eye movement, one could gain insights to the subjects' search patterns, attention, and most importantly, the causal relationship of the visual stimuli (i.e., the architectural design features) and the human emotions.

The objective of this paper is to study whether certain architectural features have any impact on human experience in buildings. Furthermore, this paper quantifies the extent of such impact by conducting user studies using a mobile eye-tracking solution, during which the participants were instructed to carry out tasks in distinctly configured virtual environments with various design features. Participants' responses were later analyzed and the implications of architectural features on human experience were discussed.

52.2 Background

52.2.1 Eye-Tracking Applications

Eye-tracking technology has been widely used in various areas of research, such as marketing, Human-Computer Interaction (HCI), safety simulation, and construction safety [10, 12–14]. A concise summary of the application areas of these research fields is presented in Table 52.1. Among these applications, the main purpose of using eye-tracking technology is to measure the attention of the users, hence inferring the users' situation awareness (i.e., safety simulation and construction safety), aesthetic preference (i.e., marketing), and viewing behavior (i.e., HCI). The experiment set-up used in the previous studies usually contain conducting interviews within a focus group while using eye-tracking technology to monitor the participants attention towards the Area of Interest (AOI), which is defined as the specific parts of a product or a design that is of interest to the researcher [15]. However, this kind of set up will not work for Architecture, Engineering and Construction (AEC) applications, since the workflow in AEC either requires onsite visits [10, 11] or immersive representation of a design model [16, 17].

In the Architectural Engineering and Construction (AEC) domain, eye-tracking has not received much recognition until the past decade due to some technological obstacles, such as the cumbersome size of eye-trackers, non-reliable eye-tracking outcomes, and hard to interpret results [15]. Accuracy (i.e., difference between actual gaze point and the measured point) and sampling frequency (i.e., average number of samples captured by eye-trackers) are the main specifications of eye-tracking technology. Low accuracy and low sampling rate used to be the roadblock for using eye-tracking technology in the AEC industry. However, with the fast technology development, eye-trackers nowadays are miniaturized to the size of a pair of glasses capable of accurate high rate sampling, and the development of eye-tracking data analyzing tools has made it possible for a larger number of AEC practitioners and researchers to utilize eye-tracking in their workflows. The most common use cases of eye-tracking in AEC include monitoring the construction workers' attention for construction safety awareness and conducting safety education for novice construction workers [10]. However, few studies focused on using eye-tracking for architectural design [1, 11]. One of the main reasons is that while designs can be rendered in a 2D or 3D

Table 52.1 Eye-tracking technology applications

Research area	Application
Marketing	• Web design [18] • Print advertisement [13]
Human-computer interaction (HCI)	• Brain-computer interface (BCI) [12] • Visual hierarchy and viewing behavior [19]
Safety simulation	• Flight simulator [14] • Driving simulator [20]
Construction safety	• Construction worker safety [11] • Construction safety education [10]

drawing, it is still challenging for people to experience the design features when they are only seeing a static drawing on a screen [16]. As a result, to achieve the measurement of the subjects' attention when experiencing various architectural designs, there is a need to create interactive virtual environments [7, 17].

52.2.2 Eye-Tracking Metrics

Fixations and saccades are the main metrics used when analyzing eye-tracking data [21]. A fixation is defined as a relatively motionless gaze on an AOI, whereas a saccade is defined as a quick eye movement that separates fixations [10]. Fixation and saccade each has a suite of related metrics that can be generated from eye-tracking data, such as fixation location/duration, saccade amplitudes/count. Fixation location indicates the person's attention, and fixation duration indicates the level of cognitive difficulty [1]. On the other hand, saccades only represent rapid eye movement, during which no visual information is stored or recognized [11]. As a result, only fixation related metrics are used in this study. A brief summary of those metrics is provided in Table 52.2.

52.3 Method

The authors conducted experiments with human subjects to monitor their attention while they were interacting with spaces configured with various design features. The total number of participants was 22, all of whom were graduate students from the department of civil and urban engineering. Hence, the subjects have adequate knowledge of architectural design.

To measure human responses towards different architectural features, two virtual environments with polarized features (marked as positive and negative) were developed in a game engine, by converting building information models to virtual environments [26]. The two virtual environments were identical, except for certain architectural features (see Table 52.3). On the one hand, the positive environment was designed with larger windows, ample natural light, and a view of green plants outside of the glass curtain walls. On the other hand, the negative environment was designed with smaller or no windows, only artificial lights, and closed concrete walls with no nature view. The design features included in the experiment are shown in Table 52.3.

22 participants were recruited to conduct the experiment and execute various tasks in the virtual environments. The tasks were separated into two categories, navigational and informational. For navigational tasks, the participants were directed to find specific objects located in certain rooms. For informational tasks, the participants were instructed to read an array of 10 words from an information panel, and then immediately write down the text they remember. It is hypothesized that the participants would show positive reactions (e.g., more focused, faster responses) in the positive environment, and vice versa. A widely adopted mobile eye-tracking solution was used during the user experiments to collect data about the participants' attention to the Area of Interests (AOI). The AOIs are defined as the video frames that contain different design features, while the subjects were conducting either navigational or informational tasks in those frames in two virtual environments. For example, in Fig. 52.1, the subjects were asked to go to the room at the end of the hall (navigational task). While they were walking towards the room, various design features, such as window size, natural light, and nature view were implemented in the corridor. And these features (i.e., presence of windows, window size, natural light, and nature view) are

Table 52.2 Eye-tracking metrics

Metric	Description
Area of interest (AOI)	Video frames containing design features (i.e., presence/size of windows, amount of natural light, presence of nature view)
Heat map	Distribution of the visual attention. (More hotspots indicate less focused attention) [22]
Number of fixations	Number of periods in which the eyes of a respondent are locked toward a specific object. (A large number of fixation indicates the task is complex and the subjects showed decreased efficiency in searching and navigating tasks) [23]
Time to first fixation	The amount of time it takes a respondent to look at a specific AOI. (Smaller TTFF indicates the high attention level and more focused mind) [24]
Time spent	The amount of time a respondent has spent on an AOI. (Less time spent means higher attention level) [25]

Table 52.3 Values in VEs for design features influential to human emotions

Architectural design features	Positive VE	Negative VE
Presence of windows	Has windows in measured corridors and rooms	No windows in measured corridors and rooms
Size of windows	Large size windows (60% Window to Wall Ratio)	Small windows (20% Window to Wall Ratio)
Amount of natural daylight	Sufficient amount of natural daylight (300 lx of luminance), brought in by windows in the measured room/corridor	Only artificial light and no window in the measured room/corridor
Exposure to nature view	Connection to external built environment and visible nature views	No connection to external built environment or visible nature views

Fig. 52.1 Polarized design features in positive (left) and negative (right) environments

defined as the AOIs. By looking into the eye-tracking metrics of these AOIs, the authors were able to gain insights of the subjects' attention towards the design features.

The experiment set up and flow are shown in Fig. 52.2. The virtual environments were shown on a 98-inch screen, and the user interaction was handled by an Apex device with a joystick for moving around and a button for triggering functions. The eye-tracking solution used was a mobile eye-tracking device in the form of a pair of glasses (as shown in Fig. 52.2). There is an array of infrared sensors on the inside of the frame to illuminate the subjects' eyes, and four cameras to follow the eye movement. The vision of the subjects can be recorded using an environment camera on the outside of the frame. The experiment was around 40 min in length. First, the subjects were given a short description of the experiment and a short training period to try navigating in a similar but different virtual environment to get familiar with the set up. Next, the subjects were asked to finish a short demographic survey, and put on the eye-tracking glasses. Following that, the subjects were presented randomly with one of the virtual environment (i.e., positive or negative), and asked to finish the informational and navigational tasks. A short break period was given after each subject finishes the tasks in one environment with a follow up on the other virtual environment. After finishing each environment, the subjects were asked to recall and write down the words they had seen in the environment. There are in total 10 words presented to the subjects, which are separated into two categories, as words that provoke positive emotions (e.g., strong, excited) and those provoke negative emotions (e.g., scared, nervous) [27]. The hypothesis is that the subjects will remember more words (i.e., better performance), and more positive words (comparing to negative words) in the positive environment.

52.4 Result and Discussion

The results of the experiments include two parts (i.e., results of eye-tracking metrics and information recall result). The eye-tracking metrics used in this paper are heat maps, time spent, number of fixations, and time to first fixation. Figure 52.3 shows the heat maps of one subject while he conducted the navigational task to find a thermometer in a specific room. The

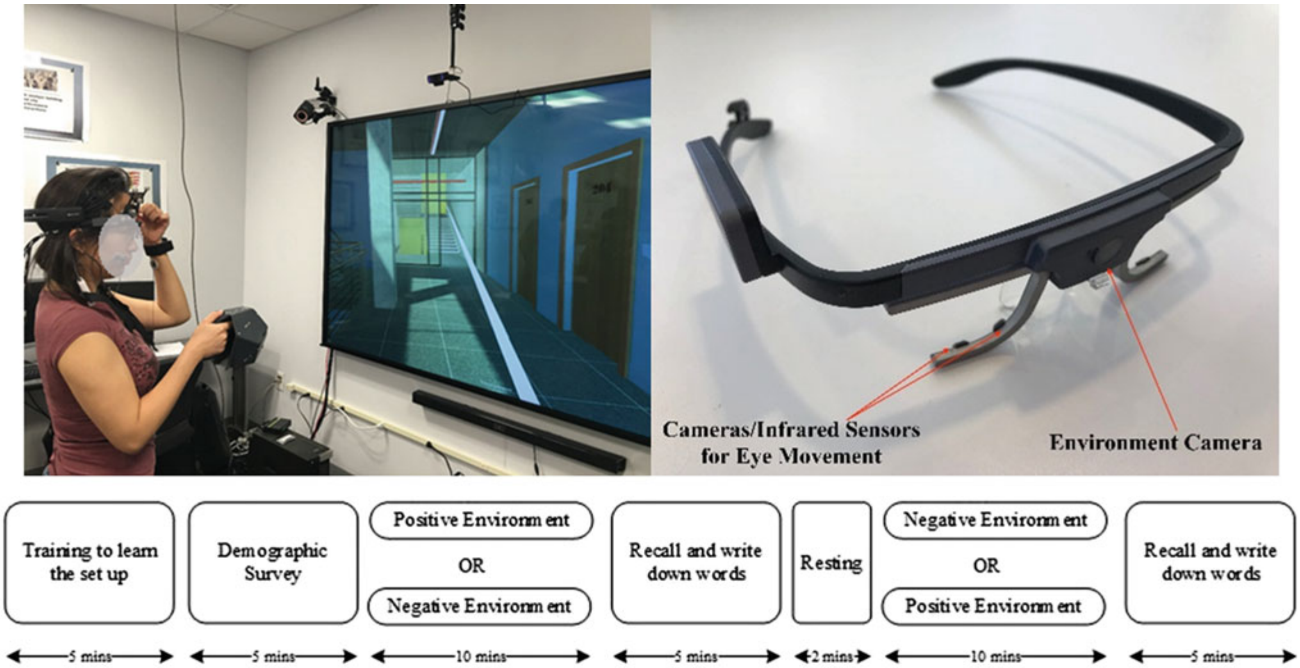

Fig. 52.2 Experiment set up and flow

authors selected a continuous part of the video recorded by the eye-tracking environment camera, where the subjects were exposed to design features evaluated, and compared the heat maps of positive and negative environment. Warmer colors (red) indicate more attention, and cooler colors (green) indicate less attention (as shown in Fig. 52.3). The result shows that in the positive environment (i.e., with ample natural lighting), the subject is more focused on the navigational task (i.e., with one main hot spot in the corridor), whereas in the negative environment (i.e., no natural light with only artificial lighting), the subject showed a more distracted attention with several separated hot spots. Similar analysis was conducted for all participants across all AOIs. The final result shows that all participants had more focused attentions (i.e., less hot spots) for all AOIs.

The authors also conducted data analysis for the other eye-tracking metrics. The results are averaged across 22 participants, and shown in Table 52.4. On average, the subjects showed less time spent in the positive environment for each AOI than the negative one, indicating the subjects were faster on the executing tasks in the positive environment. When the complexity of the tasks is identical, less time spent means higher attention level in the environment [25]. The subjects also had less number of fixations in the positive environment for all AOIs comparing to the negative one. A large number of fixation indicates the task is complex and the subjects showed decreased efficiency in searching and navigating tasks [23]. Subjects showed smaller Time to First Fixation (TTFF) for the AOI: presence of window, level of natural light, and exposure to nature views. TTFF is calculated as the time in milliseconds that the subjects took to notice a specific AOI, and smaller TTFF indicates the high attention level and more focused mind [24].

The authors also analyzed the data obtained from the informational task. For the informational task, the subjects were asked to look at an array of words (total 10 words) on an information panel for 30 s and then recall and write down the words they remember. The words were selected so that they can be clearly separated as positive or negative words that evoke positive/negative human emotions [27]. The words are shown in Table 52.5, separated as positive and negative words. The total number of times that all subjects remembered the words are shown for positive and negative environments. It is clear that in the positive environment, the subjects recalled more words (positive and negative combined) than the negative environment, indicating the positively configured design features had a positive effect on the informational task. From another angle, the positive words were recalled more times than the negative words in the positive environment, meaning the subjects felt more positive emotions in the positive environment. On the other hand, the negative words were recalled more in the negative environment than the positive words. The result of informational task showed that the subjects generally performed better in the positive environment for informational tasks, and the positive environments evoked more positive emotions from the subjects.

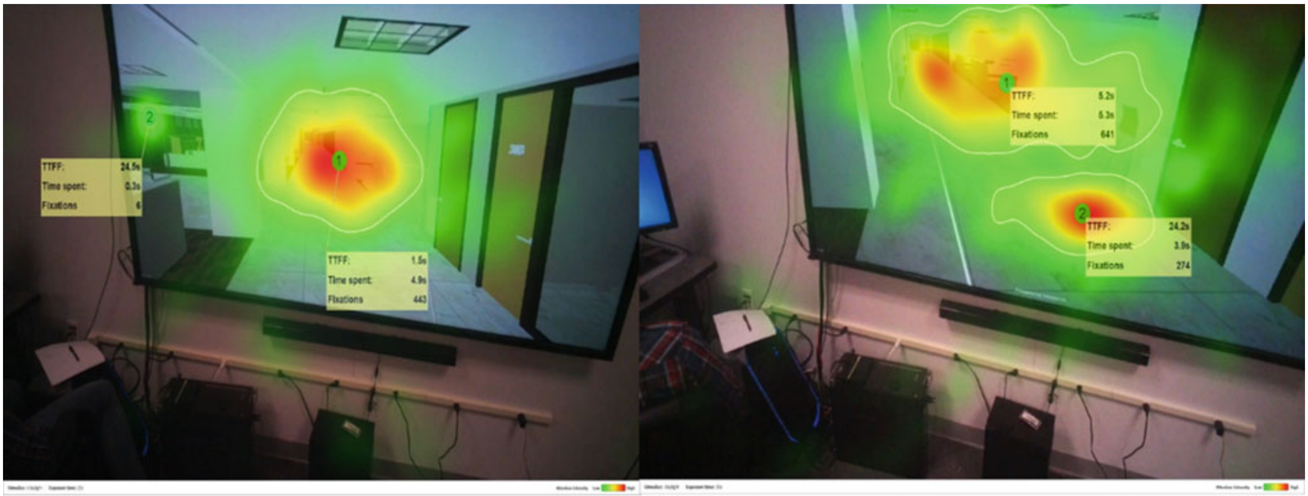

Fig. 52.3 Heat map result from one subject's eye-tracking data for AOI amount of natural lighting (left Positive, right Negative). Warmer colors (Red) indicate more attention, and cooler colors (Green) indicate less attention

Table 52.4 Eye-tracking metrics for AOIs in positive/negative environments

AOI	Time spent (s)		Number of fixations (times)		Time to first fixation (ms)	
	Positive	Negative	Positive	Negative	Positive	Negative
Presence of windows	3.0	3.5	268	290	1.0	3.0
Size of windows	3.0	7.0	300	335	5.5	3.8
Level of natural light	5.0	5.4	421	630	1.5	5.2
Exposure to nature view	6.8	8.4	647	902	2.1	2.9

Table 52.5 Count of positive/negative words recalled by subjects in both environments

Word type	Words	Recalled in positive environment (times)	Recalled in negative environment (times)	Total (times)
Positive words	Active	14	9	23
	Strong	16	10	26
	Excited	14	13	27
	Enthusiastic	17	12	29
	Interested	14	12	28
	Total	75	56	131
Negative words	Scared	15	12	27
	Irritable	12	8	20
	Nervous	12	11	23
	Upset	11	17	28
	Distressed	16	9	25
	Total	66	57	123

52.5 Conclusion and Future Work

Architectural design features' impact on human experience has long been argued. Previous research mostly focused on subjective survey studies. This study serves as one of the first studies that aimed at providing empirical quantification on human experience in architectural spaces using an integrated and rapidly replicated VR and eye tracking based data collection. 22 participants were invited to the experiment. The results provide evidence that the presence/size of windows, natural light, and natural views are indeed related to human experience in designed spaces and can positively impact the residents if present. The experimental procedure proposed in this study can be used as a general experimental method for architects to use when collecting user experience data during the design process for improving occupants' experiences. Finally, with more participants, the results could serve as guidelines (i.e., how to correctly configure architectural features) when designing spaces with human experience in mind.

For future work, the study could incorporate other types of body area sensors to provide more detailed human body metrics when experiencing different designs. Another area of improvement can be comparing the results collected from the virtual environments to that of the real environments to investigate the impact of using virtual environments to represent design rather than a real-world building.

References

1. Aries, M.B., Veitch, J.A., Newsham, G.R.: Windows, view, and office characteristics predict physical and psychological discomfort. J. Environ. Psychol. **30**(4), 533–541 (2010)
2. Dravigne, A., Waliczek, T.M., Lineberger, R.D., Zajicek, J.M.: The effect of live plants and window views of green spaces on employee perceptions of job satisfaction. HortScience **43**(1), 183–187 (2008)
3. Ehmke, C., Wilson, S.: Identifying web usability problems from eye-tracking data. In: Proceedings of the 21st British HCI Group Annual Conference on People and Computers, September 2007
4. Kaplan, S.: The restorative benefits of nature: toward an integrative framework. J. Environ. Psychol. **15**(3), 169–182 (1995)
5. Pan, B., Hembrooke, H.A., Gay, G.K., Granka, L.A., Feusner, M.K., Newman, J.K.: The determinants of web page viewing behavior: an eye-tracking study. In: Proceedings of the 2004 Symposium on Eye Tracking Research and Applications, pp. 147–154, March 2004
6. Hedge, A., Burge, P.S., Robertson, A.S., Wilson, S., Harris-Bass, J.: Work-related illness in offices: a proposed model of the "sick building syndrome". Environ. Int. **15**(1–6), 143–158 (1989)
7. Radwan, A., Ergan, S.: Quantifying human experience in interior architectural spaces. Comput. Civ. Eng. **2017**, 373–380 (2017)
8. Bratman, G.N., Hamilton, J.P., Daily, G.C.: The impacts of nature experience on human cognitive function and mental health. Ann. N. Y. Acad. Sci. **1249**(1), 118–136 (2012)
9. Franz, G., von der Heyde, M., Bülthoff, H.H.: Predicting experiential qualities of architecture by its spatial properties. In: Proceedings of 18th IAPS-Conference, pp. 1–10 (2004)
10. Dzeng, R.J., Lin, C.T., Fang, Y.C.: Using eye-tracker to compare search patterns between experienced and novice workers for site hazard identification. Saf. Sci. **82**, 56–67 (2016)
11. Hasanzadeh, S., Esmaeili, B., Dodd, M.D.: Measuring construction workers' real-time situation awareness using mobile eye-tracking. In: Construction Research Congress 2016, pp. 2894–2904 (2016)
12. Navalpakkam, V., Arbib, M., Itti, L.: Attention and scene understanding. In: Neurobiology of Attention, pp. 197–203 (2005)
13. Wedel, M., Pieters, R.: A review of eye-tracking research in marketing. Review of Marketing Research, pp. 123–147. Emerald Group Publishing Limited, Bingley (2008)
14. Sarter, N.B., Mumaw, R.J., Wickens, C.D.: Pilots' monitoring strategies and performance on automated flight decks: an empirical study combining behavioral and eye-tracking data. Hum. Factors **49**(3), 347–357 (2007)
15. Yousefi, M.V., Karan, E., Mohammadpour, A., Asadi, S.: Implementing eye tracking technology in the construction process (2015)
16. Du, J., Zou, Z., Shi, Y., Zhao, D.: Zero latency: real-time synchronization of BIM data in virtual reality for collaborative decision-making. Autom. Constr. **85**, 51–64 (2018)
17. Du, J., Shi, Y., Zou, Z., Zhao, D.: CoVR: cloud-based multiuser virtual reality headset system for project communication of remote users. J. Constr. Eng. Manage. **144**(2), 04017109 (2017)
18. Cutrell, E., Guan, Z.: What are you looking for: an eye-tracking study of information usage in web search. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 407–416, April 2007
19. Djamasbi, S., Siegel, M., Tullis, T.: Visual hierarchy and viewing behavior: an eye tracking study. In: International Conference on Human-Computer Interaction, pp. 331–340, July 2011
20. Palinko, O., Kun, A.L., Shyrokov, A., Heeman, P. Estimating cognitive load using remote eye tracking in a driving simulator. In: Proceedings of the 2010 Symposium on Eye-Tracking Research and Applications, pp. 141–144, March 2010
21. Jaimes, A., Sebe, N.: Multimodal human–computer interaction: a survey. Comput. Vis. Image Underst. **108**(1–2), 116–134 (2007)
22. Jacob, R. J., & Karn, K. S. (2003). Eye tracking in human-computer interaction and usability research: Ready to deliver the promises. In The mind's eye (pp. 573–605)
23. Ehmke, C., Wilson, S.: Identifying web usability problems from eye-tracking data. In: Proceedings of the 21st British HCI Group Annual Conference on People and Computers, September 2007

24. Thiessen, A., Beukelman, D., Ullman, C., Longenecker, M.: Measurement of the visual attention patterns of people with aphasia: a preliminary investigation of two types of human engagement in photographic images. Augmentative Altern. Commun. **30**(2), 120–129 (2014)
25. Pan, B., Hembrooke, H.A., Gay, G.K., Granka, L.A., Feusner, M.K., Newman, J.K.: The determinants of web page viewing behavior: an eye-tracking study. In: Proceedings of the 2004 Symposium on Eye Tracking Research and Applications, pp. 147–154, March 2004
26. Kasireddy, V., Zou, Z., Akinci, B., Rosenberry, J.: Evaluation and comparison of different virtual reality environments towards supporting tasks done on a virtual construction site. In: Construction Research Congress, pp. 2371–2381 (2016)
27. McGinnies, E.: Emotionality and perceptual defense. Psychol. Rev. **56**(5), 244 (1949)

53

Developing a Framework of a Multi-objective and Multi-criteria Based Approach for Integration of LCA-LCC and Dynamic Analysis in Industrialized Multi-storey Timber Construction

Hamid Movaffaghi and Ibrahim Yitmen

Abstract

To improve organizational decision-making process in construction industry, a framework of a multi-objective and multi-criteria based approach has been developed to integrate results from Life-Cycle Analysis (LCA), Life-Cycle Cost Analysis (LCC) and dynamic analysis for multi-storey industrialized timber structure. Two Building Information Modelling (BIM)-based 3D structural models based on different horizontal stabilization and floor systems will be analyzed to reduce both climate impact, material and production costs and enhance structural dynamic response of the floor system. Moreover, sensitivity of the optimal design will also be analyzed to validate the design. The multi-objective and multi-criteria based LCA-LCC framework analyzing the environmental, economic, and dynamic performances will support decision making for different design in the early phases of a project, where various alternatives can be created and evaluated. The proposed integrated model may become a promising tool for the building designers and decision makers in industrialized timber construction.

Keywords

LCA • LCC • Dynamic response • Multi-criteria • Multi-objective • BIM • Decision making • Industrialized timber construction

53.1 Introduction

In recent years, the usage of prefabricated structural components of solid wood and engineered wood products (EWPs) has increased due to the recent developments towards an industrialized construction and manufacture within the timber building sector in Sweden [19]. Multi-storey timber frame housing was identified as a field for industrialized process development in Sweden [24].

Life Cycle Analysis (LCA) assesses the sustainability of general products throughout its lifetime in environmental, social and economic perspectives (ISO Standard 14040) [16]. Flanagan and Jewell [10] define Life Cycle Cost (LCC) as the total cost of a facility/asset over its operating life including initial acquisition costs and subsequent running costs. Some applications of LCA methodology to timber buildings with comparisons to three different structural materials (timber, concrete and light steel framing) for the same house, concluded that the timber accomplished finer results for all the categories analyzed. Coelho et al. [5] presented a LCA for a single-family house built in Kiruna (Sweden), comparing two structural systems: timber frame and light steel framing, and concluding that timber-frame solution is much more economic. Buchanan and Levin [4] and Sathre and O'Connor [32] state that timber buildings considering the whole life-cycle need lower energy processes for its manufacture, than on the carbon storage itself.

Cross Laminated Timber (CLT) opening new perspectives and possible applications to the whole industry are used as slabs, shear walls, non-load bearing walls, ceilings and roofs elements and can be combined with other construction

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materials. Higher demands from customers to have more open lay out with large-span floors, 8–10 m and economic construction practices have amplified sensitivity issues concerning dynamic performances of the floor systems. This has also resulted in unaccepted floor springiness as disturbing sensation due to deflection and vibration of the floor at the point of application of a foot step load by one and the same person [40].

Some of the previous studies present a new combined LCA and LCC method [11], framework [13, 28, 34], model [2, 9, 12, 33] or tool [1, 15, 28]. Kovacic et al. [18] pointed out that development of a tool for successfully integration of LCA and LCC especially at an early design stage is crucial. In this study, a multi-criteria and multi-objective based approach will be applied to link the process-based LCA and LCC for a four-storey timber structure with optimized dynamic performance of the floor systems.

53.2 Background

53.2.1 Life Cycle Assessment and Life Cycle Costing

LCA is an organized method to assess the environmental influences related with products, processes and/or services. The evaluation comprises the whole life cycle of the product, process or an activity starting from extraction (or excavation), processing, manufacturing, transportation, distribution, use, recycle, and final disposal [31, 39]. LCC analysis is a method enabling relative cost appraisals to be prepared throughout a specific phase, considering all applicable economic factors, mutually in terms of initial costs and future operational costs (ISO 15686) [3]. LCA is divided into two major methods concerning assessment: the process-based LCA [25, 22] and the Input-Output LCA (IO-LCA) [23, 38]. The process-based LCA is based on the certain information of the life cycle processes, which comprise raw material extraction, manufacturing, use, disposal and end-of-life treatment [27]. The significant drawbacks recognized in LCA were data, results and output [34].

53.2.2 Dynamic Analysis of Timber Floor System

Timber floor system with small-span up to 4 m has normally acceptable dynamic responses because of the fact that the floor has often adequate stiffness resulting the floors first natural eigenfrequency will be in the most cases above 8 Hz. This is recognized by Eurocode 5 as the lower limit of the first eigenfrequency for timber floors where the most sensitive area lies between 4 and 8 Hz which corresponds to the eigenfrequencies of some of the organs of the human body. But when the floors span length increases the stiffness become lower and the floors first eigenfrequency normally goes below 8 Hz. Effects of structural and non-structural modifications of floor systems on the dynamic performance of the case studies will be analyzed by parametric studies based on the design criteria and modal dynamic analysis together with both multi-objective optimization. Vibration levels and deflection of different floor systems as two objective functions will be optimized simultaneously to create a Pareto front.

53.2.3 Analytical Network Process

Analytic Network Process (ANP) proposed by Saaty [30], admits complex interrelationships among decision levels and attributes [21] and signifies a decision problem as a network of elements gathered into clusters [6]. Deniz [8] created an ANP model to examine LEED-certified buildings' operational performance. Promentilla et al. [29] developed an ANP technique to rank the potential CO_2 sources and sinks to identify sites for CO_2 capture and storage demonstration projects. Theißen and Spinler [37] developed an ANP model for collaborative CO_2 reduction management for strategic analysis of manufacturer-supplier partnerships. Senante et al. [35] proposed an ANP approach for assessment of wastewater treatment alternatives for small communities. Wudhikarn et al. [41] proposed a framework for new product selection decision using ANP and knowledge management involving LCC. Lam and Laib [20] developed an environmental sustainability by ANP-Quality Function Deployment approach for the case of shipping operations.

53.3 Developing a Multi-objective and Multi-criteria Based Integrated Framework of LCA-LCC for Industrialized Timber Structures

The model of framework for the multi-story industrialized timber structure residential building is presented in Fig. 53.1. A multistory industrialized timber structure residential building is identified in Jönköping, Sweden. A multi-objective optimization will be performed based on the design criteria and modal dynamic analysis to reduce both the vibration levels and deflection of floor systems. Then a ANP based multi-criteria analysis will be used to choose optimal designs on Pareto front. ANP based multi-criteria analysis will be even performed on the case study with enhanced dynamic performances using LCA and LCC results. A gradually multi-objective and multi-criteria based framework and its application for the multi-story industrialized timber structure residential building is presented in the following sections.

53.3.1 Structural Design and Finite Element Models

Two BIM-based 3D structural models as seen in Figs. 53.2 and 53.3 below based on different timber horizontal stabilization systems and several different floor systems will be analyzed to enhance both the dynamic performance of the floor systems and reduce life cycle impact in terms of CO_2 emissions and material and production costs of whole structure.

53.3.1.1 Model 1

The multi-story industrialized timber structure of residential building including basement, with the overall dimensions L × W × H = 20.2 × 13.2 × 14.7 m. The model consists of reinforced concrete walls and slab at basement, reinforced concrete shaft and stair-way along the height for horizontal stability of the structure and timber structural elements from height 2.6 m up to 14.7 m. Timber structural elements includes glulam columns with different dimensions and several different structural floor systems as seen in Fig. 53.2.

53.3.1.2 Model 2

The only difference between model 2 and model 1 is that in model 2 concrete shaft and stairway as horizontal stabilization of structure has been replaced by shear walls along all four facades as horizontal stabilization of structural system. Timber structural elements includes glulam columns with different dimensions and several different structural floor systems as seen in Fig. 53.3.

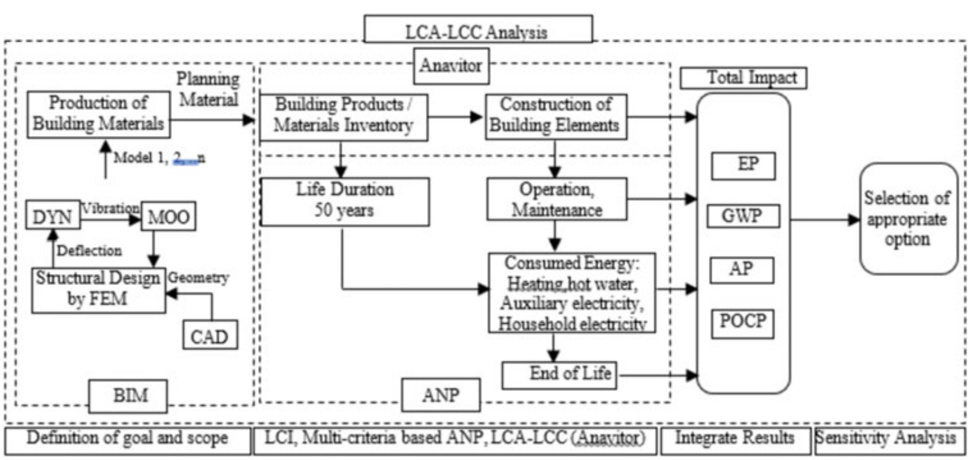

Fig. 53.1 Model of framework of a multi-objective and multi-criteria based LCA-LCC analysis for multi-storey in industrialized timber structure

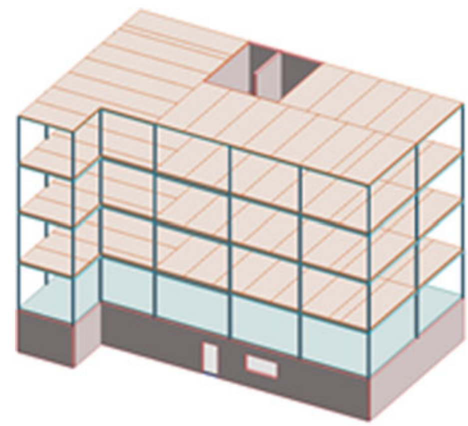

Fig. 53.2 3D structural finite element model for the multi-storey industrialized timber structure with concrete shaft and stairway—model 1

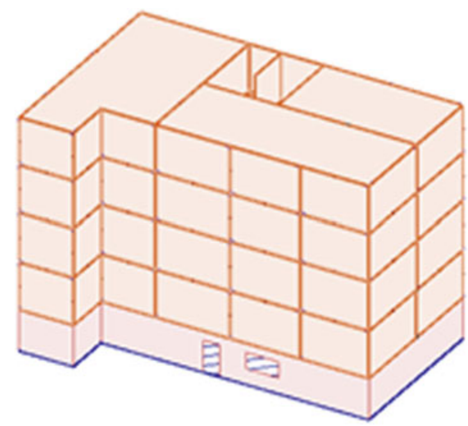

Fig. 53.3 3D structural finite element model for the multi-storey industrialized timber structure with CLT shear walls—model 2

53.3.2 Life Cycle Assessment

53.3.2.1 Definition of Goal and Scope

A four-storey industrialized timber structure residential building is identified for the case study. Accordingly, "The delivery of comfortable living area for its residents for the duration of 100 years, in a four-story residential building with 8 apartments having an area of 1066 m^2 located in Jönköping" is defined as the functional unit. The number and size of structural members as per the design drawings and plans will be identified. Inventory will be detailed for the building shell and main construction options. Foundations will not be included in this study. The residential building will be analyzed for the 22 sustainability criteria that cover their environmental, structural safety, economical and serviceability footprints as shown in Fig. 53.4.

53.3.2.2 Life Cycle Inventory Analysis

LCI analysis is a record of input and output data of the examined system to evaluate the environmental significance of potential impacts [18]. The boundary of the system is defined, and a flow model of inputs and outputs is determined to develop the inventory. An LCI which will provide information about all inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved in the study will be the result of the inventory. IVL Svenska Miljöinstitutet (Swedish Environmental Institute)-Miljöstatus för Byggnader (Swedish system for environmental auditing and assessment of buildings) and Anavitor software will be used for environmental inventory analysis of the building in the city of Jönköping.

53.3.2.3 ANP Model for LCC in Industrialized Timber Construction

ANP can be applied to choose from options or rate a restrained number of factors by means of their relative importance values. In this study, ANP is used to find the relative importance weights of sustainability parameters in assessing the

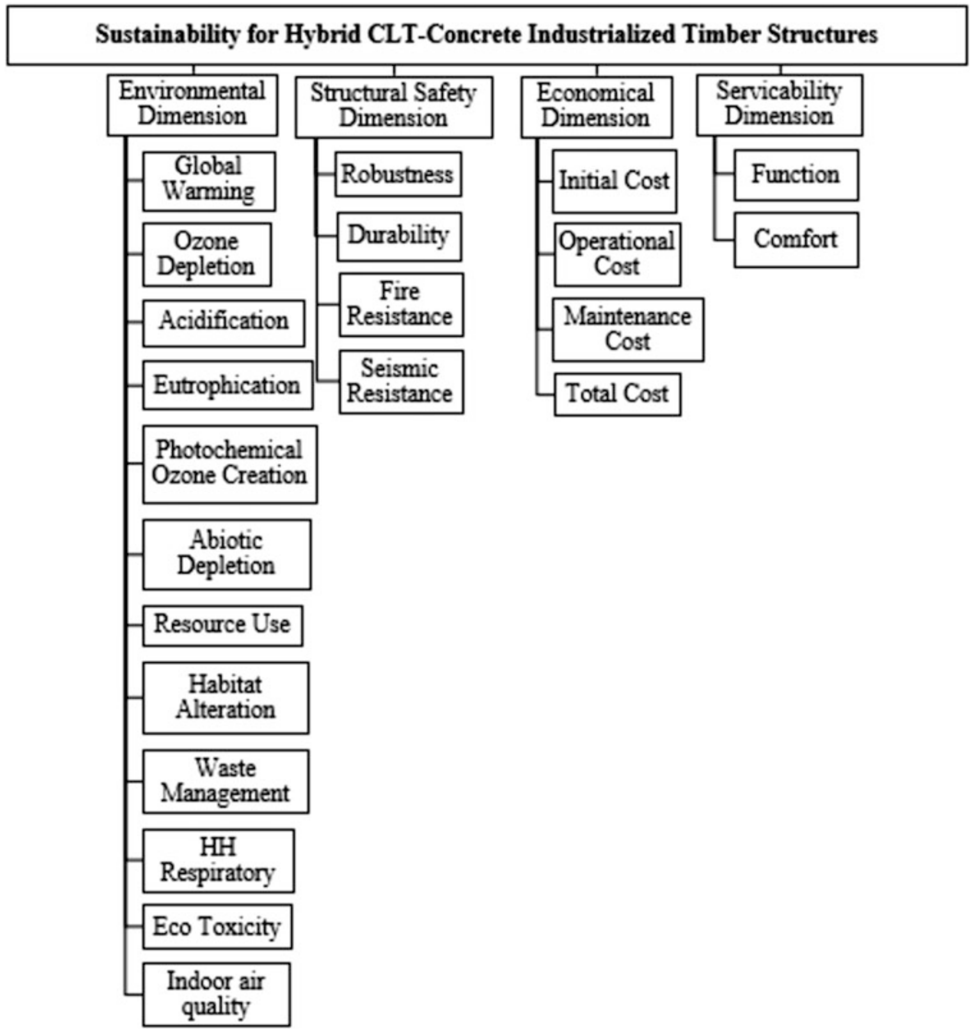

Fig. 53.4 Sustainability factors for hybrid CLT-concrete industrialized timber structures

performance of industrialized timber construction. The procedure undertaken in this research study to form and implement the ANP model is as follows: (1) the identification and categorization of sustainability parameters: a systematic literature review and the formation of a "sustainability breakdown structure" by classifying and determining sustainability parameters based on expert views, (2) the formation of a limit super matrix by developing an ANP model using the Super Decisions software, making pair-wise comparisons of the sustainability parameters and sustainability categories followed by the estimation of eigen vectors and the consistency ratio to form the matrix to enable expert decision makers to make pair-wise comparisons using Saaty's scale, and prioritizing sustainability parameters and their categories, (3) sustainability factors are identified according to a standard list of parameters based on relevant literature studies, documents and records as well as interviews and focus groups in which all possible parameters are discussed. In this study, the sustainability factors confronted in industrialized timber construction are obtained from an extensive literature analysis, as presented in Fig. 53.4.

53.3.2.4 Environmental Impact Assessment

The sustainability framework comprises twelve environmental impact groups as illustrated in Fig. 53.4. The life cycle environmental impact assessment is based on IVL Svenska Miljöinstitutet (Swedish Environmental Institute)-Miljöstatus för Byggnader (Swedish system for environmental auditing and assessment of buildings). All these criteria will be assessed by using the LCA performed by Anavitor Software. The flowchart of Anavitor LCA and LCC is presented in Fig. 53.5.

53.3.2.5 Economic Impact Assessment

LCC analysis considers the total cost of the building project by design and construction, operation and maintenance, and end of life costs of demolition and recycling/reuse of building materials. 5D BIM-LCC workflow starts from the process of

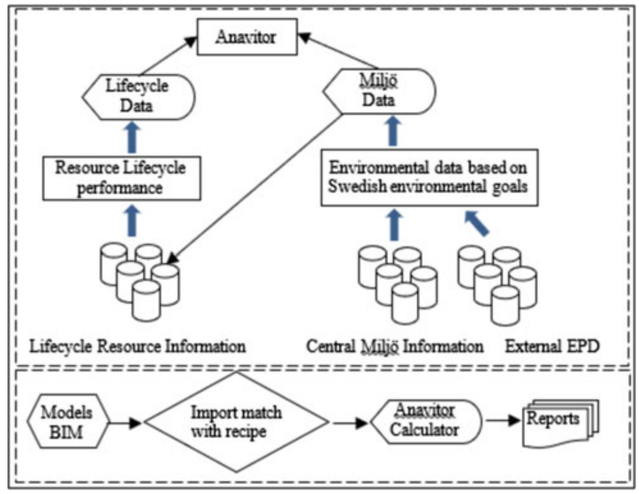

Fig. 53.5 Flowchart of Anavitor LCA and LCC

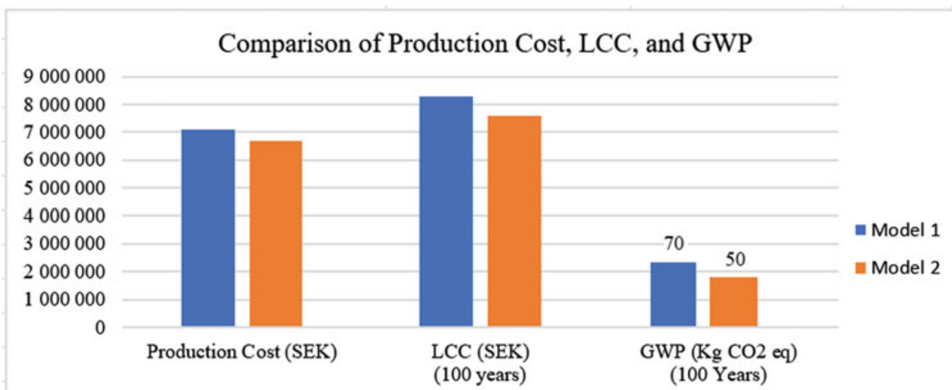

Fig. 53.6 Comparison of production costs, LCC, and GWP for model 1 and model 2

importing 3D BIM models. Based on the 3D models and related information, 5D simulation is conducted in the simulation program. Thereafter the simulation results are generated in excel spreadsheet as the available format. Then LCA applications import this excel spreadsheet, conducting LCA and generate assessment results. Cost drivers of a product is identified by Anavitor software to compare and evaluate alternatives related with a process or flow throughout the life cycle. The interpretation phase involves the integrated assessment of the LCA and LCC results to visualize the economic and environmental performances graphically presented in combined arrangement and the trade-offs between environmental and financial cost turns into clearer to the user for the decision-making process. Comparison of Production Costs (cost of land and foundation are excluded), LCC, and GWP for Model 1 and Model 2 is presented in Fig. 53.6. Afterwards, a sensitivity analysis is performed to test the validity of the ranking of the sustainability factors (i.e. Global Warming Potential-GWP, Eutrophication Potential-EP, Acidification Potential-AP, Photochemical Ozone Creation Potential-POCP) based on subjective judgements and to reduce the ambiguity related with changes in expert's experiences. The decision-making process is finalized by selecting the appropriate option.

53.4 Discussion

Increasing the use of EWPs and constructing industrialized timber structures can contribute to a more emission-efficient production of construction materials substituting for carbon and energy intensive concrete and steel-based building constructions and reducing the climate change impact [14, 36]. Currently, the LCA tool is used to calculate the environmental impact of manufactured products and systems from the "cradle to the grave". LCC is the result of an economic analysis where total costs and revenues for a system or product are compiled over its useful life [17]. However, for both LCA and LCC, there is a need to develop more robust and standardized analyzes. One tool for this is a BIM based LCC solution where LCC is integrated into the 5D BIM process by embedding an LCC calculation model structure within an existing 5D BIM technology [17]. The rapid development within BIM constantly offers new opportunities for analyzes and simulations, where more and more aspects can be analyzed and checked earlier in the construction projects. Another method that will be used is multi-objective optimization to enhance dynamic performance of the floor systems. Both weight and vibration levels used as objective functions for capturing pareto front and hence optimal design configurations regarding dynamic performances of the floor systems. ANP is a MCA to analyze complex decision-making problems using a systematic approach and make detailed analysis of priorities and interdependencies between clusters' elements. Currently, there are no (or limited) opportunities for the decision maker to ensure that the delivered building will meet both environmental and cost requirements. The reasons are that, in particular, there is need of (1) reliable and robust LCA and LCC during the design and (2) integration of various analysis and simulations during the design process. The integration of MCA with LCA-LCC could be a practical solution to facilitate interpretation of results and to aid decision-making for analyzing the environmental impact of products and costs throughout their life cycle [7]. MCA can enrich LCA-LCC outcomes by providing studied methods to assess trade-offs mainly because it allows a broader view of different aspects [26].

53.5 Conclusions

This paper outlines a framework of multi-criteria and multi-objective based approach for the integration of LCA and LCC in a multi-storey industrialized timber structure. Two Building Information Modelling (BIM)-based 3D structural models based on different horizontal stabilization and floor systems is analyzed to reduce both climate impact, material and production costs and enhance structural dynamic response of the floor system. Moreover, sensitivity of the optimal design is analyzed to validate the design. The multi-objective and multi-criteria based LCA-LCC framework analyzing the environmental, economic, and dynamic performances will support decision making for different design in the early phases of a project, where various alternatives can be created and evaluated. The proposed integrated model may become a promising tool for the building designers and decision makers in industrialized timber construction.

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References

1. Anastaselos, D., Giama, E., Papadopoulos, A.M.: An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. Energy Build. **41**(11), 1165–1171 (2009)
2. Bierer, A., Götze, U., Meynerts, L., Sygulla, R.: Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. J. Clean. Prod. **108**, 1289–1301 (2015)
3. British Standards Institute: Standardized Method of Life Cycle Costing for Construction Procurement BS EN ISO 15686-5, United Kingdom (2008)
4. Buchanan, A.H., Levine, S.B.: Wood-based building materials and atmospheric carbon emissions. Environ. Sci. Policy **2**(6), 427–437 (1999)
5. Coelho, A.C., Lopes, A., Branco, J.M., Gervásio, H.: Comparative Life-Cycle Assessment of a Single-Family House: Light Steel Frame and Timber Frame, https://repositorium.sdum.uminho.pt/bitstream/1822/20801/2/Ecowood_paper.pdf
6. De Felice, F., Petrillo, A.: Multicriteria approach for process modelling in strategic environmental management planning. Int. J. Simul. Process Model. **8**(1), 6–16 (2013)
7. De Souza, R.G., Clímaco, J.C.N., Sant'Anna, A.P. Rocha, T.B., do Valle, R.A., Quelhas O.L.G.:Sustainability assessment and prioritization of e-waste management options in Brazil. Waste Manage. **57**, 46–56 (2016)
8. Deniz, G.O.: An analytic network process (ANP) model to examine LEED-certified buildings' operational performance. Built Environ. Proj. Asset Manage. **7**(4), 366–376 (2017)
9. Ding, G.K.C.: Developing a multi-criteria approach for the measurement of sustainable performance. Building Res. Inf. **33**(1), 3–16 (2005)
10. Flanagan, R., Jewell, C.: Whole Life Appraisal for Construction. Blackwell, Oxford (2005)
11. Gu, L., Lin, B., Zhu, Y., Gu, D., Huang, M., Gai, J.: Integrated assessment method for building life cycle environmental and economic performance. Build. Simul. **1**(2), 169–77 (2008)
12. Hamdy, M., Hasan, A., Siren, K.: A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy Build. **56**, 189–203 (2013)
13. Heijungs, R., Settanni, E., Guinée, J.: Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. Int. J. Life Cycle Assess. **18**(9), 1722–1733 (2013)
14. Hildebrandt, J., Hagemann N., Thränac, D.: The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. Sustain. Cities Soc. **34**, 405–418 (2017)

15. Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M.: Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ. Impact Assess. Rev. **48**, 27–33 (2014)
16. International Organization for Standardization, Standard 14040: Environmental management—Life cycle assessment: Principles and Framework (2006)
17. Kehily, D., Underwood, J.: Embedding life cycle costing in 5D BIM. J. Inf. Technol. Constr. **22**, 145–167 (2017)
18. Kovacic, I., Reisinger, J., Honic, M.: Life cycle assessment of embodied and operational energy for a passive housing block in Austria. Renew. Sustain. Energy Rev. **82**, 1774–1786 (2018)
19. Kuzman, K.M., Sandberg, D.: Comparison of timber-house technologies and initiatives supporting use of timber in Slovenia and in Sweden—the state of the art. iForest **10**, 930–938 (2017)
20. Lam, J.S.L., Laib, K.H.: Developing environmental sustainability by ANP-QFD approach: the case of shipping operations. J. Clean. Prod. **105**, 275–284 (2015)
21. Lee, J.W., Kim, S.H.: Using analytic network process and goal programming for interdependent information system project selection. Comput. Oper. Res. **27**(4), 367–382 (2000)
22. Lenzen, M.: Errors in conventional and input-output-based life-cycle inventories. Ind. Ecol. **4**(4), 127–148 (2000)
23. Leontief, W.: Environmental repercussions and the economic structure: an input-output approach. Rev. Econ. Stat. **52**, 262–271 (1970)
24. Levander, E., Stehn, L.: Addressing uncertainties about timber housing by whole life costing. In: Proceedings of 4th Nordic Conference on Construction Economics and Organisation: Development Processes in Construction Management, pp. 249–258 (2007)
25. Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., Sonnemann, G.: Critical review of life cycle assessment (LCA) for the built environment at the neighbourhood scale. Build. Environ. **93**, 165–178 (2015)
26. Manzardo, A., Ren, J., Piantella, A., Mazzi, A., Fedele, A., Scipioni, A.: Integration of water footprint accounting and costs for optimal chemical pulp supply mix in paper industry. J. Clean. Prod. 72, 167–173 (2014).
27. Menzies, G.F., Turan, S., Banfill, P.F.: Life-cycle assessment and embodied energy: a review. Proc. Inst. Civ. Eng. Constr. **160**(4), 135–144 (2007)
28. Petrillo, A., De Felice, F., Jannelli, E., Autorino, C., Minutillo, M., Lavadera, A.L.: Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system. Renew. Energy **95**, 337–355 (2016)
29. Promentilla, M.A.B., Tapia, J.F.D., Arcilla, C.A., Dugosa, N.P., Gaspillo, P.D., Roces, S., Tan, R.R.: Interdependent ranking of sources and sinks in CCS systems using the analytic network process. Environ. Model Softw. **50**, 21–24 (2013)
30. Saaty, T.L.: Decision Making with Dependence and Feedback: The Analytic Network Process. RWS Publications, Pittsburgh (2001)
31. Sadiq, R., Khan, F.I.: An integrated approach for risk-based life cycle assessment and multi-criteria decision-making: selection, design and evaluation of cleaner and greener processes. Bus. Process Manage. J. **12**(6), 770–792 (2006)
32. Sathre, R., O'Connor, J.: Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ. Sci. Policy **13**(2), 104–114 (2010)
33. Savino, M.M., Manzini, R., Della, S.V., Accorsi, R.: A new model for environmental and economic evaluation of renewable energy systems: the case of wind turbines. Appl. Energy **189**, 739–752 (2017)
34. Schmidt, M., Crawford, R.H.: Developing an integrated framework for assessing the life cycle greenhouse gas emissions and life cycle cost of buildings. Procedia Eng. **196**(988–995), 1877–7058 (2017)
35. Senante, M., Gómez, T., Caballero, R., Hernández-Sancho, F., Ramón Sala-Garrido, R.: Assessment of wastewater treatment alternatives for small communities: an analytic network process approach. Sci. Total Environ. **532**, 676–687 (2015)
36. Skullestad, J.L., Bohne, R.A., Lohne, J.: High-rise timber buildings as a climate change mitigation measure - a comparative lca of structural system alternatives. Energy Procedia **96**, 112–123 (2016)
37. Theißen, S., Spinler, S.: Strategic analysis of manufacturer-supplier partnerships: an ANP model for collaborative CO_2 reduction management. Eur. J. Oper. Res. **233**, 383–397 (2014)
38. Treloar, G.J., Love, P.E., Holt, G.D.: Using national input/output data for embodied energy analysis of individual residential buildings. Constr. Manage. Econ. **19**(1), 49–61 (2001)
39. Tukker, A.: Life cycle assessment as a tool in environmental impact assessment. Environ. Impact Assess. Rev. **20**, 435–456 (2000)
40. Weckendorf, J., Zhang, B., Kermani, A., Reid, D.: Dynamic Response of Timber Floors. In: 2nd PRoBE 2005 Conference, Postgraduate Researchers of the Built and Natural Environment, Glasgow, UK, 1617 November 2005
41. Wudhikarn, R., Chakpitak, N., Neubert, G.: A framework for new product selection decision using analytic network process and knowledge management. Adv. Mater. Res. **538–541**, 3098–3105 (2012)

Collective Decision-Making with 4D BIM: Collaboration Group Persona Study

54

Veronika Bolshakova, Annie Guerriero, Hugo Carvalho, and Gilles Halin

Abstract

4D BIM assures more detailed costs and error control, whilst also improving scheduling and coordination. It relies on interoperability and high levels of collaboration, which have increased the value of collective competencies. In addition to the competencies, the collaboration group internal influences and subordination must be considered as well. While the knowledge and competencies of each and every individual team member are important, BIM allows the team to use the entire set of collective knowledge, skills and competencies, which are the key feature for advanced digital management of the AEC project. Such management requires a successful implementation and efficient use of 4D or nD BIM. This study proposes to summarize collaboration personae of AEC project collaborative groups, and to associate the collective knowledge and competencies to 4D BIM uses. Further, it will be completed with interviews on current 4D practices with BIM professionals. Moreover, through this research, we continue to progress towards a new 4D collective decision-making support proposition.

Keywords

4D BIM • 4D BIM uses • Decision-making • Digital collaboration • Collaboration persona • Collaboration group • Collective decision support

54.1 Introduction

AEC industry transformation, influenced by the latest information and communication technologies, is due to a major shift of this economic sector towards the new digital globalized economy [1]. The changes brought in the last decades by digital tools and by the progressive adoption of Building Information Modeling/Management (BIM) have had an impact on the common practices of design, management and construction of projects, and subsequently, have brought in new business models [2]. The advanced digital project management is one of the key features for an effective BIM project management [3]. Over the project development, collective competencies are implemented into both the project design development and

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value engineering processes [4]. In the literature and in practice 4D BIM is mostly used as a process visualization support [5], whereas we focus on 4D BIM uses for decision-making [6].

Decision-making sessions unite the stakeholders' competencies to benefit from better communication and from collective intelligence as a decision assistance tools. But how does a group organize decision-making? Which competencies are required to efficiently support 4D? How should the collaboration persona adjust to 4D BIM uses?

Firstly, this paper describes a methodology of the current research program. The next part introduces collaboration and decision-making in the scope of the BIM era, in order to understand collaboration types and their place in the project workflow. The final part introduces 4D BIM uses, and proposes a collaboration personae summary study.

54.2 4D Collective Decision-Making Support Development Steps

4D BIM offers more detailed cost and error control, whilst also improving scheduling and coordination. It relies on interoperability and high levels of collaboration, which have increased the value of collective competencies. Thus it is important to understand which competences are relevant for which decisions, and how should the collective decision-making be organized in correlation with project phases, scale, contracts, etc.

54.2.1 4D Collab Project Research Stages

This paper is a part of research conducted for the 4D Collab (http://www.4dcollab-project.eu) international project which aims to develop a proposition of decision-making support configuration and collaboration scenarios for 4D BIM. Figure 54.1 shows the research stages, where firstly, a series of experiments with existing digital synchronous collaboration tools ("Shariiing" software https://www.shariiing.com by Immersion and multi-touch screens table and wall) have already been conducted.

The experiment scenario required AEC professionals to collaborate and to resolve some design development and value engineering tasks with the assistance of 3D models, and it summarizes the limits of present collaboration solutions and the users demand for more natural and AEC customized interactions [7]. As the next stage, this paper summarizes collaboration groups and also personae study and 4D BIM uses, which will be evaluated and improved with the further research (Sect. 54.4.4). Subsequently, a decision-making tools evaluation and specification will complete the tool proposition. Finally, AEC professionals decision-making sessions with the use of 4D, a touch table and Shariiing software, altered to 4D interactions, conclude the research.

54.2.2 Digital Interactive Interfaces for 4D BIM Collaborative Context

Digital project development and management rely on specific technical tools, with BIM the tools are in the core of a sociotechnical system, and they are operated by social elements: synchronous collaboration, coordinated work practices, institutional and cultural frameworks [8, 9]. Various systems provide users with necessary options and interactions. Yet, there is a gap in solutions for synchronous co-located collaboration and decision-making. Thus, we propose to develop a multi-user digital documents interaction interface, which will complete a digital continuity of project documents at decision-making sessions, with an aim to avoid printing documents and primarily to keep the same BIM model in the center

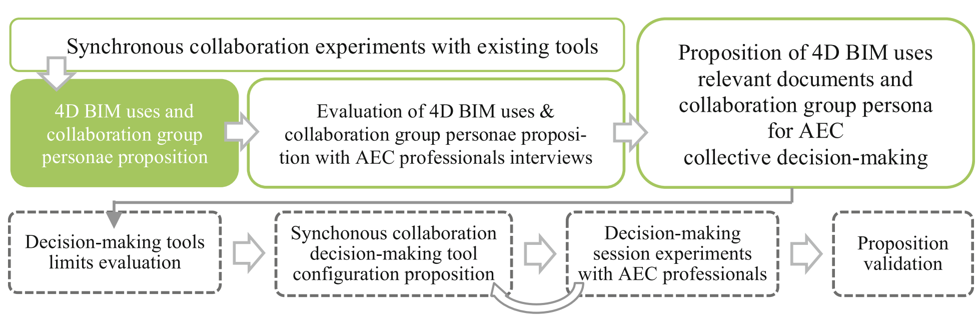

Fig. 54.1 Summary of methodology steps for decision-making support proposition

of discussions as in the center of design development. The solution aims to avoid incorrect interpretation and losses of information. For users' comfort it is important to offer the best usability and relevant interactions.

Natural user interfaces (NUI) offer the ease of access and low appropriation time with a tool [10], therefore we propose to implement a multi-touch collaborative table and wall within a NUI as a technical support for decision-making. The interface fosters 4D BIM uses with project documents convergence with the ease of interactions.

54.3 AEC Project Collaboration, Decision-Making and 4D BIM Uses

Any project development includes decision-making activities, with a collaborative BIM model and a range of project participants' competencies (e.g. knowledge, skills, experience) assisting decision-making. This part introduces AEC decision-making essentials with an objective to outline potential 4D BIM collaboration process requirements.

54.3.1 AEC Project Collaboration

AEC projects are highly dependent on local conditions, they usually involve stakeholders who have not been working together before [11]. The project team is almost always temporary, and has specific tasks and responsibilities [12], these factors do not foster stakeholders to integrate completely into the BIM collaboration process and network.

Naturally, different ways of working together are implied in project development, with networking at a basic level, followed by coordination, then cooperation and the highest level is collaboration, where actors have information exchanges, alternate activities, share resources and have a mutual benefit (collaborative continuum) [13]. In addition, "the integration" is a concept where the parts are no longer apparent. A custom collaborative BIM decision framework implementation, suggested by Gu and London [14], offers to provide the actors with the understanding and implementations of BIM technologies. Even if BIM relies on technology, as a core of BIM socio-technical system, collaboration still stays a human activity. Collaboration can be synchronous or asynchronous, collocated or distant. Collocated synchronous project sessions are the main subject of our study on collective decision-making with 4D.

54.3.2 AEC Project Decision-Making

According to Hughes and Murdoch, an AEC project starts and ends with decision points, the decision classes are: Policy, Strategic, Tactical and Operational [15]. Also any project requires various types of decision roles systems summarized in Table 54.1, where three systems have various action types involved. Depending on project lifecycle, and on decision types there will be relevant decision-making constitutes involved.

54.3.3 AEC Project Lifecycle and 4D BIM Uses

The first concepts of time management are usually introduced even earlier than the design development starts, and with the design progress the time management evolves from a simple programming, to a planning and then to a detailed scheduling [16]. This evolution also involves the BIM model development with an increase of level of detail (LOD) (Fig. 54.2). The phase of Operation and Maintenance does not enter into the scope of current study due to the specifics and phases' relevance mostly to activity management.

Table 54.1 Decision roles systems (by Hughes and Murdoch [15])

Operating	Control	Managing
Operating	Monitoring	Coordinating
Cooperating	Supervising	Directing
Advising	Resourcing	Recommending
Receiving		Approving

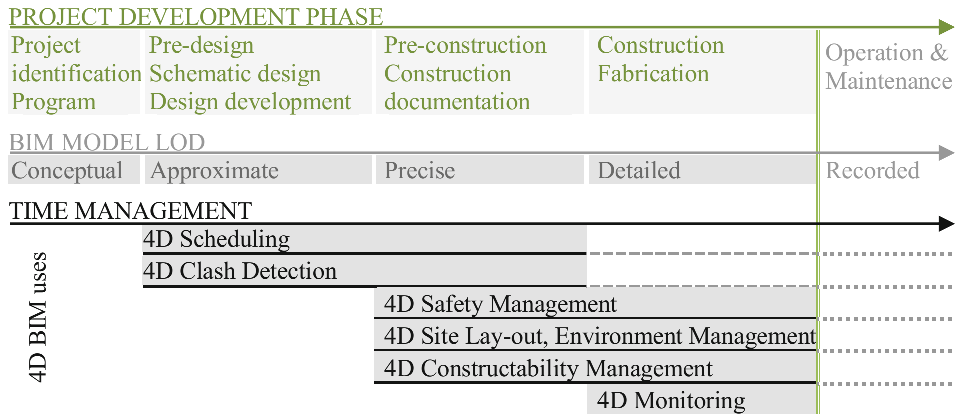

Fig. 54.2 Project phases and model LOD with 4D BIM use potential introduction

When the "3D" dimension of the enriched virtual model of a project is completed with the notion of "Time", introduced as the "fourth dimension", the information from time management (time dimension and related data) enriches the 3D Model (x, y, z geometry and related spatial model elements data) and creates a 4D model with 4D relationships of attending data. Thus 4D is a model, but also a simulation, as "conceptually 4D CAD represents a type of graphic simulation of a process" [17]. One of 4D major benefits is information accessibility and clear visualization—all actors have access to a 3D model and an attached schedule, moreover they can access to simulations and analysis.

Kreider and Messner studied BIM uses and proposed a definition that: "BIM Use: A method or strategy of applying Building Information Modeling during a facility's lifecycle to achieve one or more specific objectives." [18]. Based on this uses study Guerriero et al. [6] summarized 4D BIM uses: 4D Scheduling, 4D Clash Detection, 4D Safety Management, 4D Site Lay-out and Environment Management, 4D Constructability Management, 4D Monitoring and 4D Visual communication is core use. These uses can be introduced into the project on specific phases (Fig. 54.2).

For example it is possible to forecast construction phases and sequencing as 4D Scheduling, once the first "3D" and "time" concepts are present, when the construction is started the scheduling is followed by 4D management, monitoring. All the uses involve stakeholders' expertise and collaboration. Digital documents, such as 4D BIM simulations, foster new collaborative project workflow implementation and develop new requirements for synchronous collaborative decision-making methods and supports (e.g. tools, documents, interactions).

54.4 Designing a Collective Decision-Making Support for 4D BIM

54.4.1 AEC Project Collaboration Groups and Decision-Making

BIM engages the collective decision-making for design development or value engineering. The project stakeholders have many roles, influences and interactions [19] (Responsible Validator, Responsible Coordinator, Participant Production, Participant Expert, Participant Reader [20]), but the current scope focuses on a group and not individuals.

Table 54.2 summarizes a proposition of main AEC project collaboration groups. The summary is general, it may vary from a project type, stakeholders contracts, etc. The groups are united by a General group's goal, which is related to a project development phase. The stakeholders collaborate on the project in various groups, carrying their project roles and bringing their expertise as a member of various groups in order to complete the goals. Group collaboration typology proposed by Matthews et al. [21], summarizes the types and their descriptions (personnel, work style, leadership), thus in the table below Group collaboration style proposes to apply the types to AEC project teams.

The proposed summary (Table 54.2) suggests that collaboration type and decision class are related. Project development starts with a client-supplier collaboration type, engages a stable deliverable oriented professional design team with a democratic leadership to produce a design and then a democratic Committee with a BIM manager brings an order and control to the design collaboration. From a Pre-construction phase the project teams become more dynamic with a designated leader, also they continue the decision order from Management to Operation and then Control.

For example, on an early stage of project development a Project program team establishes the program and project requirements, approves design production, thus this group will have a collaboration type: client supplier, with the same core

Table 54.2 Main characteristics, collaboration styles and decision-making classes study

Phases: program—design			Phases: pre-construction—construction					
Group main characteristics								
Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Group name								
Project program team	Project design team	Design process team	Pre-construction management team	Construction design team	Construction document management team	Construction team	Construction process team	Safety management team
Group members roles								
Client Architects Engineers	Architects Engineers	BIM manager Architects Engineers	Construction manager Architects Engineers Client	Contractors Architects Engineers	BIM manager Contractors Architects Engineers	Contractors Subcontractors	Construction manager Contractors Architects Engineers Client	Safety manager Construction manager Contractors Architects Engineers Client
General goal								
Conceive the project program and requirements, approve design production	Design the project and the project's BIM model	Control and manage the project design collaboration and BIM models quality	Prepare, coordinate and survey the project pre-construction phase	Design the project construction documentation	Manage the project construction documents and efficient teams collaboration	Construct the quality project by the program and requirements	Prepare, coordinate and survey the project construction phase	Manage the project construction site security over the construction process
Group collaboration style								
Collaboration type								
Client-supplier	Stable team	Committee	Client-supplier	Dynamic team	Committee	Dynamic team	Dynamic team	Dynamic team
Personnel								
Stable	Stable	Stable	Dynamic	Dynamic	Stable	Dynamic	Dynamic	Dynamic
Work style								
Communication focused	Pooling and co-creation	Pooling and co-creation	Communication focused	Pooling and co-creation	Pooling and co-creation	Pooling and co-creation	Communication focused	Communication focused
Leadership								
Designated leaders	Democratic	Democratic	Designated leaders	Designated leaders	Democratic	Designated leaders	Designated leaders	Designated leaders
Group decision-making class								
Decision class								
Policy	Strategic	Tactical	Policy	Strategic	Tactical	Operational	Tactical	Tactical
Decision system role: inside system role								
Management: approving	Operation: co-operating	Control: Supervising	Management: coordinating	Operation: co-operating	Control: supervising	Operation: co-operating	Control: supervising	Control: supervising

members of the team focusing on communication, with a designated leader. This group will make Policy class decisions, with a focus on management system roles, however other roles are possible as well, as the secondary ones. In addition, all the collaboration groups are the long life length groups, have an objective as a constant element and a motivation factor, except the BIM project team with the shared interest as a motivation. Also, most of the groups contain more than three members. However, for a BIM project team BIM is a core element, thus members receive guidance and coordination from BIM management. Moreover the teams must have technology and BIM basic skills and knowledge.

54.4.2 4D BIM Uses AEC Project Collaboration Groups

Collaboration groups may imply various 4D BIM uses according to the stage of progress of the project, as illustrated in Fig. 54.1. Thus the proposed Project design team and Design process team on a design phase may use 4D Scheduling and Clash detection.

Further, these uses are required for Pre-construction management, Construction design and Construction document management teams, who also benefit from 4D Safety, Site lay-out, Environment, Constructability management. The groups encompass a large specter of 4D uses since the project model is well developed and there is a high concentration of management and coordination tasks on a pre-construction phase.

The Safety management team mostly benefits from 4D Safety management, however, keeps the connection with other 4D uses. For a Construction process team the 4D Monitoring and Construction management are the main uses. The Construction team may benefit from 4D Visualization for a better communication. The relevant uses for collaboration groups will be defined within the series of interviews (54.4.4) and 4D Collab research project experiments and survey results.

54.4.3 Collaboration Personas Approach

When project stakeholders collaborate in groups, the knowledge and competencies of every individual team member are important. Furthermore, BIM allows the team to use the entire set of collective knowledge, skills and competencies as parts of collective intelligence, which is the key feature for advanced digital management of the project.

In order to describe a project group collective activity, we propose to implement a collaboration persona (CP) approach [22], which is derived from the original user persona method, also called Individual Persona. CP describes a new type of persona which focuses on group goals and needs, instead of personal needs, and includes collaborative work aspects. According to Judge et al., "[c]ollaboration personae are empirically derived descriptions of hypothetical groups of people with specific qualities, goals and needs." [22]. In addition to the competencies, the collaboration group internal influences and subordination must be considered as well, because "[c]ollaboration personas include individual personas (playing the roles), who enact scenarios at different phases of the collaboration" [23]. In AEC project case the phases relate to development phases.

Matthews et al. [21] developed a CP based on collaboration types: dynamic project team, stable project team, customer-supplier relationship, committee, community and professional relationship. Every type is described with dimensions: goals (group tasks and motivation), group members (if the members are stable or dynamic), work style and leadership style (designated or democratic), etc. By the approach, CP are built from real work observations and guided interviews with a focus on group members (actors) experiences. CP aims to describe the needs and collaboration of group, interactions among actors and their goals. CP approach allows equipment designers to consider different actor roles throughout the collaboration process, and to be more focused on the group needs and interactions, in addition to the common user persona benefits [24].

54.4.4 Design Methodology of Collaboration Personae Proposition

This study suggests CP approach within an alteration to BIM specifics, and with a correlation to different problems encountered by the professionals' workgroups. Further research will run a series of BIM familiar professionals interviews, which will gather a real practices vision on the relevance of personae proposition and of specific 4D uses.

Methods: the non-directive interviews will gather personal experiences of participants about collaborative group work, and will focus on following themes: Who must be participating at the collaboration? Who participates on a collaboration in relevance to the project phase? Who participates in relevance to the 4D BIM use? Who is the role and responsibility of every member of the collaboration group and his contribution to the collective intelligence? How does a collaboration group organize decision-making? How are the collaboration sessions managed and held? Which information on the project was necessary for a decision-making and which competences? How does 4D BIM influence a decision-making at collaboration sessions?

The collected data will be studied with thematic analysis which is a qualitative method for analyzing and identifying themes or patterns [25]. The data sets gathered from the interviews will be classified, according to the research question, into the following themes: *group and member goals; members and roles; group tasks; group work style; current 4D BIM collaboration tools and methods gaps*. In addition, to test and to improve the CP, we conduct a group interview with persona experienced designers.

Population: the interviews participants will be BIM experienced AEC project professionals: architects, structure, civic and MEP engineers, construction firms, construction managers, BIM mangers, safety, site and quantity managers and clients. The interviews provide a complementary information about the collaboration and project development process, also they will test our proposition relevance, additionally, they allow us to adjust the model of Matthews to the complex 4D BIM collaboration situations.

54.4.5 4D BIM Uses and Collaboration Persona Study

With this research we continue to progress towards a new collective decision-making support proposition, which will be adapted to AEC specific needs and 4D BIM uses. Thus we need to study the support users and their needs. To study AEC collaboration groups we propose to apply the CP approach, since the single user persona description does not encompass collaborative aspects. The study proposition is based on common practices of project development and BIM implementation guides and protocols. The CP example for one of stakeholders group synopsizes main persona dimensions [21]:

Context: a large public building project “A-project” is in development with BIM.

Collaboration Persona Name: “A-project” Pre-construction management team.

General goal: Prepare, coordinate and survey the project pre-construction phase.

Roles: Client, Construction manager, Architects, Engineers (sometimes BIM manager, contractors, construction site, safety, quantities managers).

Project phase: Pre-construction, construction.

Work style: based on communication with a BIM model is in the core of collaboration, it evolves with the project, being more of a client-designers dialogue in the beginning, and changing to interdisciplinary collaboration.

Tasks: Identification of project limits; Establish the basis and progressive development of time management; Offer order to the project development process; Assure project deadlines and the basis for construction monitoring; etc.

Needs: strict aims and objectives of the program, an access to a digital workflow, work protocol, BIM methodology, technological core, interactions system, etc.

Skills and knowledge: related to roles, basic and advanced BIM and technology understanding, and collective intelligence and professional experience.

Dependences: Inside the group a Design team of architects and engineers supports the design basis of work and decision supports, and the construction manager is in strong dialogue with them, the client has a strong interaction with design team.

Decision-making: Policy and Strategic classes, focused on management: co-operating.

4D BIM place: 4D BIM model with a detailed schedule information, as a collaboration and decision-making support for 4D Scheduling, Clash Detection, Safety Management, Constructability Management, Site Lay-out and Environment Management.

Every 4D BIM use requires specific decisions, in addition a relevant digital collaboration support for project documents must assist as a decision-making session equipment with relevant and easy interactions, and provide the digital documents continuum.

54.5 Conclusion

4D becomes a part of common practices for the professionals who have adopted high BIM and collaboration levels. Collaboration and precise project management are very important for the complex projects. The design, time, BIM process and construction managements play their role in development, and also require a collective decision-making, with collective skills and competences brought in by project stakeholders.

There are many collaboration groups on a construction project, and in correlation with the project goals we summarize general collaboration groups descriptions, identify their collaboration type and decision-making class.

Groups are highly dependent on a project, however, with a collaboration persona approach for such a group description it is possible to design a new configuration for the methodology and equipment which will be relevant for a collaborative decision-making scenario on BIM projects, and for 4D BIM uses in particular. The new configuration aims to provide an efficient collocated synchronous digital collaboration and preserve the digital continuum. Thus, it is important to understand how the project groups collaborate and interact at decision-making to optimize the configuration.

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References

1. Weippert, A., Kajewski, S.L.: AEC industry culture: a need for change. In: CIB World Building Congress 2004: Building for the Future. Toronto, Canada (2004)
2. Schultz, A., Essiet, M., Souza, D., Kapogiannis, G.: The Economics of BIM and added value of BIM to construction sector and society. Int. Counc. Res. Innov. Build, Constr (2013)
3. Jadhav, S.: Application of building information modeling in construction projects—a critical review. Int. J. Eng. Res., 26–31 (2016)
4. Tory, M., Staub-French, S., Po, B.A., Wu, F.: Physical and digital artifact-mediated coordination in building design. Comput. Support. Coop. Work **17**, 311–351 (2008)
5. Boton, C., Kubicki, S., Halin, G.: Designing adapted visualization for collaborative 4D applications. Autom. Constr. **36**, 152–167 (2013)
6. Guerriero, A., Kubicki, S., Berroir, F., Lemaire, C.: BIM-Enhanced Collaborative Smart Technologies for LEAN Construction Processes, pp. 1063–1070 (2017)
7. Bolshakova, V., Halin, G., Humbert, P., Boton, C.: Digital synchronous collaboration workspace and 3D interactions for an AEC project. Decis. Mak. Scenario Eval. CDVE **2017**, 168–176 (2017)
8. Sackey, E.: A Sociotechnical Systems Analysis of Building Information Modelling (STSaBIM) Implementation in Construction Organisations, pp. 12–22 (2014)
9. WPS Group and Kaoris Future: Truths about BIM. (2018)
10. Steinberg, G.: Natural User Interfaces. Human-Computer Interact. INTERACT 2011.1 (2012)
11. McGraw Hill Construction: SmartMarket Report The Business Value of BIM for Construction in Major Global Markets: How Contractors Around the World Are Driving Innovation With Building Information Modeling, Bedford (2014)
12. Kubicki, S.: Assister la coordination flexible de l'activité de construction de bâtiments. Une approche par les modèles pour la proposition d'outils de visualisation du contexte de coopération. UL, Nancy, France (2006)
13. Himmelman, A.T.: Collaboration for a change. Fourth Int. Conf. Multi-Organizational Partnerships Coop. Strategy. Oxford University, England. **11**, 2004 (July 8–10 1997)
14. Gu, N., London, K.: Understanding and facilitating BIM adoption in the AEC industry. Autom. Constr. **19**, 988–999 (2010)
15. Hughes, W., Murdoch, J.: Roles in Construction Projects: Analysis and Terminology. Construction Industry Publications, Birmingham (2001)
16. The Chartered Institute of Building: Guide to Good Practice in the Management of Time in Major Projects. Dynamic Time Modelling. Wiley-Blackwell, Hoboken, HJ, USA (2018)
17. McKinney, K., Kim, J., Fischer, M., Howard, C.: Interactive 4D-CAD. Proc. third Congr. Comput. Civ. Eng. **135**, 1261 (1996)
18. Kreider, R.G., Messner, J.I.: The Uses of BIM: Classifying and Selecting BIM Uses. The Pennsylvania State University, University Park, PA, USA (2013)
19. Halin, G., Hanser, D., Malcurat, O., Bignon, J.C.: A relational approach of cooperation in building design. In: 8th International Conference on Concurrent Enterprising, Rome, Italy (2002)
20. Bolshakova, V., Guerriero, A., Halin, G.: Identification of relevant project documents to 4D BIM uses for a synchronous collaborative decision support. In: Creative Construction Conference 2018. p. Accepted for Publication. Ljubljana, Slovenia (2018)
21. Matthews, T., Whittaker, S., Moran, T., Yuen, S.: Collaboration personas : a new approach to designing workplace collaboration tools. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 2247–2256 (2011)
22. Judge, T., Matthews, T., Whittaker, S.: Comparing collaboration and individual personas for the design and evaluation of collaboration software. In: Proceedings of 2012 ACM Annual Conference for Human Factors Computers System—CHI' 12, pp. 1997–2000 (2012)
23. Matthews, T., Whittaker, S., Moran, T., Yang, M.: Collaboration personas: A framework for understanding & designing collaborative workplace tools. In: Workshop Collective Intelligence in Organizations: Toward a Research Agenda at Computer Supported Cooperative Work (CSCW), pp. 582–595 (2010)
24. Bornet, C., Brangier, E.: The effects of personas on creative codesign of work equipment: an exploratory study in a real setting. CoDesign. **12**, 243–256 (2015)
25. Braun, V., Clarke, V.: Using thematic analysis in psychology. Qual. Res. Psychol. **3**, 77–101 (2006)

Post-occupancy Evaluation Parameters in Multi-objective Optimization–Based Design Process

55

Elie Daher, Sylvain Kubicki, and Annie Guerriero

Abstract

In the design process the main challenge of the designer is to generate an efficient project resulting from different objectives and associated criteria. These objectives are often conflicting and they are related to programmatic requirements, aesthetic, structural, and cost or energy performance. Multi-objective optimization (MOO) can guide the designer towards efficient design solutions. Parametric tools enable integrating MOO techniques and algorithms in 3D modeling environment. They allow the designers to take decisions during the design process. While the optimization tools are considering physical objectives (building energy, performance and daylighting, form generation, structural optimization …) the current applications often lack the evaluation of performance as perceived by occupants, e.g. based on post-occupancy evaluation studies. POE is defined as the evaluation of the building performance by users. Implementing POE in a parametric environment can improve the design and in particular the reorganization of an interior layout space design.

Keywords

Post-occupancy evaluation • Parametric modelling • Simulation • Decision support • Multi-objective optimization

55.1 Post-occupancy Evaluation Research

55.1.1 Definition and State of the Art

Post-occupancy evaluation (POE) is a diagnostic tool and system which allows facility managers to identify and evaluate critical aspects of building performance systematically. This system has been applied to identify problem areas in existing buildings, to test new building prototypes and to develop design guidance and criteria for future facilities [16]. Obviously technical evaluations of a building performance can be conducted, routinely. This can include structural testing, mechanical systems performance checks, lighting checks … However, the POE varies in that since it addresses issues that cannot be easily measured, such as occupant performance, worker satisfaction and productivity [8]. Indeed, users spend significant time in buildings for multiple reasons, and indoor conditions have an influence on their well-being. Poor indoor conditions can affect the productivity and health of the users. Many actors are involved in the life cycle and uses of the buildings, from different points of view and different interests: investors, owners, operators, and the end users occupying the facilities. Recently, different understandings of POE have emerged in the architectural field. These understandings or opinions suggest that POE should cover not only the observation and evaluation of critical aspect of a building but also POE should cover user satisfaction and the impact of the built environment [5]. POE draws on an extensive quantitative and qualitative toolkit: measurements and monitoring, on the one hand, and methods such as walk-throughs, observations and user satisfaction questionnaires on the other [10].

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POE carried out on a number of projects of a similar type allows for comparisons between these buildings and helps to highlight and develop their strengths, and addressing their weaknesses and points that need further consideration. However, POE is furthermore helpful to clients' parties in defining the significances and requirements for a new project based on the methodical evaluation of a similar existing facility or project, or even for a new organization of the interior layout of an existing building.

Generally, POE is conducted by using surveys or interviews. With buildings becoming more intelligent and responsive to varying conditions, and thanks to the advent of new technologies (easy-to-integrate wireless solutions), capturing facts inside a building via a set of sensors is being developing significantly today with a real-time data feedback [17]. Measurements of the indoor post-occupancy evaluation are carried out on a number of different factors. Moreover, these sensors make it possible to raise and control eight different categories: "(1) Electricity metering, (2) Gas metering, (3) Air temperature, (4) Mean radiant temperature (5) Indoor air velocity, (6) Relative humidity, (7) Indoor air quality, (8) Occupancy and daylight sensors [1]. However these data do not necessarily represents the feelings by the users and occupants. Sensor-based monitoring supplied to buildings can perform dual roles. First, sensor networks are part of building management systems (facility and energy management), and the second role is that sensors can be of a process intending the validation of the design intent [5].

55.1.2 Benefits of POE

Traditionally, the POE relies on three sources of information: occupants' feedback, bills and Metrics, and measurements and readings. After data collection and analysis, the outputs of the POE can be distinguished in three types of benefits [16].

- Short-term benefits: Identification of problems and solutions in facilities, improvement of space utilization, improvement of the occupant's attitude by their implication in the evaluation process.
- Medium-term benefits: Improvement of the capability of the building to address new change (e.g. organizational change) during its lifecycle, significant costs savings in the building process, etc.
- Long-term benefits: Improvement of building performance, improvement of standards and guidance for building design, etc.

Even if the importance of POE is largely recognized in the academic literature, currently the POE studies are not sufficiently deployed in the construction sector. Professionals are aware of the potential of this evaluation, especially architects that consider in the future that could be a standard mission in the architectural practice. This is an important perspective for the sustainability of building and the whole AECO -Architecture, Engineering, Construction and Operation sector [9]. However, this statement faces the following issues that delayed the POE implementation in the current practices [9, 3]: difficulty to deploy POE on every project, long process required for building quality improvement, high costs of the studies, impacts for professionals in case of negative evaluation of building, availability and heterogeneity of information sources about buildings, engagement of users at long term, uncertainty about the manner the feedback will be used, etc. Today, the digitalization in the AECO sector lets place to new prospects, but the process of POE is not fully supported.

55.1.3 POE and Digitalization

The use of IoT appears in the academic literature as another interesting perspective for POE, because it allows to easily collecting real-time data about the use of the building. Coates and al. [5] are amongst the first researchers that imagined connecting sensors and 3D model to improve the POE data collection. Motawa and al. [15] propose an ontological framework of energy-related information/knowledge which is connected with BIM in order to evaluate the use of energy inside a building with the aim of improving facility management, and occupants comfort based on the sensors data collection. Further, Autodesk Research with the project Dasher [12] has also contributed to this research field with Dasher 360,[1] which connects BIM and the sensors and provides real-time visualization. This type of dashboard contributes to

[1]https://dasher360.com.

refining the understanding of the occupants about how they are interacting with the building, and especially from the energy consumption point of view.

55.2 Parametric Modelling Design Approach

Computational tools are fundamentally shifting architectural design practice to another paradigm [11] and are more and more used in the design process and the generation of forms for contemporary architecture. They are offering new ways to design, evaluate, collaborate and manufacture architecture. Parametric and generative design, simulation, as well as Building Information Modelling, digital fabrication or 3D printing are disruptive technologies implies new practices of design. Computational tools have been developed to help the specialists in the decision making [13] and to accelerate the design of facilities [2]. Over the last 20 years, developments have been made in academic research and practice to design tools and techniques allowing to connect implicit geometrical relations through declared parameters responsible for the geometrical behavior. A well-defined parametric model ensures a control over the geometry without losing the design principles and defined requirements. Constraints can be implemented in the early design phase and can be maintained during the design process. Several tools have been developed in order to support the parametric modelling: Grasshopper a plugin for Rhino, Dynamo a plugin for Revit, Generative component and Houdini.

For decades, architects and designers have been trying to optimize their projects based on criteria such as energy consumption, structural weight, daylight and cost, and more recently, optimization processes in architectural design have been made easier through using computational methods [14]. Several optimization plug-ins were integrated into parametric modelling software allowing numerical simulation and iteration of different solutions [4]. With parametric modelling software the designer is able to evaluate the design iteration in terms of quantitative indicators. Optimization plug-in will also generate different solutions and enable to compare between the quantitative performances related to criteria such as energy, daylight analysis, shadow, view to a landmark, view to the sky, illumination … In order to optimize a problem in parametric modelling tools, a designer has to create a so-called "fitness function" describing the objective to achieve [18]. This process will be linked to the input parameters of the design and the designers should investigate multiple iterations to choose the optimal one.

55.3 Research Objective, Hypothesis and Research Methodology

55.3.1 Research Objectives

Our statement is that the tools enabling optimization in design process are acting on physical parameters that can be integrated as parameters into these computer-based environments, thus providing the simulation of different variables and the optimization of the geometry while following some pre-defined constraints and objectives. However, such tools usually do not enable using "non-physical parameters" [7] such as the people/users evaluations of spaces and projects. In particular the POE can be considered as relying on a set of such non-physical parameters. For dealing with input parameters to define a fitness function of a multi-objective optimization process, the related values do not take into account the user evaluation and satisfaction. The hypothesis is that the current practice with computational aided design tools integrating the MOO methodology could therefore be extended to include user's post-occupancy satisfaction. To answer this challenge, surveys are usually conducted amongst buildings' occupants. Such studies enable to evaluate the perceived comfort in a building which may differ from what is thought by the architects in the design phase.

However, POE research appears in the early 60s but it has been facing some limits and has not been adopted by professionals. More recently, with the growth of green buildings which are more exploratory realizations and change profoundly the design patterns, the POE appears as an interesting method to capitalize on each experience [6], especially in UK, where RIBA (Royal Institute of British Architects) encourages the use of POE. Since the comfort of the user is an important factor in the context of new constructions, and which can differ from the intention of the designers, our research focuses on how to integrate the users' comfort with the 3D visualization systems. Further we aim to link the POE with MOO process through parametric modelling approach to, either develop a new design for the interior layout or the reorganization and adaptation of interior layout in existing building.

55.3.2 Hypothesis

The gap between the real behavior of a designed project and the performance expected by the users justifies the hypothesis to include information related to the post-occupancy evaluation in the digital design process. POE can be used to improve the space layout design in existing building and to be included in the MOO function as a criteria to enhance the design of the working spaces in office buildings. In order to support the requirements of the users in an office building, we consider that design tools should offer additional capacities to include the POE. Taking advance of the POE for either the renovation or design of a facility is useful and important for the life cycle of the project and for the satisfaction of the users.

55.3.3 Research Methodology

The digital evaluation of the building performance can be nowadays easily recorded. In particular information from sensing devices is a way for collecting building behaviour's data, this is easy to achieve since sensing devices have become more and more present in buildings. These sensing devices can track movements within the building. They also allow monitoring the building and collecting information which can be connected to its digital twice, i.e. BIM. Many sensing devices can be integrated into the building related to the indoor air quality, the occupancy, the daylighting or the noise. A comprehensive overview has been provided by Ahmad et al. [1]. Computational and generative design tools are facilitating the integration of optimization techniques into the design processes. These optimization solvers are usually included in the parametric software providing features to search for diversity in solutions. Our research methodology relies on case study implementation to validate a global conceptual framework formulated from the state-of-the-art analysis. The case study applies the approach on the design and reorganization of an office building situated in Luxembourg. The parameters retained for the POE are related to the view, the noise, the daylight and the indoor thermal comfort considered by users as primordial. The tasks realized are related to the reconfiguration of local offices in order to answer the requirements and needs of the occupants in the "Maison de l'Innovation" building (Fig. 55.1).

55.4 Proposed Conceptual Framework

55.4.1 A Conceptual Framework for Including the POE into a Parametric Approach

To address the issues raised in the state of art we consider a conceptual framework representing the design situation with: (1) processes and (2) actors involved, and the (3) digital technologies enabling to provide a parametric modeling environment. The framework thus deals with the (A) design process and situation presented, for each situation, the (B) data collection should be performed related to the physical parameters, later, the integration and (C) digitalization of the collected data, and the technologies associated to perform a MOO process (see Fig. 55.2). In the context of this article, the innovation in such a MOO is by including the POE items as a set of parameters in the design process (yellow box).

However, it is important to note that the conceptual framework proposed is grounded in a wider theoretical paradigm developed in a context of a PhD and related to the participation of users on the design of their products. Indeed, taking into account the POE to design new interior layout of an office building is considered as a type of participation involving the users in the new design.

In our use case, the designer is considered as the facility manager responsible for the reorganization of the interior layout. The users, themselves, are the occupants of the building who answered the surveys.

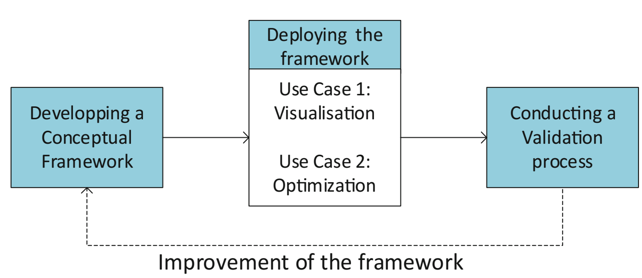

Fig. 55.1 The methodology

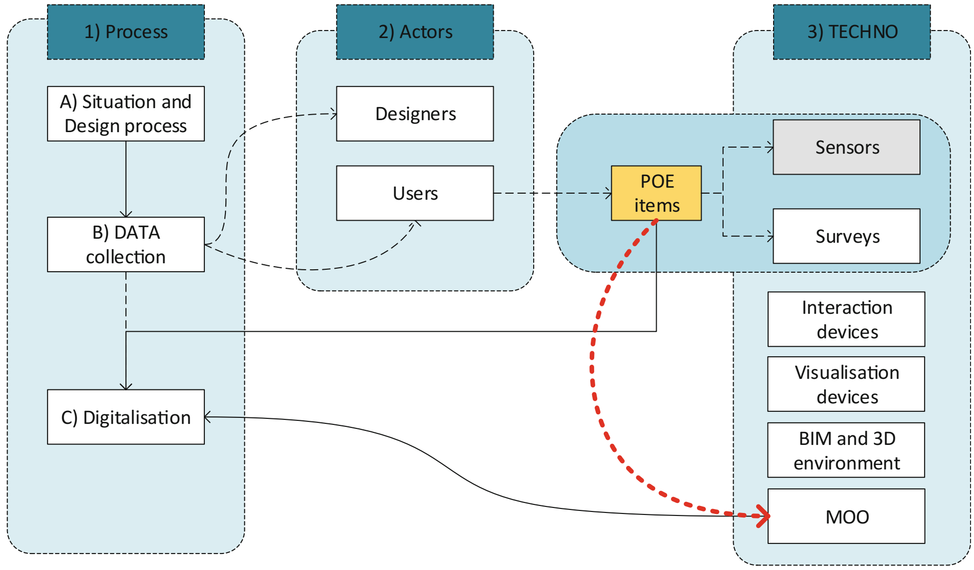

Fig. 55.2 The proposed conceptual framework

55.4.2 Application to POE-Based Floorplan Layout Design

As our interest in parametric approach relies mainly on its application in design processes, it is important to carefully choose the software and devices to be used. The choice to implement the software and devices in our framework was made according to the accessibility, functionality and ease to use. These tools and technologies are related to the (1) visualization, (2) 3D environment and (3) sensing technologies. For the visualization, these interaction technologies were linked to virtual environment allowing the visualization of the 3D and the 3D simulation in a VR/AR environment. The use of these technologies produces a simple understanding of the design model proposed and ensure a better understanding of the proposed solutions.

The use of parametric modelling tools is justified by their ability to easily manipulate algorithms based on visual components and to create dependency between the model and the input parameters. The modification of input parameters will result in real-time modification of the 3D geometry. As for BIM (Building Information Modelling) tools, it was important to extract the semantic information of the spaces and to attribute the POE result to each space as well as to understand the relation between the space and the POE result. This relation between both space and POE helps in identifying the reason of the resulting perception of users about the spaces, and to record the important points to take into account in future development of design. These values should then be compared with the POE conducted via surveys. After the identification of relation between the two sensing approaches (human and physical), each indicator would be translated into input parameter for the model. Optimization techniques integrated into the parametric modelling tools will be acting on these input parameters to search for optimal solutions. These parameters will be weighted according to their importance. The weight for each input will be concluded from the objective data recorded through sensors and human evaluation collected by surveys. These optimization techniques will integrate in addition as inputs the Post-Occupancy evaluation data enabling the evaluation and analysis of different solutions generated by our system.

55.4.3 First Prototype Implementing the Approach

The purpose of this prototype (see Fig. 55.3.) is to visualize the answers given by the users in a 3D environment and to be able to connect the spaces occupied by employees to the average answer of the POE. Based on a 3D BIM model for the “Maison de l’Innovation” (MIN), each space was connected to the average evaluation of the POE survey exploited in Grasshopper with a connection to the data in an excel sheet. The POE survey answered by users covers different items of comfort. These items were related to sound, light, natural daylight, view to the outside, equipment (related to the furniture of the offices), and indoor air quality (for summer and winter). The evaluation of each item was scaled from 0 to 4. In this

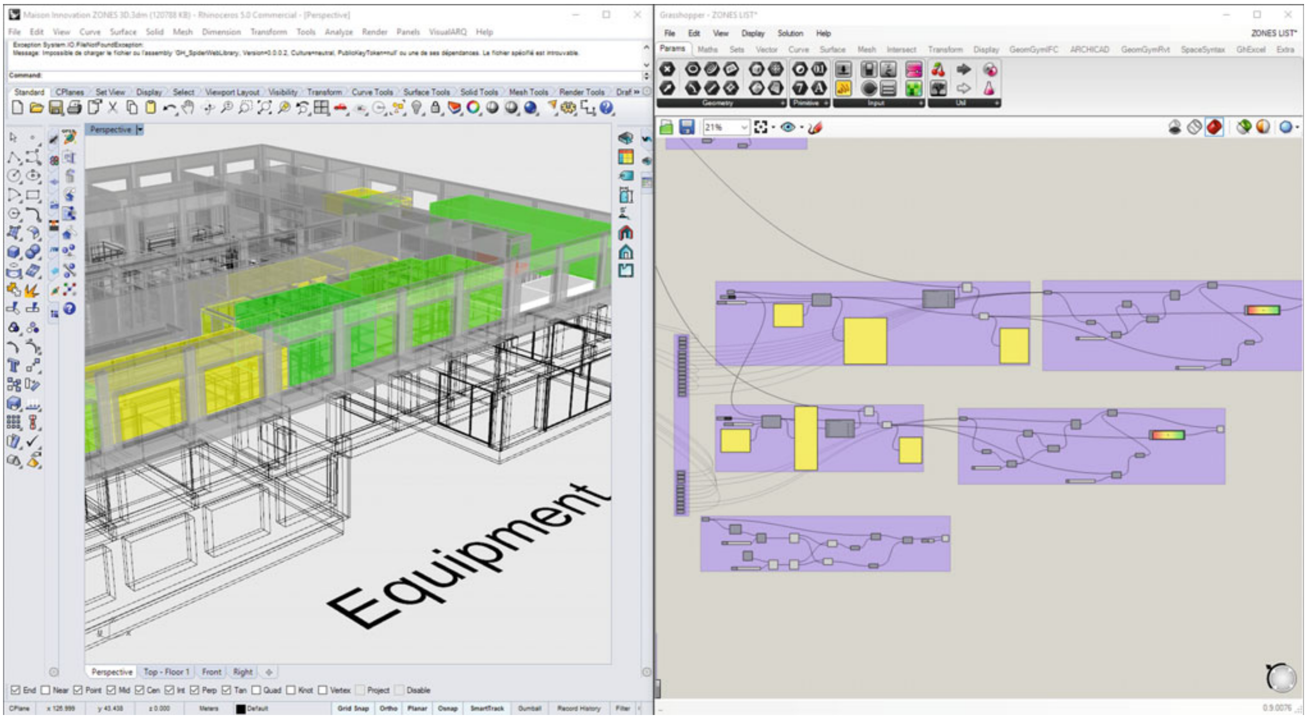

Fig. 55.3 The first prototype showing the visualization of the post-occupancy evaluation item for equipment

figure, the POE item shown is related to the equipment, where each space is showing the average of the result of the evaluation with a color code indicating the level of evaluation.

Thanks to the IFC format, the related spaces were exported and implemented in the Grasshopper environment. The objective of this first prototype is to use the parametric model to better understand the survey according to answers, and to interpret the results in a more informed manner. The visualization of the POE data in each space allowed us to rethink new layouts to answer some of the issues raised by the user's evaluations. Another interest in this workflow is the link created between the BIM environment and the parametric design environment.

55.4.4 Second Prototype

The second prototype (see Fig. 55.4) proposes to study the reconfiguration of the interior layout taking into consideration not only physical parameters but also human collected parameters, and in particular the POE data set. In this prototype we only considered the values of the sound comfort and the view. These evaluations have been transformed into input parameters and integrated into the parametric models with weighting criteria according to the importance of each indicator as shown in the framework. With integrated optimization plugins in the parametric tools, we are able to iterate different solutions based on our input. A few combinations were defined in this second prototype, and the work is ongoing to develop optimization functions that are more complete.

55.5 Validation

The proposed prototypes present opportunities for further development. However, even though the limits of the prototypes are identified, the validation of the hypothesis and the associated framework is conducted at three levels.

First, the development of the first prototype demonstrated that parametric modelling can be used for the visualization of the information concerning the POE, thus facilitating the understanding of the information and data represented.

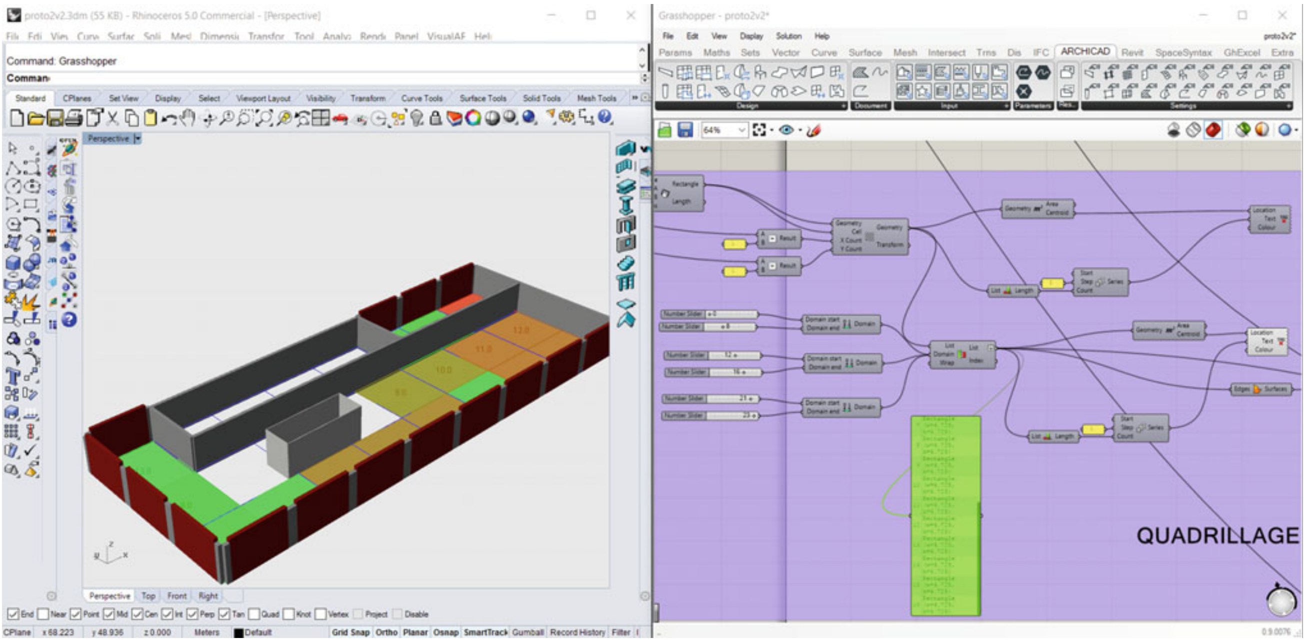

Fig. 55.4 The second prototype developed according to the users' post-occupancy evaluation

Second, the development of the second prototype demonstrated that the optimization techniques integrated in such parametric tools make sense, and can be based on the POE as input parameters, thus introducing "non-physical parameters" into the model.

In a third phase, both prototypes were confronted to the occupants from the concerned building. This development enabled for occupants to first visualize the results of their evaluations. Occupants also showed an interest in the second prototype which helps in the generation of workspace layout taking into account their own evaluations.

55.6 Discussion and Conclusion

This ongoing research aims to demonstrate the interest of taking into account the POE in the design process. Indeed, the simulation tools usually available at design time have shown a gap between the predicted results of simulations and the real perception and evaluation of the users. To fill that gap, this research aims to develop a framework where the POE items would be integrated as new parameters that can be computed towards discovery of design solutions. These new parameters related to the POE can be presented as non-physical parameters since they are dealing with the human evaluation and in most cases to unpredicted evaluations. By introducing this type of parameters, the solution presented at the design stage would ensure that the gap between simulation tools and human evaluation is filled, or reduced. Users can evaluate the spaces they occupy and the way they feel their performance. The research presented in this paper proposes a prototype to visualize the POE result in a 3D parametric model. The results obtained are then evaluated to better understand them and to be transformed into parameters as another input in the parametric model before the reconfiguration of the new layout spaces. Further evaluations with the occupants shall be undertaken to test the efficiency of the prototype. In a future version, we expect that physical indicators about the building will be collected by sensors placed in the different spaces of the building. Intersecting the questionnaires collected from the occupants with the physical data recorded by such sensing devices is a promising method to improve the quality of future buildings. Although this framework focuses on the buildings, our future developments will also address the POE as parameters at the area/neighbor level.

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References

1. Ahmad, M.W., Mourshed, M., Mundow, D., Sisinni, M., Rezgui, Y.: Building energy metering and environmental monitoring—a state-of-the-are review and directions for future research. Energy Build. **120**, 85–102 (2016)
2. Boeykens, S.: Bridging building information modeling and parametric design. In: eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2012, p. 453 (2012)
3. Bordass, B., Leaman, A.: Making feedback and post-occupancy evaluation routine 1: A portfolio of feedback techniques. Building Res. Inf. **33**(4), 347–352 (2005)
4. Brown, N., de Oliveira, J.I.F., Ochsendorf, J., Mueller, C.: Early-stage integration of architectural and structural performance in a parametric multi-objective design tool. In: International Conference on Structures and Architecture (2016)
5. Coates, P., Arayici, Y., Ozturk, Z.: New concepts of post occupancy evaluation (POE) utilizing BIM benchmarking techniques and sensing devices. In: M'Sirdi, N., Namaane, A., Howlett, R.J., Jain, L.C. (eds.) Proceedings of the 3rd International Conference in Sustainability in Energy and Buildings (SEB'11), pp. 319–329. Springer, Berlin (2012)
6. Cooper, I.: Post-occupancy evaluation-where are you? Building Res. Inf. **29**(2), 158–163 (2001)
7. Daher, E., Kubicki, S., Guerriero, A.: Data-driven development in the smart city. Generative design for refugee camps in Luxembourg. In: Proceedings of the Sustainable Places 2016 Conference, France (2016)
8. Fischer, J., Vischer, G.: User evaluation of the work environment: a diagnostic approach. Le travail humain **68**(1), 73–96 (2005)
9. Hay, R., Samuel, F., Watson, K.J., Bradbury, S.: Post-occupancy evaluation in architecture: experiences and perspectives from UK practice. Building Res. Inf. **46**(6), 1–13 (2017)
10. Meir, Isaac A., Yaakov, G., Dixin, J., Alex, C.: Post-occupancy evaluation: an inevitable step toward sustainability. Adv. Build. Energy Res. **3** (1), 189–219 (2011)
11. Kalay, Y.E.: The impact of information technology on design methods, products and practices. Des. Stud. **27**(3), 357–380 (2006)
12. Khan, A., Hornbæk, K. Big data from the built environment. In: Proceedings of the 2nd international workshop on Research in the large ACM, pp. 29–32, September 2011
13. Kolarevic, B. (ed.): Architecture in the Digital Age: Design and Manufacturing. Taylor & Francis, Milton Park (2003)
14. Lawson, B.: How Designers Think: The Design Process Demystified. Routledge, Abingdon (2006)
15. Motawa, I., Carter, K.: Sustainable BIM-based evaluation of buildings. Procedia Soc. Behav. Sci. **74**, 419–428 (2013)
16. Preiser F.E.: Post-occupancy Evaluation. New-York (1988)
17. Wang, H., Gluhak, A., Tafazolli, H.: Integration of BIM and live sensing information to monitor building energy performance. In: The CIB 30th International Conference on Applications of IT in the AEC Industry, October 2013
18. Wortmann, T., Nannicini, G.: Introduction to architectural design optimization. City Networks, pp. 259–278. Springer, Cham (2017)

56 Social Paradigms in Contemporary Airport Design

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Abstract
Increased demand for traffic puts the Aviation industry in front of multiple challenges. Traditional airport design matrices do not cope properly with the evolution of design requirements and project participants' needs, especially in a multidisciplinary context that requires high skilling. In this setting, Architects are rulers of the terminal and lead managers of Project Information. These are generated and managed through Social processes who leverage the joint use of knowledge to fulfill project requirements. Often the need for reliable project information is not understood by project participants and project clients, therefore causing reworks, overtimes and an overall increase in project cost. Innovative project management methodologies based on social aspects are needed to implement common practices and support collaboration, shared design, problem-solving. The target is producing consistent Project Information. In this exploratory paper, way lay down the foundation and research background for a proposed research that aims to re-align people, process, and technology in Airport Design. A lean design methodology proposal is built on the project sociotechnical system to maximize project value for passengers, airlines, and airport management companies.

Keywords
Design process • Social sciences • Lean design

56.1 Background

The role of airports in the global social and economic scenario has consistently evolved in recent times because of their role of connection between people and markets. Communities and territory have been shaped by the layout of the transport network and globalization depends on connections and their speed. Strengthening of the market and aviation was fostered by the progressive liberalization of markets, also overcoming the hills and slopes of the recent global economic crisis [12, 15, 23]. The air transport network will experience major service disruptions if Airport will not cope with the evolution of traffic and aircraft requirements, with a larger-scale chain reaction on the global economy.

This capacity challenge is being faced in a context of increased competition and a shift in the global aviation market, driven by globalization, technological progress and the rise of new economies. In addition, air traffic, airport user basin and freights will be influenced by changes in customers and airlines habits and practices [2, 14, 17]. Removal of service bottlenecks is a priority for the future of the Airport Network targeting the Capacity and Quality challenges of ground infrastructures. These have a deeper bond to the Airport project since they both take act mostly inside the passenger terminal.

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56.1.1 Capacity Challenge

To confront the increased demand for air traffic [11], Aviation industry has to face multiple challenges to deliver the expected capacity. Demand is increasing ad a steady pace [13, 11], with a foreseen growth of about +4.5–5% per year until 2035, managing to double the total passenger number in 20 years reaching 490 M/passengers only in Europe. This demand for connectivity—both in terms of longer-range flights and faster connections in general—has a massive impact on the economy, shaping the possibilities of global markets [12]. Capacity of ground infrastructures does not meet flights demand, creating bottlenecks in air service. Soon passenger terminals will not be able to process as many passengers as needed [6] especially in case of operational irregularities or a sudden need for extra flights when already at full capacity. In Europe for example airports' capability to meet the demand, already operated by the unique European Airport Traffic Management, needs larger and more efficient ground infrastructures. If this demand will not be met, by 2035 around 120 million travelers will not be able to complete their trip because of congestion. To cope with this growth and to offer continuity to the economy, aviation industry must be supported by proper infrastructures that meet airline needs, connectivity requirements and transform passenger processing into an economic benefit, connecting people and markets [6, 13]. The airport capacity gap will have to be filled by expansions, new infrastructures and by increasing operation efficiency of current terminals. Both passengers and cargo demand for a higher service quality to cope with the ever-growing foreseen traffic scenario [19].

56.1.2 Service Quality Challenge

The quality of offered services is crucial to obtain flight slots by the European regulation and in general by the global market. If the terminal is built without sufficient attention to users' (passengers and airlines) requirements, then the chances to obtain more slots are jeopardized [13]. Politics have their part in this scenario, resulting in incoherent aviation strategies and airports updated at a pace slower than needed. European Commission has proposed to use performance-based assignment rationales for landing slot assignments following the recent trends of airspace management [11, 12]. Taking this into account, the Aviation Industry needs innovative paradigms and methodologies for the development of ground infrastructure projects [4, 7, 9, 28] aiming to overall sustainability and flexibility. Airports gather passengers, airlines, ancillary service providers and visitors: their business model includes providing accessibility, stress-free processing procedures and satisfying Levels of Service in the so-called Passenger Experience [5, 6, 10]. Reliability, steadiness, accessibility, and quality of transport infrastructure have the highest importance along with attractive frequencies and intermodal integration also considering the need to promote public transport, the ageing of population that Europe is facing and the need to move big quantities of commercial goods [8, 10].

56.1.3 The Role of the Architect as a Social Mediator in Design

The productivity of the airport terminal is critical when evaluating capacity and service quality of the airport, intended as the capacity to process inbound and outbound flights and passengers [10]. Passenger terminals introduced a new typology of space, characterized by big dimensions and ruled by complex technical references and international regulations. Considering the need to cover the ever-changing and unpredictable capacity demand, terminals are the outcome of a challenging design process [24]. The traditional terminal development approach has demonstrated its weakness, leading to multiple projects failures throughout history because of the variegated stakes of the involved parties and their clashing objectives [2]. Sometimes certain stakeholders are excluded from the decisional processes, turning design outcome rapidly turns out-of-date and eliciting conflicts between parties, institutions and local communities [29]. Considering the general timeline of an airport expansion, obtaining the papers and permissions to build often takes longer [6] than the actual construction phase: often built projects are outdated when compared to the current needs and traffic scenarios. Therefore, collaboration in design during the authorization phase is fundamental to provide a project that satisfies the requirements of not only passengers, airlines and all the service companies that operate inside the airport, but also of the airport management company, prime user of the infrastructure. To confront the capacity challenge, enlarging infrastructures is not the only nor the most suggested way: there have been many cases demonstrating how hastily extending an airport can lead to undesired turnouts without proper planning, consultation and shared agreement between stakeholders and project participants [6, 17, 26]. When an airport ground infrastructure is not adequate for the demand because overdesigned or under-designed [18], social processes implied in analyzing and understanding needs and requirements help directing design solutions. Coordination, collaboration and information sharing are the most important processes both at design inception and in latter phases. Stakeholders have to understand the needs of communities, signing a "social agreement" with them. In this context, architects are the rulers of terminals. The terminal is not any more a box meant to supply passengers to the airplanes; it becomes a definite space that interfaces land and air while guaranteeing public space functionalities, always running operative areas and a commercial infrastructure, in addition to ancillary spaces and services offered to third parties. The Terminal project has an overall impact on the surroundings under every meaning of sustainability: social, economic, environmental, etc. Project Information sharing and collaborative management are fundamental **social processes and experiences** of Airport Project Participants in the trail to overall sustainability. This is the optimal use of joint knowledge and practice for planning, design, procurements and field operations to reach project objectives and meet clients' requirements and user experience as well, while limiting and removing such processes, sub-processes and activities that do not contribute delivering building quality, hence satisfaction.

56.2 State of the Art of Aviation Industry Design

Aviation industry sets boundaries, conventions and standards for the Airport design process [10]. Common design practices struggle to cope with the evolution and changes of this conventions, being hazy at best due to the design being highly operation-sensitive especially regarding the project context [6, 26]. Generally, literature does not present ground-breaking airport terminal architectural design methodologies [6, 7]: such studies are set in a challenging research area, given the relentless dynamism of aviation industry and operation-bound complications. The development and implementation of common practices of innovative project management methodologies founded on social aspects are now more urgent than ever. The interaction between Project Design management and Social Sciences implies and supports an extensive range of phenomena like the shared design, collaboration, problem solving and creativity that can contribute to consistent project information. Achieving a reliable flow of information is one of the most critical difficulties in the Design process since all involved project participants are meant to generate, manage and transform project information that composes an "abstract description" of a product. These difficulties are not steadily understood because of missing knowledge by project participants, leading to wastes such as reworks caused by missing updates on documents, an increase of production times due to growing information complexity, non-value-adding design iterations.

56.2.1 Lean in Project Design Management

Lean is a principle-based approach that aims to maximize clients' value and minimize resource consumption and waste production in a process [22]. Born in industrial production and progressively applied to construction and design, Lean's objective is to mitigate project failures trough active management of process variables and project design management. Considering this, the architectural project development of an airport terminal can be assimilated to a temporary production system. In this framework, Lean mindset fosters the idea of the project as a transformation-based process with a focus on the management of the process itself. Leading to the production of a one-of-kind "prototype"—the project information model and later the building as its materialization—the Airport Terminal Design process can be considered a product development process. There is a notable difference with industrial production: building production acts in a temporary setting with recurring changes in the project organization structure during its life cycle, instead of happening in a stable and uniform environment, i.e. the factory [16]. Design process management is the focus of production, aiming to obtain a project production system that maximizes project quality and minimizes waste of resources, time, and the effort for project participants [1].

56.3 The Role of Virtual Design and Construction Technologies

Europe is soliciting the use of Virtual Design and Construction technologies towards a program a Construction Digitalization [25], highlighting the need to reshape the Design Processes and integrate innovative methodologies in the creation and sharing of Project Information models. In this scenario, Project information is supported by collaboration, creativity and information management Interactions between Design Process management and social aspects of project participants must be fostered. Virtual Design and Construction technologies—namely Building Information Modeling and Management—are used by the industry to overcome such difficulties, but often must compete with the barriers of the resiliency of its components. In a social Lean-infused process, project participants collaborate to generate Project Information Organizational Memories and gather them in a coordinated and integrated model: these processes exploit synergies between BIMM and the Lean mindset by a "natural alignment". The work of several project participants has involved the definition of a Project Information Organizational model (or BIMM model), with the objective of achieving a complete model constituted by coordinated information. This evolution demands new knowledge and skills also in social aspects for the AECOO practice, implying the discard of the obsolete *Fordist* approach and filling a gap in process-centered improvement. Moreover, process and technology integration in the Industry present another gap caused by the inability to determine systematic Lean and Virtual Design and Construction Technologies integration strategies and methodologies [3]. BIMM integration in the architectural process is enabled by some of the most prominent Lean thinking features: predictability, reliability and collaborative/learning environment striving to the perfection of the project production system. This contributes to overcoming BIMM complexity barrier for project organizations. Given that Lean promotes theoretical principles close to integrated project information modeling, the integration of BIMM technology must be considered as a Lean tool [21]. Being both Lean and BIMM transformative technologies [27], we argue the transfer and anticipation of the benefits of Lean/BIM to earlier phases of the building lifecycle up to project development, hence fostering the realignment of the People (lean) pillar in project organization in its collaborative information sharing environment, with the objective of enhancing value generation for final users. In this framework BIIM—and more in general Virtual Design and Construction (VDC) Technologies—support the activities of multidisciplinary project organizations that span both through space and time, connecting project participants and bridging their knowledge trough time for the use of all the latter phases.

56.4 Methodology

Design Science Research is the methodological reference area used in the research. Design Science Research produces *artifacts* that allow to better understand the scientific and industrial problem and to develop a methodology to improve the quality of the design process, conveying more value with its final product.

The first artifact is a matrix that associates Lean Product Development principles [22] with the traditional stages of the Airport Design Process. The matrix has an order of 4 by 13, with the Airport Design Process stages in row headers and Lean Principles in the column headers (Fig. 56.1).

Every stage of the process has been mapped, cross-referencing the architectural process and all its sub-phases and steps. The whole process was broken down into forty-nine stages. Every single stage was then confronted with Lean Product Development principles, pointing out if the interaction has a foreseen value generation potential or waste removal potential according to both Lean literature and experience. Interactions were described with postulates in the final column of the table, drawing useful elements from Lean literature. The combination of interactions and their potential is the cornerstone for the proposed methodology that aims to satisfy evolving requirements of the Aviation Industry, fostering the use of joint knowledge of Project Participants and their collaboration to maximize the value. Then, fostering the expertise of recognized experts in the field, a semi-structured survey was sent to Project Participants of the Aviation Industry to investigate issues related to project management, design management project development and project information generation, management and hand-over and refine the preliminary findings of the matrix development, according to the principles, tools and techniques of the Lean Mindset. Answers analysis under a qualitative and quantitative point of view allowed to individuate problems related to the tree aspects of project development interested by Lean: the design process, project participants and

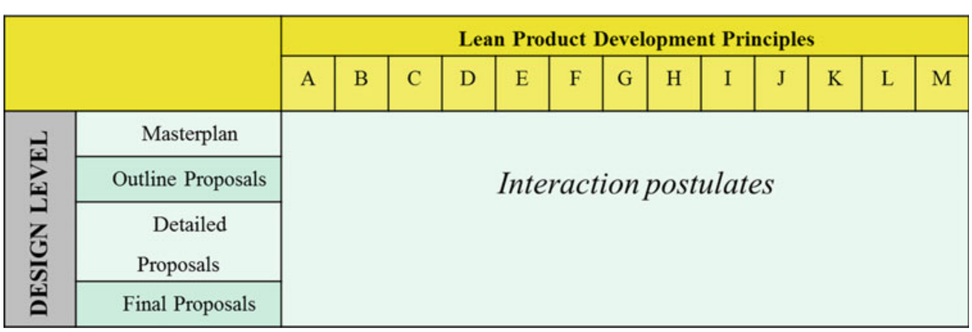

Fig. 56.1 Interaction matrix scheme overview (from Bosi [6])

technologies and tools involved in it. Results were then used to propose and add value-generating activities for project development to be integrated into common practices.

In general, the interviewee population had almost no Lean awareness. This result was expected since Lean mindset and its methods are not generally diffused in the common practices, despite some of their answers showing lean traits. Still, this is not sufficient to achieve a significant Lean integration. Project development and delivery processes in particular are seen as a sequential and static series of activities involving project participants that relate to share mostly finished products, more than coordinated project information. There is a strong lack in the implementation of continuous organization improvement measures. The industry in general is able to delivery project quality to its clients, but with an extremely waste of resources due to scarce coordination and integration between the three pillars of People, Process and Technology. Realignment of the three pillars and additional focus on Process and Project Information structuring.

56.4.1 Development of the Innovative Methodology Model

Lean Airport Project Integrated Delivery is a process methodology built on thirteen principles for Airport Lean Design, derivative from the application of Toyota Product Development Principles and the construction of a common practices/TPS principles interaction matrix set. This matrix set is a Design Science Research artifact used to define postulates of interactions between the common airport design practices and lean product development principles. A survey involving project participants from the Aviation Industry is used to refine and evaluate preliminary findings, proposing new value-generating activities to be integrated into the common practices, aiming to deliver additional value and reduce resource wastes for airport owners, airlines, and passengers with the airport project. Value-adding and waste-removing activities individuated during the matrix development and with survey results are integrated into the beginning matrices and later in the process map (i.e. *Value Stream Map* in the Lean Mindset), defining a two-fold tool for Project Participants: (A) an active artifact useful to structure Project Design Management and evaluate the lean grade of the design process; (B) a leaner airport project design process methodology.

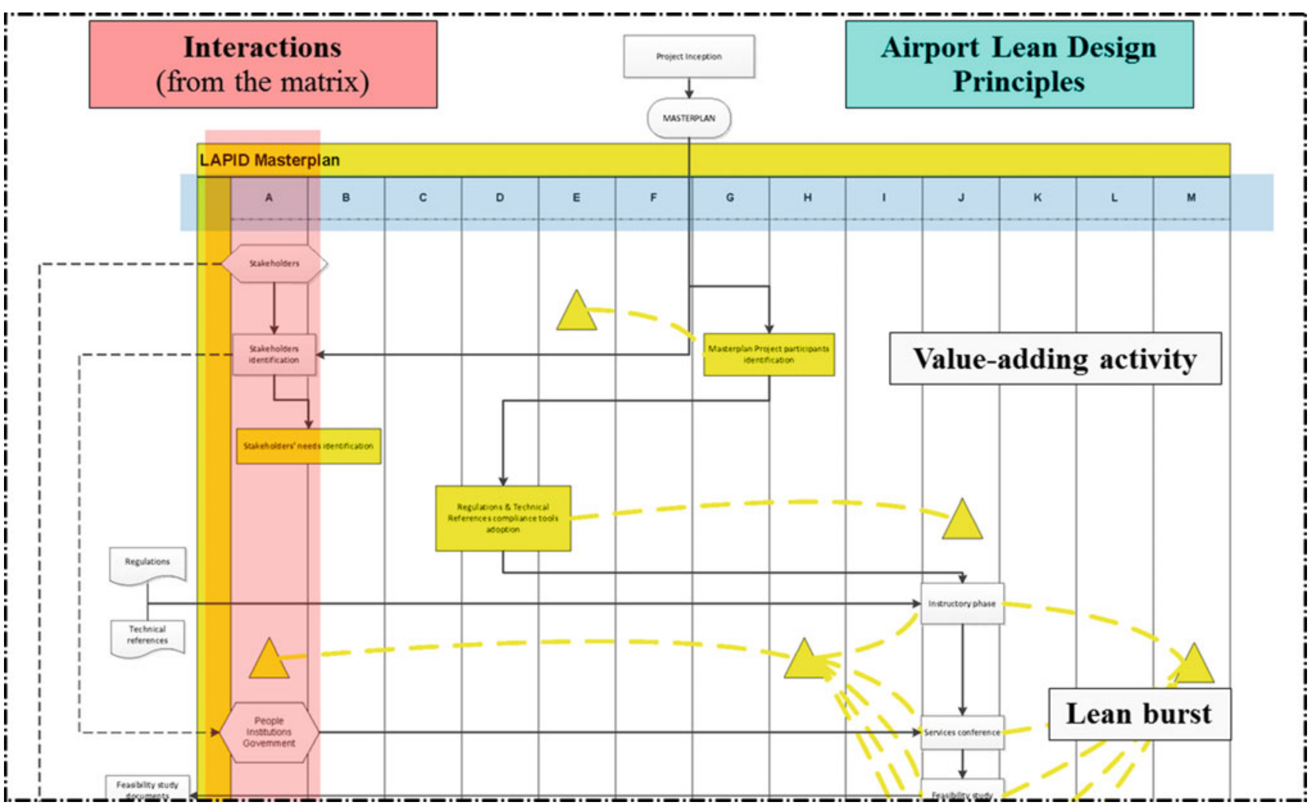

Fig. 56.2 Extract from LAPID process methodology map (from Bosi [6])

This second artifact is represented with a series of intertwined flowcharts sporting swimming lanes—Process, People, Technology Lean pillar lanes, each divided in its corresponding Lean Principles. The flowchart describes lean correlations between activities and Lean Bursts—i.e. the activities/steps that concentrate most value conferment for the clients—to support Project Design management (Fig. 56.2).

Innovative project management methodologies based on social aspects are needed to implement common practices and support collaboration, shared design, problem-solving. The aim is promoting production of consistent Project information that can overcome time barriers of the various stages of the airport terminal life cycle. The proposed methodology—possibly to be field tested on airport design case studies—implies a change of paradigms for all project participants involved in new airports or terminal extension design, with different priorities related to Lean thinking and efficient Project Information management rather than only achieving design targets. With the joint use of Lean mindset and BIMM tools, the project organization could avoid resources (man-hours) wastes and limit possible delays within the project process (e.g. due to redundant or misplaced activities). Its expected contribution during the design phase is the enhancement of the Project Information flow, using Lean principles to manage the team workflow and workload, in addition to communication and information sharing. Improvements theorized by the proposed methodology offer to airport owners' technical units a more consistent workshop. These changes have potential benefits for both material and immaterial processes occurring during and beyond the design phase.

56.5 Conclusions

The research proposes an innovative methodology aimed at the parallel enhancement of the three pillars of the design process—people, process, and technology. It is tailored for the project's socio-technical system to maximize the value for passengers, airlines, and airport management companies generated by the project. Achieving the benefits expected from Lean and BIMM requires greater consideration of the characteristics of the work and management environment, which are deeply influenced by social phenomena. Lean offers methodologies for closer collaboration and people integration that goes beyond the traditional matrices of design methods, bridging the gaps of collaboration between project clients and project participants. In addition, the combined use of Lean and Virtual Design and Construction (VDC) technologies—both intended as *transformative technologies* [27]—fosters a holistic approach to project design and development aimed towards the Operation & Maintenance phase of the airport, because of the constructive implications of Lean. Stakeholders of the Aviation Industry, their Project Participants and consultants are primary recipients of the suggested methodology, in addition to airport owners' technical units and managers as well regulatory bodies interested in design verification. Airport owners are direct beneficiaries as the first and primary users of the methodology, followed by the whole Airport supply chain—being the parties in charge of feeding the digital Project Information model that is the actual backbone of the proposed methodology.

References

1. Aapaoja, A., Haapasalo, H.: The challenges of standardization of products and processes in construction. In: Proceedings of the 22nd Annual Conference of the Int'l Group for Lean Construction. IGLC, Oslo, Norway (2014)
2. Airports Commission: Interim Report, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/271231/airports-commission-interim-report.pdf (2013). Last accessed 24 Apr 2018
3. Alarcon, L.F., Mandujano, M.G., Mourgues, C.: Analysis of the Implementation of VDC from a Lean Perspective: Literature Review. In: Proceedings of the 21st Annual Conference of the Int'l Group for Lean Construction. IGLC, Fortaleza, Brazil, (2013)
4. Bosi, F., Esposito, M.A.: Achieving lean project design delivery. In: Esposito, M.A., Ciribini, A., Dell'Osso, G., Daniotti, B., Carbonari, A., Alaimo, G. (eds.) Energy, Sustainability and Building Information Modeling and Management, pp. 217–235. Maggioli, Milano (2014a)
5. Bosi, F., Esposito, M.A.: Passenger Experience Design. In: Proceedings of Constec 2014 Miradas a la investigación arquitectónica: construcción, gestión, tecnología Architectural research findings: building construction, management, technology, Escuela superior Tecnica de Arquitectura de Madrid, Madrid (2014b)
6. Bosi, F.: Airport Lean Integration, Ph.D. Dissertation, Università degli Studi di Firenze and Technion, Israel Institute of Technology (2016)
7. Bosi F., Esposito M.A, Sacks R.: Lean mindset for the improvement of airport design process. In: Ciribini et al. Back to 4.0: Rethinking the digital construction Industry, pp. 192–120 (2016). ISBN 978-88-916-1807-8
8. de Neufville, R., Odoni, A.: Airport Systems: Planning, Design, and Management. McGraw-Hill Professional, New York, NY (2003)
9. de Neufville, R., Scholtes, S.: Flexibility in Engineering Design. MIT Press, Cambridge, Massachusetts (2011)
10. Esposito, M.A.: Tecnologie di progetto per il terminal aeroportuale, 2nd edn. FUP, Firenze University Press, Firenze (2010)
11. Eurocontrol, Challenges of Growth 2013 Summary Report, Eurocontrol, https://www.eurocontrol.int/sites/default/files/content/documents/official-documents/reports/201307-challenges-of-growth-summary-report.pdf. Last accessed 24 Apr 2018 (2013a)

12. Eurocontrol, Challenges of Growth 2013—Task 4: European Air Traffic in 2035, https://www.eurocontrol.int/sites/default/files/article/content/documents/official-documents/reports/201306-challenges-of-growth-2013-task-4.pdf. Last accessed 24 Apr 2018 (2013b)
13. Eurocontrol, Challenges of Growth 2008 Summary Report, Eurocontrol, https://www.eurocontrol.int/sites/default/files/article/content/documents/official-documents/facts-and-figures/statfor/challenges-of-growth-2008.pdf. Last accessed 24 Apr 2018
14. European Union: European Commission, Airport policy in the European Union—addressing capacity and quality to promote growth, connectivity and sustainable mobility, December 1st, 2011, COM(2011) 823 final, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0144:FIN:EN:PDF. Last accessed 24 Apr 2018 (2011)
15. Hakfoort, J., Poot, T., Rietveld, P.: The regional economic impact of an airport: the case of Amsterdam Schiphol Airport. Reg. Stud. **35**(7), 595–604 (2001)
16. Hickethier, G., Tommelein, I.D., Lostuvali, B.: Social network analysis of information flow in an IPD-project. In: Proceedings of the 21st Annual Conference of the Int'l Group for Lean Construction, IGLC, Fortaleza, Brazil (2013)
17. IATA, Airport expansion: Bright thinking, available at http://airlines.iata.org/analysis/airport-expansion-bright-thinking?_ga=2.245615683.638330240.1517417548-1818978628.1517417548. Last accessed 24 Apr 2018 (2015b)
18. IATA (International Air Transport Association): Airport Development Reference Manual, 10th edn. IATA, Montréal (2014)
19. IATA Air Passenger Market Analysis, available at https://www.iata.org/whatwedo/Documents/economics/passenger-analysis-may-2015.pdf. Last accessed 24 Apr 2018 (2015a)
20. Joint Research Center, Technical Reports: Building Information Modelling (BIM) Standardization, http://publications.jrc.ec.europa.eu/repository/handle/JRC109656. Last accessed 24 Apr 2018
21. Koskela, L.: The implementation of Lean Construction and BIM should be Integrated! http://www.infrastructure-intelligence.com/article/oct-2014/implementation-lean-construction-and-bim-should-be-integrated. Last accessed 24 Apr 2018
22. Lander, E., Liker, J.K.: The Toyota Production System and art: making highly customized and creative products the Toyota way. Int. J. Prod. Res. **45**(16), 3681–3698 (2007)
23. Pitfield, D.E.: The economics of airport impact. Transp. Planning Technol. **7**(1), 21–31 (1981)
24. Politecnico di Milano: Le grandi piattaforme aeroportuali europee, Recuperare l'edilizia, 38, http:/IYN.w.infobuild.it/approfondimentile-grandi-piattaforme-aeroportuali-Europee/ (2004). Last accessed 24 Apr 2018
25. Poljanšek, M.: Building Information Modelling (BIM) standardization, Ispra: European Commission, Varese, 2017, ISBN 978-92-79-77206-1, https://doi.org/10.2760/36471
26. Queensland University of Technology (2012) Project airports of the future. http://www.airportsofthefuture.qut.edu.au/overview/. Last Accessed 24 April 2018
27. Sacks, R., Koskela, L.J., Dave, B., Owen, R.: The interaction of lean and building information modeling in construction. J. Constr. Eng. Manage. **136**(9), 968–980 (2010)
28. Shuchi, S., Drogemuller, R., Kleinschmidt, T.: Flexible airport terminal design: towards a framework. Proceedings of the IIE Asian Conference 2012, Department of Industrial and Systems Engineering, NUS, Singapore, pp. 348–356 (2012)
29. Wijnen, R.A.A., Walker, W.E., Kwakkel, J.H.: Decision support for airport strategic planning. Transp. Planning Technol. **31**(1), 11–34 (2008)

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A Method for Facilitating 4D Modeling by Automating Task Information Generation and Mapping

57

Murat Altun and Asli Akcamete

Abstract

4D modeling integrates 3D model with project time schedule to provide virtual simulation for identifying spatio-temporal problems earlier in construction projects. However, constructing a 4D model takes a significant amount of time and is prone to man-made errors due to its manual steps and repetitive nature. Therefore, in this study, a model based two-phase method is developed to facilitate linking 3D model with the schedule by automating the cumbersome steps. In the first phase, 4D Task IDs are created and assigned automatically to the model elements using a pattern that depends on their properties. In the second phase, using these IDs, the method generates a task ID list for scheduling and the search sets for simulation in order to map the model elements with the schedule tasks automatically, according to matching IDs. Hence, using shared IDs enhances the communication between 4D modeling tools. The efficiency of the method was tested with a well-known office building model constructed in Revit. The schedule was completed in Microsoft Project and 4D simulation is performed in Navisworks. The automated steps offered by the method were coded in Dynamo add-in of Revit. The analysis result showed that the developed method generated a 4D model in a shorter time compared to the manually performed one.

Keywords

Building information modeling • 4D modeling • Automated information generation • Dynamo

57.1 Introduction and Background

In construction projects, construction planning depends on numerous factors. This complicated nature imposes excessive burden for conventional scheduling approach to address spatio-temporal issues. Therefore, 4D modeling approach is developed to relate 3D model with project schedule for enabling virtual simulation by visualizing the sequence of the tasks with their linked model elements [1]. The simulation provides an observation on construction sequences; to improve the project stakeholders' understandings and communication [2, 3], to detect missing tasks and logical errors in the schedule [1], to identify time-space conflicts [4], and to allocate resources more efficiently [5]. Besides the visual examination, with the help of supportive algorithms, 4D model is also used to analyze; time dependent construction structural stability [6] and construction site accessibility [5] for constructability, and workspace safety [7]. Hence, these analyses provide early inspection before the construction to avoid possible problems causing delays in project, cost overruns, productivity decrease in workplace and safety problems.

Weldu and Knapp [8] divided the evolution of construction schedule generation and visualization into phases. In the first primitive phase, the schedule is developed using historical data and the scheduler's expertise. In the second phase, the

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schedule is integrated with 3D model to provide visualization and virtual simulation. Therefore, in this phase, the schedule tasks are linked with model elements manually; however, integrating 3D model with project schedule is quite repetitive, labor-intensive and time-consuming [1, 9, 10]. Hence, previous studies focus on accelerating this process by automating the linkages in a third phase. Park and Cai [11] offered a model based framework to provide compatibility between Element Breakdown Structure of BIM and Work Breakdown Structure (WBS) of the schedule for facilitating automated scheduling. According to their framework, information from model elements is extracted to generate the WBS lists and the precedence relationships between the model elements under the WBS levels. In order to provide compatibility between schedule tasks and model elements, the WBS lists are linked with the model elements for generating the schedule. Ciribini et al. [12] proposed an approach to semi-automatically match the schedule tasks with BIM elements via common identifier. In the study, the schedule is developed according to common identifiers and the linking identifier of the schedule tasks are defined as parameters in the model elements' properties. Therefore, using a predefined rule, the tasks are auto-matched with the elements considering their identifiers. This process overcomes the burden of manual linking of 3D model elements with the schedule tasks; however, assigning the identifiers to the model elements also requires time and may cause man–made errors due to its repetitive nature. In the fourth phase, focus of the studies is automating the processes of scheduling for 4D modeling. Therefore, by using spatial information, de Vries and Harink [13] proposed a knowledge based algorithm to determine the order of the building construction according to topology of 3D solid model. Similarly, Kim and Cho [14] developed more flexible algorithms to provide automatically generated precedence information between model elements according to their geometric relations for supporting construction schedule development. Furthermore, Weldu and Knapp [8] offered a rule based spatial reasoning method to generate construction sequences according to topological relations between the model elements considering the structural construction and hierarchy, material layers, and work access. Moreover, previous studies recommended the use of predefined construction methods [15] and process templates [16] to accelerate manually updated steps of the 4D modeling process.

In 4D modeling process, as explained above, manually associating schedule tasks with model elements takes a significant amount of time and this process is prone to human errors. Studies such as Ciribini et al. [12] as well as some of the current 4D tools like Navisworks, offer using common identifiers to semi-automatically link the tasks with model elements; however, in that approach, the unique common identifiers need to be assigned to each model element one by one. Therefore, the provided improvements in modeling process are not adequate to facilitate 4D modeling process significantly and this process is still open to the human errors due to the repetitive manual task id assignments. As a result, considering these drawbacks of the current practice and overall process of 4D modeling, we have developed a model based method to automate the error-prone and time-consuming steps of 4D model generation in order to (i) speed up 4D model generation process, (ii) avoid possible human errors in data generation and mapping and (ii) provide better communication between the modeling tools.

57.2 Methodology

In this study, first, 4D modeling process in current practice is examined to determine cumbersome steps that elongates the process and is prone to human errors due to manual processes and updates in the model. After this investigation, a method is developed to eliminate the drawbacks of these steps. Therefore, in the following section, the steps of 4D model generation are explained. In the next section, the logic behind the developed method and the improvements it brings are presented in detail.

57.2.1 4D Modeling Process

Today's 4D practice generally starts with project scheduling. The scheduler develops a time schedule using her expertise and according to calculations based on 2D drawings or the model. In parallel to this process, the 3D model is completed according to design decisions and/or 2D drawings. However, the scheduler and 3D modeler need to be coordinated to create a consistent 4D model where the granularity of 3D model is compatible with the level of details in the project schedule [12]. Then, in order to link schedule tasks with model elements to generate a 4D model, manual and semi-automated linking methods are followed.

In manual linking method, schedule tasks and model elements are collected in the same environment and each element is assigned to its linked task manually one by one. Therefore, this step (i) consumes quite time, (ii) requires special attention to avoid linking mistakes, and (iii) needs expertise to determine which element links to which task [10].

In semi-automated linking method, the model elements are attached to schedule tasks according to a unique common identifier. These identifiers are defined by the scheduler and shared with the 3D modeler to update the 3D model with these task IDs. The 3D modeler creates a task ID parameter for each element in the model and assigns relevant task IDs to the elements/groups of elements one by one. After that, the model is exported into simulation tool and the elements are grouped according to their task IDs by generating search sets for each task ID. Then, search sets map with schedule tasks via task IDs for linking 3D model with project schedule to generate the 4D model. In this linking method, the coordination between the scheduler and 3D modeler is quite important to generate all relevant task IDs. Therefore, the scheduler should be familiar with the 3D model. Moreover, (i) assigning task IDs to model elements and (ii) generating search sets, are manually performed bottleneck steps of 4D modeling process that consume time and probably generate inaccurate 4D models due to missing task IDs or improper task ID assignments for some elements.

Revisions in construction projects require updates in the 4D model. Therefore, in any update that is causing change in the 3D model, all cumbersome steps are again followed to reflect the changes in the 4D model. Hence, these steps need to be improved to generate accurate 4D models in a shorter time.

57.2.2 A Method for Facilitating 4D Modeling Process

A method is developed to automate the manually performed, repetitive, and error-prone steps of 4D modeling process. The method offers a two-phase solution to facilitate 4D modeling. In the first phase, 4D Task IDs are automatically generated for all model elements in the 3D model using their own properties. In the second phase, these IDs are used to automatically generate inputs for scheduling (task list) and simulation tool (search sets), to improve bottleneck steps and to facilitate integration of 4D modeling tools. In the current practice and the relevant studies, 4D modeling starts with the manually created 4D Task IDs by the scheduler; however, in our method, the 3D model is the starting point and the properties of the elements in the model determine the task IDs. In the second phase, the method lists all element based (physical) task IDs to facilitate the scheduler's work. The schedule is developed using the given task ID list. Moreover, using same 4D Task IDs, search sets are generated automatically to transfer 4D Task IDs from the model to the simulation tool. Both search sets and schedule tasks are imported into the simulation tool to link the elements with schedule tasks directly according to matching IDs. Thus, 4D Task IDs govern the modeling process and automate bottleneck steps. As a result, possible human errors in the modeling process are eliminated to generate an accurate 4D model output.

The flowchart of 4D modeling with semi-automated linking is explained in Fig. 57.1. The colors in the figure indicate different tools the steps are implemented in, except the orange color representing the improved steps in this method. As figured out, after 3D model is constructed, 4D modeling process starts with stimulating this model to create a shared 4D Task ID parameter for BIM elements. Then, a pattern based on BIM elements' properties is followed to label task IDs, depending on the planned level of detail in the schedule. This pattern should also provide technical information to the scheduler for facilitating scheduling process. Using the pattern constructed in an order such as "Assembly Code (UniFormat II)–Family Name-Family Type-Level", information about the building element that needs to be constructed can also be given. For instance, the task ID "A4020-Foundation Slab-6″ Foundation Slab-L00" represents the foundation element with family type of 6″ Foundation Slab in a Structural Foundation Slab that rests on ground level with an assembly code of A4020 which means Structural Slab-on-Grade. After that 4D Task IDs are assigned to the element/element groups automatically. If the required information in the task ID pattern of any model element is missing, then some 4D Task IDs will be incomplete. Therefore, an inspection step is added to the method to check the model and warn the user by listing BIM elements with improper task IDs. Hence, the missing data in 3D model would be completed at this step. After that task IDs are re-assigned to BIM elements to complete implementation of the method's first phase. In the second phase, a unique list of task IDs are generated to create (i) search sets and (ii) task ID inputs for the project schedule.

In order to generate search sets automatically, data structures of different search sets are examined and task ID dependent patterns are detected. Therefore, a function is coded that takes the unique task ID list as an input and generates search set file as an output. The search sets can be imported to the simulation tool after opening the 3D model in the tool. Thus, BIM elements with same task IDs are grouped in the search sets within the simulation tool. For scheduling, our method offers a unique task ID list with its BIM element properties to the scheduler. The data structure of the list is adequate to construct a WBS easily. Therefore, the scheduler can directly import the list to the scheduling tool or rearrange this list according to her

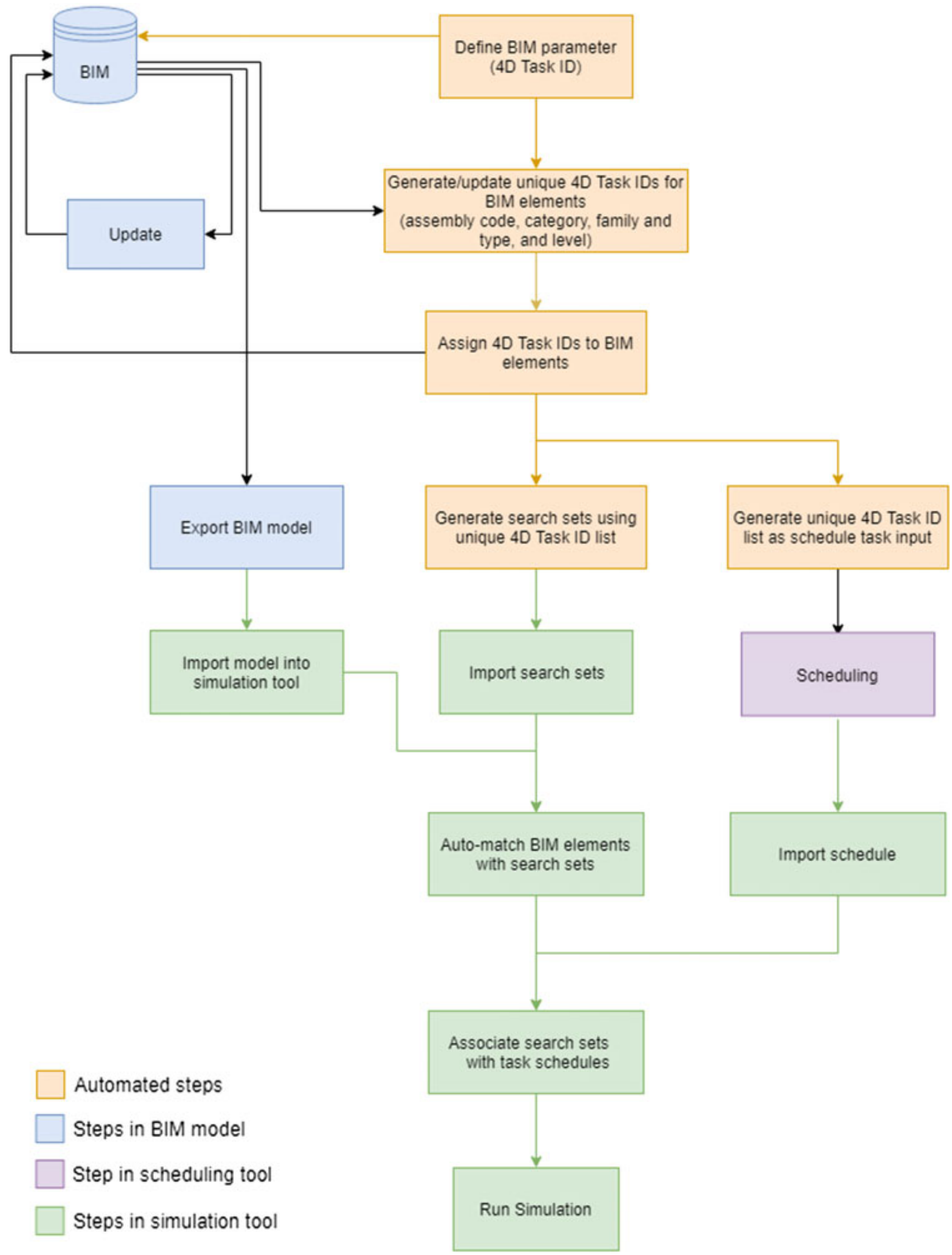


Fig. 57.1 Flowchart of the developed method in 4D modeling process

easiness to develop a WBS-based schedule. The scheduler can complete the plan by adding the tasks that are not or cannot be represented as elements in the model. Then, the scheduler develop the project plan by adding duration to each task and determining precedence relationships between the tasks. The next step is importing the schedule into the simulation tool and mapping the search sets with schedule tasks to provide automatic linking. After that, the 4D model is completed and it's ready to run the simulation.

This method also automatically updates the task IDs of BIM elements when the design is updated and generates the search sets file and the task ID list according to the revised model. Moreover, unique task ID lists of the base and the revised schedule are compared and new and pre-existing task IDs are identified to inform the scheduler for update of the schedule.

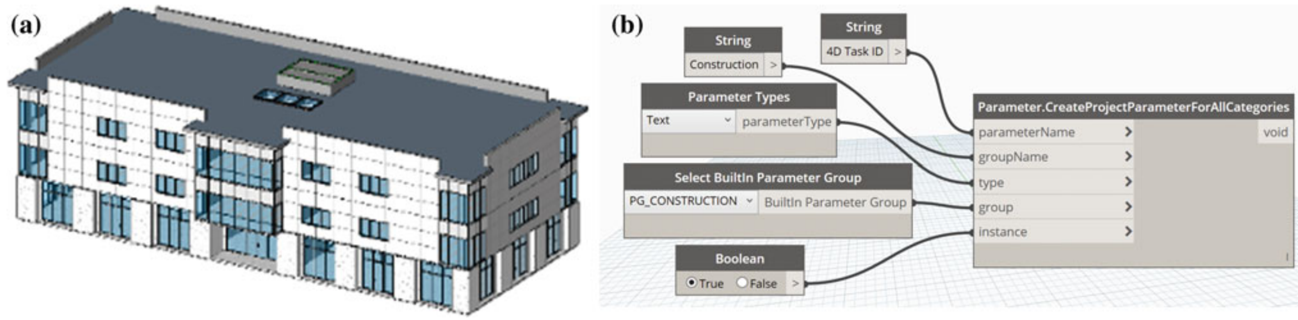


Fig. 57.2 **a** Test case office building and **b** coding of creating project parameter

57.3 Test Case: 4D Modeling with Autodesk Office Building Example

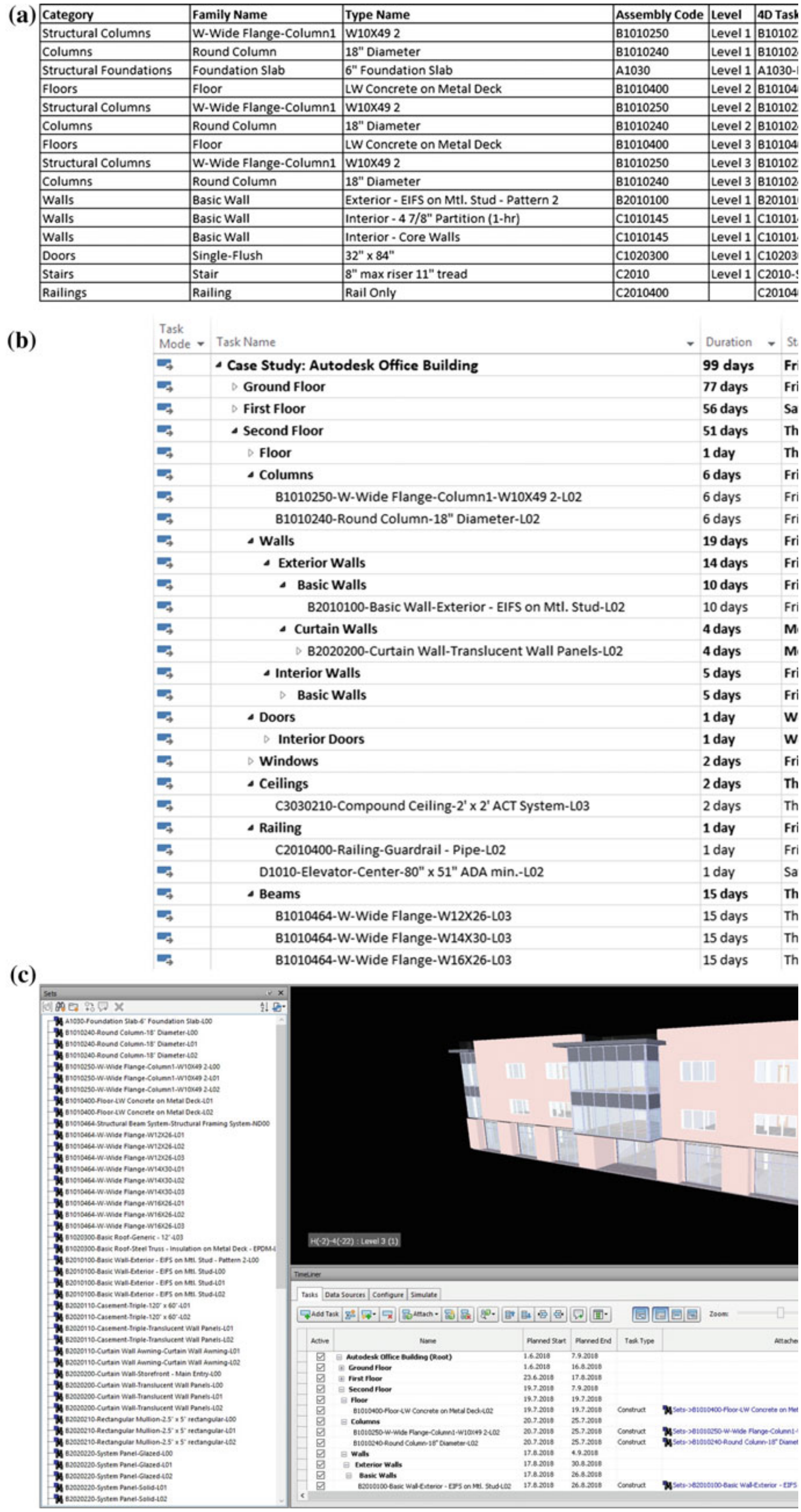
In order to test the developed method, a well-known three-story Autodesk office building example model (Fig. 57.2a) which is created in Revit is selected to construct the 4D model; because, in Middle East Technical University, this model has been used to teach all steps of 4D modeling with semi-automatic linking within the scope of CE 4002 “Introduction to Building Information Modeling” course. Therefore, it is possible for the authors to implement the developed method on this model and inspect missing and incomplete steps in automated 4D modeling process. Moreover, the schedule tasks were planned in Microsoft Project and simulated in Navisworks. The method is encoded in Dynamo visual programming, the Add-in for Revit, as Dynamo can communicate with Revit model to filter and extract necessary information and to manipulate data in the model. Hence, Dynamo interacts with Revit model to create 4D Task ID parameters and to assign their values for each BIM element. Moreover, the code in Dynamo generates inputs for Microsoft Project and Navisworks. Thus, Dynamo facilitates the implementation of the method during the whole 4D modeling process.

The test case office building model consisted of 5005 model elements with 54 different family types initially; however, most of these were supportive model elements (grids, views etc.) to manage model efficiently. Therefore, using the logic “supportive model elements cannot be used in the cost analysis”, where assembly code parameter is used in cost analysis to give brief information about model element category and location in the building envelope, the model elements without any assembly code value were filtered out. However, in this case the model elements with missing assembly codes would also be eliminated. Therefore, an early inspection step was added into Dynamo model to list unique family types of the eliminated elements and to detect the required model elements for updating their assembly code values. At the end of this process, number of elements and different family types were reduced to 1859 and 37, respectively. Therefore, parameters of these elements have been altered during 4D modeling process.

The initial step of 4D modeling is to create 4D Task ID parameter for all model elements. Compared to other steps, this is the simplest and shortest step of 4D modeling. Therefore, the user can either create the parameter in BIM model or generate the same parameter in Dynamo. In this study, 4D Task ID parameter was created in Dynamo using its own built-in function as shown in Fig. 57.2b.

The next steps are determining the pattern for labeling 4D Task IDs and assigning these task IDs to the filtered model elements. As a pattern, “Assembly Code—Family Name—Family Type—Level” was used to govern 4D modeling. This pattern groups model elements according to their family type and level information. Dynamo extracted the family name and family type of the model elements using their own parameters whereas assembly code was gathered from properties of the model elements’ family types. Moreover, the used assembly code data in this model is the specialized format of UNIFORMAT II in Revit which gives more detailed information about building elements. The level information was obtained using different parameters such as “Level”, “Base Constraint”, “Base Level” and “Reference Level”. Moreover, level (“Reference Level”) of the beam elements in the model gives one level higher output. This is also same in manual process. Therefore, it is assumed that the scheduler is informed about the reference level information for beam elements. Hence, Dynamo extracted all necessary data to label task IDs and assigned the corresponding task IDs to the model elements automatically.

In the second phase of the method, Dynamo communicated with the model to obtain all task IDs and eliminate the duplicates to prepare a unique list of 4D Task IDs. After that an empty.xml file was created and its path was given as an input, together with unique task ID list, to the search set generation function. The function is run to generate search set



Category	Family Name	Type Name	Assembly Code	Level	4D Task
Structural Columns	W-Wide Flange-Column1	W10X49 2	B1010250	Level 1	B10102
Columns	Round Column	18" Diameter	B1010240	Level 1	B10102
Structural Foundations	Foundation Slab	6" Foundation Slab	A1030	Level 1	A1030-
Floors	Floor	LW Concrete on Metal Deck	B1010400	Level 2	B10104
Structural Columns	W-Wide Flange-Column1	W10X49 2	B1010250	Level 2	B10102
Columns	Round Column	18" Diameter	B1010240	Level 2	B10102
Floors	Floor	LW Concrete on Metal Deck	B1010400	Level 3	B10104
Structural Columns	W-Wide Flange-Column1	W10X49 2	B1010250	Level 3	B10102
Columns	Round Column	18" Diameter	B1010240	Level 3	B10102
Walls	Basic Wall	Exterior - EIFS on Mtl. Stud - Pattern 2	B2010100	Level 1	B20101
Walls	Basic Wall	Interior - 4 7/8" Partition (1-hr)	C1010145	Level 1	C10101
Walls	Basic Wall	Interior - Core Walls	C1010145	Level 1	C10101
Doors	Single-Flush	32" x 84"	C1020300	Level 1	C10203
Stairs	Stair	8" max riser 11" tread	C2010	Level 1	C2010-
Railings	Railing	Rail Only	C2010400		C20104

Task Name	Duration	St
Case Study: Autodesk Office Building	99 days	Fri
Ground Floor	77 days	Fri
First Floor	56 days	Sa
Second Floor	51 days	Th
Floor	1 day	Th
Columns	6 days	Fri
B1010250-W-Wide Flange-Column1-W10X49 2-L02	6 days	Fri
B1010240-Round Column-18" Diameter-L02	6 days	Fri
Walls	19 days	Fri
Exterior Walls	14 days	Fri
Basic Walls	10 days	Fri
B2010100-Basic Wall-Exterior - EIFS on Mtl. Stud-L02	10 days	Fri
Curtain Walls	4 days	M
B2020200-Curtain Wall-Translucent Wall Panels-L02	4 days	M
Interior Walls	5 days	Fri
Basic Walls	5 days	Fri
Doors	1 day	W
Interior Doors	1 day	W
Windows	2 days	Fri
Ceilings	2 days	Th
C3030210-Compound Ceiling-2' x 2' ACT System-L03	2 days	Th
Railing	1 day	Fri
C2010400-Railing-Guardrail - Pipe-L02	1 day	Fri
D1010-Elevator-Center-80" x 51" ADA min.-L02	1 day	Sa
Beams	15 days	Th
B1010464-W-Wide Flange-W12X26-L03	15 days	Th
B1010464-W-Wide Flange-W14X30-L03	15 days	Th
B1010464-W-Wide Flange-W16X26-L03	15 days	Th

Fig. 57.3 Case study results: **a** scheduling sample input list, **b** project schedule, and **c** final 4D model in the simulation tool

pattern and to write this pattern into the.xml file. Next, the model and.xml file were imported into Navisworks successively to generate search sets automatically. Hence, all the model elements were assigned to search sets according to their task IDs.

The following step is generating the input list for scheduling. The list includes information of element groups such as their category, family name and type, level and assembly code, and 4D Task ID. Dynamo generated this list and exported it into Excel file (Fig. 57.3a). The list was rearranged according to the scheduler preference to facilitate construction of WBS-based schedule and the schedule was developed by categorizing the tasks in the list under WBS structure in Microsoft Project (Fig. 57.3b). After the schedule has been completed, the project schedule file was imported into Navisworks. In Navisworks, applying auto-attach using the rule as "Name" of the activities matches with "Search Sets", the search sets were mapped with schedule activities automatically. The result showed that except 2 types of 4D Task IDs (curtain walls and structural beams systems), the rest of the search sets were auto-attached to their activities. Curtain wall system consists of mullions and panels and structural beam system is composed of beams. Therefore, the mullions, the panels, and the beams were assigned with different 4D Task IDs and no element existed for curtain walls and structural beam systems in Navisworks. Due to this, the search set did not find any elements to map the schedule tasks with. Finally, Task Type is selected as "Construct" and simulation options were adjusted and 4D simulation was run (Fig. 57.3c).

Throughout the implementation of automated 4D modeling with test case building, the output of each step was compared with the manually created model's outputs for checking the accuracy of the developed method. The differences between two model outputs in each step were examined and the comparison showed that same output can be correctly generated with the automated method. Moreover the repetitive actions in manually created 4D model, especially during task ID assignments in the model and search sets generation in the simulation tool, performed in a fraction of a time with the developed method.

57.4 Discussion and Conclusion

In this study, a model based method is developed to facilitate 4D modeling by automating the labor-intensive, time-consuming and error-prone steps. This method saves time, eliminates the possibility of man-made errors in the process and improves communication between 4D modeling tools. The performance of the developed method was tested with a well-known office building model. The results showed that improvements offered by this method enabled to automate the critical steps in 4D modeling and reduced the process time without any information loss.

The developed method conceptually offers a generalized solution to generate 4D models for different types of construction projects. However, besides the test case model, a good number of 4D models needs to be examined to develop a generalized encoded method which is applicable to any construction project.

This method presents accurate simulation results when the 3D model is complete. Therefore, missing information in model elements is checked via inspection step to detect the problems and complete the model; however, if incorrect data is entered into the model, this would result in generation of erroneous task ID information which may cause logical problems in 4D scheduling. Moreover, level of detail in BIM model determines the level of detail in 4D modeling and scheduling. For instance, if the temporary structures are modeled in BIM model, its effect can be analyzed in 4D modeling. Therefore, quality of BIM model is one of the main precondition for obtaining accurate and detailed simulation results.

This study offers automated task ID generation using model elements' properties; however, labeling of task IDs depends on the availability of the information in the 3D model and the required level of detail in the schedule. Hence, considering the compatibility of the model granularity with schedule details, the scheduling preferences should be taken into consideration for labelling task IDs. Therefore, a level of detail framework for 4D scheduling should be developed to determine (i) number and types of WBS levels and (ii) properties of the model elements that should be used to label task IDs in each level.

In theory, the method reveals that different 4D Task IDs can be assigned to same model elements; however, in current practice, as a one of the limitations of this study, only one 4D Task ID is assigned to each model element. Therefore, improvements are required in 4D Task ID generation/assignment process to enable assigning more than one 4D Task IDs (such as for; brick laying, insulation, plastering, painting, etc.) to the same model element (e.g. wall) to develop more realistic 4D models reflecting layers of elements or steps of construction methods. The other limitation of the developed method is that, it does not generate nonphysical tasks (e.g. procurement of the construction material) or physical tasks for elements that are not modeled (e.g. formwork) as inputs for the schedule. Therefore, process templates compatible with WBS as in [11] should be developed to complete missing tasks and facilitate the scheduling process.

In future studies, this method will be improved by (i) adding process templates to reflect the activities in the schedule for nonphysical tasks and physical task that are not modeled, (ii) assigning multiple task IDs to the same model element for more realistic scheduling, and (iii) developing a level of detail framework for determining the pattern to label task IDs for 4D scheduling; in order to provide a more comprehensive automated solution to 4D modeling process.

References

1. Koo, B., Martin, F.: Feasibility study of 4D CAD in commercial construction. J. Constr. Eng. Manag. **126**, 251–260 (2000)
2. Balakina, A., Simankina, T., Lukinov, V.: 4D modeling in high-rise construction. In: E3S Web of Conferences (2018)
3. Dawood, N., Sikka, S.: Development of 4D based performance indicators in construction industry. Eng. Constr. Archit. Manag. **16**, 438–458 (2009)
4. Akinci, B., Fischen, M., Levitt, R., Carlson, R.: Formalization and automation of time-space conflict analysis. J. Comput. Civ. Eng. **16**, 124–134 (2002)
5. Bansal, V.: Integrated CAD and GIS–based framework to support construction planning: case study. J. Archit. Eng. **23**, 5017005 (2017)
6. Zhang, J.P., Hu, Z.Z.: BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. Autom. Constr. **20**, 155–166 (2011)
7. Martínez-Aires, M.D., López-Alonso, M., Martínez-Rojas, M.: Building information modeling and safety management: a systematic review. Saf. Sci. **101**, 11–18 (2018)
8. Weldu, Y.W., Knapp, G.M.: Automated generation of 4D building information models through spatial reasoning. In: Construction Research Congress 2012, pp. 612–621 (2012)
9. Hamledari, H., McCabe, B., Davari, S., Shahi, A.: Automated schedule and progress updating of IFC-Based 4D BIMs. J. Comput. Civ. Eng. **31**, 4017012 (2017)
10. Tulke, J., Hanff, J.: 4D construction sequence planning-new process and data model. In: Proceedings of CIB-W78 24th International Conference on Information Technology in Construction, pp. 79–84 (2007)
11. Park, J., Cai, H.: Automatic construction schedule generation method through BIM model creation. In: 2015 International Workshop on Computing in Civil Engineering, pp. 620–627 (2015)
12. Ciribini, A.L.C., Mastrolembo Ventura, S., Paneroni, M.: Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM pilot project. Autom. Constr. **71**, 62–73 (2016)
13. de Vries, B., Harink, J.M.J.: Generation of a construction planning from a 3D CAD model. Autom. Constr. **16**, 13–18 (2007)
14. Kim, K., Cho, Y.K.: Construction-specific spatial information reasoning in building information models. Adv. Eng. Inform. **29**, 1013–1027 (2015)
15. Kataoka, M.: Automated generation of construction plans from primitive geometries. J. Constr. Eng. Manag. **134**, 592–600 (2008)
16. Sigalov, K., König, M.: Recognition of process patterns for BIM-based construction schedules. Adv. Eng. Inform. **33**, 456–472 (2017)

Part IV

Intelligent Autonomous Systems

58 An Autonomous Thermal Scanning System with Which to Obtain 3D Thermal Models of Buildings

Antonio Adán, Samuel A. Prieto, Blanca Quintana, Tomás Prado, and Juan García

Abstract

This paper presents a mobile platform that autonomously collects 3D thermal/coloured data and obtains a raw 3D thermal model of the insides of buildings. This platform has been developed with two objectives, the first of which is to develop a new hybrid 3D colour/thermal laser scanner system that will provide 3D thermal points of the 360 × 180 space. The second consists of making the earlier thermal scanner autonomous, such that the best scanner positions required to completely cover the scene can be carried out. This entails proposing an original and efficient new next-best-thermal-scan algorithm (NBTS). After collecting, aligning and mixing 3D thermal data from different positions of the scene, a complete thermal point cloud of the scene is generated. The output of the autonomous system is a raw 3D thermal model of a scene, which can be further processed. The system has been tested in the insides of buildings under occlusion conditions, providing promising results.

Keywords

3D laser scanner • Thermal camera • 3D thermal modelling

58.1 Introduction: A Brief State of the Art

The monitoring and inspection of the energy efficiency of buildings have taken place for many years and have, to date, primarily been carried out by humans carrying thermal cameras. This signifies that 2D thermal imaging and, more precisely, indoor thermography, has been used to visually detect thermal characteristics, such as thermal bridges, a loss of energy or humidity. The world of the automatic 3D thermal modelling of buildings is, however, now flourishing with the advent of the latest precise 3D sensors, reliable mobile robots and efficient AI algorithms [1].

The autonomous thermal scanning problem appeared as a new and challenging subject in the last decade. However, little research has been carried out to date, and only partial aspects of the whole problem have been solved. The vast majority of the existing methods are focused on the thermal sensorial system, which is essentially composed of LiDARs [2], photogrammetric cameras [3] or depth cameras [4], all of which are combined with thermal cameras through the use of different

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methodologies. However, these systems collect only 3D thermal data of the part of the scene that is covered by the field of view of the thermal camera. Additionally, autonomy is frequently tackled not by a robot, but by a human being carrying or pushing the whole sensorial system [5]. Other indoor thermal mapping approaches are commanded or teleoperated, as is the case of that presented by Mader et al. [6]. This is a complex system composed of three UAVs equipped with a thermal camera and laser scanner, which is used for building inspection tasks.

Very few autonomous platforms have been developed to date. A representative example of an autonomous system is that of Borrmann et al. [7]. This is a thermal scanning mobile system that automatically creates low resolution thermal mesh models of the indoors of buildings. The robot initially uses a 2D next best view approach until it is assumed to be inside a room. From one position of the robot, the system covers 360-thermal scans but with a limited vertical FOV. Since the platform cannot rotate vertically, the completeness of the thermal model of the scene is not guaranteed.

In this reduced world of autonomous mobile thermal scanning systems, our principal contributions are as follows.

First, our scanning platform is complete in the sense that the sensorial setup (3D laser scanner + colour camera + thermal camera) can obtain 360 thermal data per scan and, if necessary, rotate vertically in order to cover a higher vertical FOV of the scene. Second, our original 3D next best view algorithm is based on maximising the visibility of the structural components of the building (i.e. ceiling/ground/walls) from the next robot position and is able to work in the presence of occlusion. Third, an original robot positioning and navigation procedure is proposed.

58.2 An Overview of the Autonomous Thermal Scanner System

A brief summary of our system is provided as follows. The scanning platform is prepared to obtain separate 3D thermal models of each room on the floor of a building, which are subsequently aligned to eventually generate a single model. Since we are dealing with inhabited environments, a room should probably be sensed from different robot positions, which are calculated by our NBTS algorithm. This is a probabilistic-based approach that minimises the uncertainty of finding new regions of structural elements (i.e. walls, floor and ceiling) (SEs) in the next scan position. In each new scan, the already visible (sensed) space is discretized into minute voxels and those that lie on the voxels of the recognised SEs are characterised by their colour and temperature. When no new SE voxels are found, a stopping criterion is satisfied, and the final 3D thermal model of the room is created. The robot then moves towards the door of the room, enters an adjoining room and runs a new room-scanning process.

Figure 58.1a shows a flowchart in which the scanner and the actions of the robot appear separately but are, simultaneously, connected at several points. The scanner is focused on taking 360-thermal scans, generating the obstacle map and calculating the position of the next best thermal scan. With regard to the robot, it provides the odometry data, aligns the

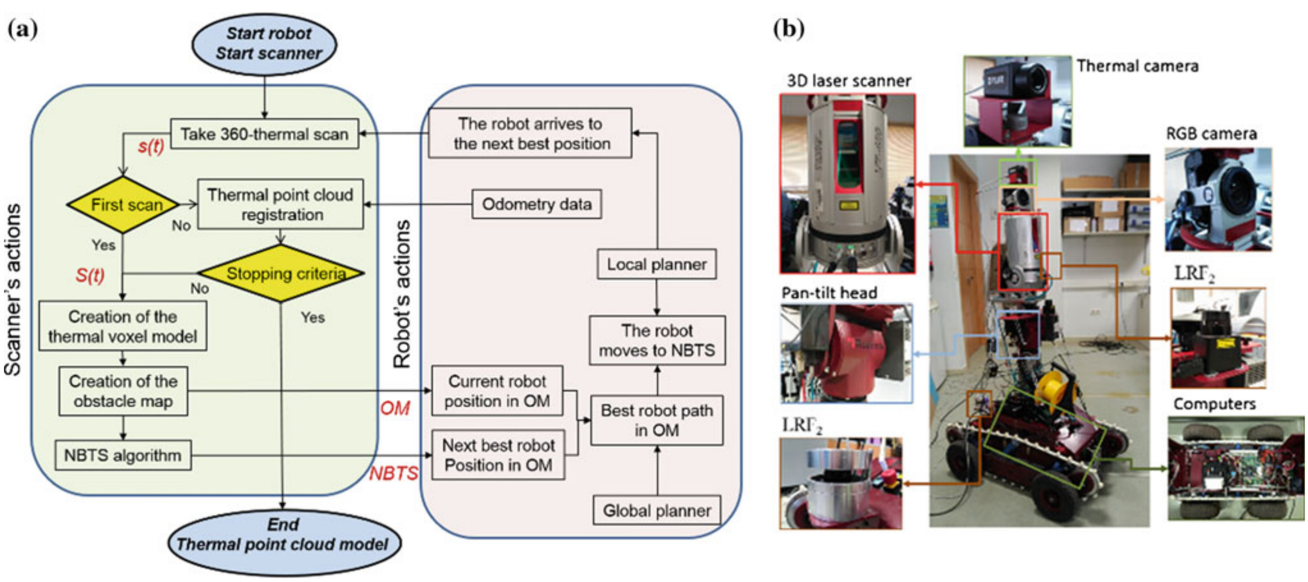

Fig. 58.1 **a** Performance of the autonomous thermal scanner system. **b** Components of MoPATD

accumulated thermal data with the current thermal point cloud and navigates safely towards the next position calculated by using its global and local planners. A description of the components of the mobile platform follows.

We have implemented the autonomous scanning system on the MoPATD (Mobile Platform for Autonomous Thermal Digitization) platform, which is composed of several components: a Robotnik Guardian mobile robot, a Riegl VZ-400 3D laser scanner, an RGB Nikon D90, a FLIR A65 thermal camera and two Hokuyo URG-04LX-UG01 laser range finders (denominated as LRF1 and LRF2). The whole system is managed by two computers. Figure 58.1b shows the components of MoPATD.

The mobile robot is 103.87 cm (length) × 78.20 cm (width) × 100 cm (height) in size and weighs 111.22 kg. Two 300 W motors are used to power four wheels. The speed of the mobile platform is 20 cm/s at maximum velocity. LRF1, like LRF2, has a maximum range of 5.60 m, a scan angle of 240° and a data rate of 10 Hz.

The 3D scanner is used to collect 3D dense point clouds in a range of 500 m. A single scan covers an area of 360° × 100°, takes around 73 s and yields 8.5 million coordinates in the scanner reference system. In our experimental tests, the horizontal and vertical angular resolution was set to 0.065°. The accuracy of the distances measured is 5 mm and the precision is 3 mm (one sigma 100 m range). The scanner is placed on a pan-tilt servo motor, signifying that it can be rotated vertically.

The RGB Nikon D90 camera has a field of view (FOV) of 94° × 70° and provides images of 4288 × 2848 pixels. The FLIR A65 thermal camera has a resolution of 640 × 512 pixels, with a FOV of 45° × 37° at a frequency of 30 Hz. The temperature range in the High Mode is between 233° and 823° K with a precision of 0.4° K.

58.3 Obtaining a 360-Thermal Point Cloud

58.3.1 Obtaining a Single 3D Thermal Shot

Before obtaining 3D thermal data, several off-line processes concerning vignetting, intrinsic and extrinsic calibrations are tackled. The intrinsic calibrations of both the RGB and thermal cameras have been carried out following the standard method of [8]. The vignetting effect have been empirically corrected after calculating a function that provides the radial temperature loss.

The external calibration consists of finding the projective transformation M between the laser scanner and the thermal camera coordinate systems. Assuming that (X_p, Y_p, Z_p) are the coordinates of a certain point in the scanner coordinate system and that (X_f, Y_f) are the coordinates (in pixels) of the corresponding point projected onto the thermal image, matrix M is represented as a 3 × 4 matrix in Eq. (58.1).

$$\begin{pmatrix} \lambda X_f \\ \lambda Y_f \\ \lambda \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \end{pmatrix} \begin{pmatrix} X_p \\ Y_p \\ Z_p \\ 1 \end{pmatrix} \tag{58.1}$$

In order to automatically recognize a point in the 3D space and its projected pixel in the thermal image, we have designed targets with discriminative properties as regards reflectance and temperature. The target consists of a small plastic ice cube to which a reflective circle is attached. Owing to its high reflectivity and low temperature the target is easily identified in the reflectance polar image and thermal image, respectively (see Fig. 58.2a).

If $r_{34} = 1$ and λ is removed, Eq. (58.1) is extended to n points in Eq. (58.2), which is resolved for variables $r_{11}, r_{12}, \ldots, r_{33}$.

$$\begin{pmatrix} X_{f1} \\ Y_{f1} \\ \vdots \\ X_{fn} \\ Y_{fn} \end{pmatrix} = \begin{pmatrix} X_{p1} & Y_{p1} & Z_{p1} & 1 & 0 & 0 & 0 & 0 & -X_{f1}X_{p1} & -X_{f1}Y_{p1} & -X_{f1}Z_{p1} \\ 0 & 0 & 0 & 0 & X_{p1} & Y_{p1} & Z_{p1} & 1 & -Y_{f1}X_{p1} & -Y_{f1}Y_{p1} & -Y_{f1}Z_{p1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X_{pn} & Y_{pn} & Z_{pn} & 1 & 0 & 0 & 0 & 0 & -X_{fn}X_{pn} & -X_{fn}Y_{pn} & -X_{fn}Z_{pn} \\ 0 & 0 & 0 & 0 & X_{pn} & Y_{pn} & Z_{pn} & 1 & -Y_{fn}X_{pn} & -Y_{fn}Y_{pn} & -Y_{fn}Z_{pn} \end{pmatrix} \begin{pmatrix} r_{11} \\ r_{12} \\ r_{13} \\ r_{14} \\ r_{21} \\ r_{22} \\ r_{23} \\ r_{24} \\ r_{31} \\ r_{32} \\ r_{33} \end{pmatrix} \tag{58.2}$$

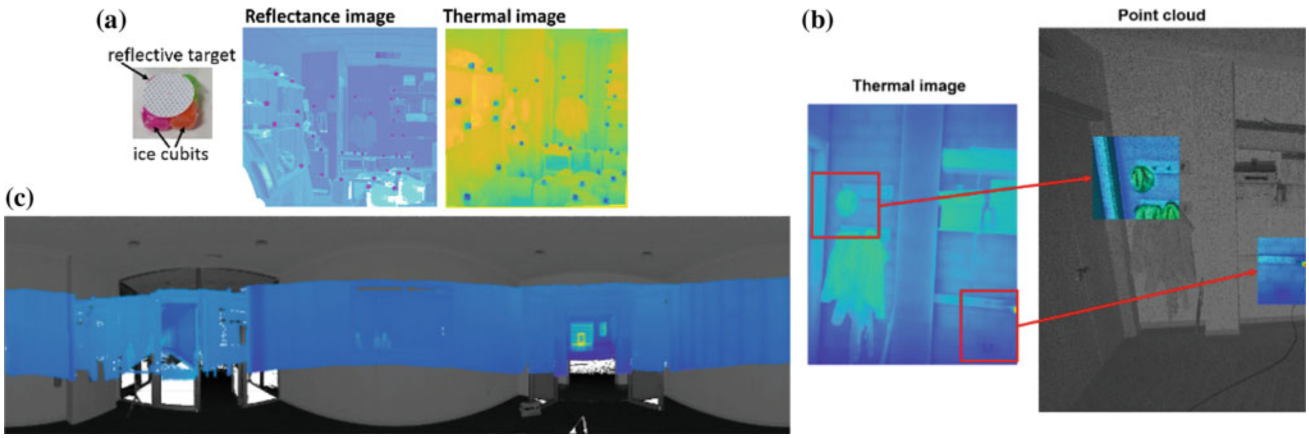

Fig. 58.2 **a** Reflectance and thermal images with reflective frozen targets used for calibration. Targets are clearly identified in both images. **b** A detail of a single thermal image and the corresponding 3D points. **c** A 360-thermal point cloud represented on a polar image

In a matrix notation, the corresponding equation $\boldsymbol{C} = \boldsymbol{WP}$ is solved in Eq. (58.3) and the matrix M is eventually found.

$$P = \left(W^T W\right)^{-1} W^T C \tag{58.3}$$

58.3.2 360-Thermal Point Cloud from a Position of the Robot

After calculating matrix M, the temperature is assigned to each 3D point in five sequential steps, thus obtaining a thermal point cloud of the scene.

The pant-tilt head is fixed at a certain tilt angle α. Initially, $\alpha = 0$, and the set scanner-RGB camera-thermal camera remains in a vertical position.

The laser scanner takes a 360-scan and captures n points, with coordinates $\left(X_{p(i)}, Y_{p(i)}, Z_{p(i)}\right), i = 1, 2, \ldots, n$, according to a specific vertical FOV of the scanner.

1. The thermal (and the RGB) camera rotates around the Z-axis of the scanner taking m shots, thus covering a horizontal range of 360°. Note that the scanner, the RGB and the thermal camera rotate together.
2. The coordinates $\left(X_f, Y_f\right)_k$ in the k-th thermal shot corresponding to a subset of points $\left(X_p, Y_p, Z_p\right)_k$ are then calculated taking into account the k-th horizontal rotation angle of the camera. Finally, the temperature is assigned to the points $\left(X_p, Y_p, Z_p\right)_k$. Figure 58.2b shows an example of this.
3. If $\alpha \neq 0$, the thermal point cloud is aligned with the initial scanner coordinate system and the accumulated 360-thermal point cloud is stored (Fig. 58.2c).

58.4 Autonomous Thermal Scanning

58.4.1 3D Data Processing to Find the Next Thermal Scan

Since the objective is to produce a 3D thermal model of the indoor of a building, our scanning method is focused on collecting as much temperature data regarding the structural components as possible. The majority of the current 3D mapping approaches (not exclusively thermal mapping) that aim to create a 3D model of a building may be inefficient because the scanning stage is viewed as a process in which the objective is to accumulate data, no matter what the origin of the data is [9]. However, our NBTS algorithm is based on collecting the thermal data of the hypothetical potential structural elements in the scene.

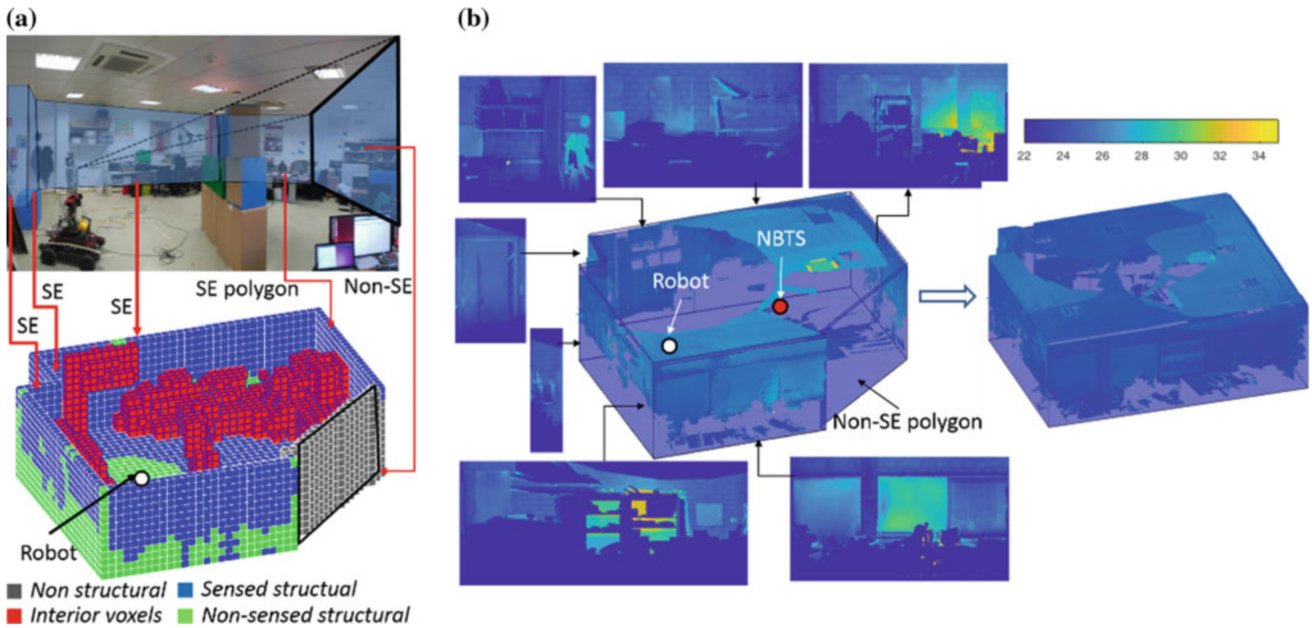

Fig. 58.3 **a** Example of a voxel space for the first thermal scan with SE and Non-SE polygons. **b** RoI of the scene with the associated temperature, the NBTS (first candidate in list $\{l\}_{NBTS}$) and the thermal orthoimages of the walls detected in the RoI (left). Thermal model after three thermal scans (right)

After the *t*-th scan, we define a temporal region of interest (RoI) of the scene as the polyhedron that contains the accumulated thermal point cloud. In contrast with other scanning methods [10], the boundaries (i.e. the RoI) of our workspace are not hypothesized, but rather update as a new scan is taken. This makes our approach versatile for arbitrarily-shaped scenes.

In order to work in a structured dataset, the 3D space inside the RoI-which includes the 3D sensed points and their associated temperatures—is discretised into voxels, each containing the average temperature of the points inside the voxel. If a voxel does not contain data, no temperature is associated with it. We thus generate a voxel space in which the RoI is made of polygons labelled as *structural element* (SE) and *non-structural element*. This classification is carried out by following the SVM learning algorithm published in [11]. Intuitively, an SE polygon contains one or more zones of concentrated sensed voxels, whereas a Non-SE polygon has a low number of (or no) disperse sensed voxels. An SE polygon additionally contains *sensed* and *non-sensed structural voxels* (see Fig. 58.3a for a better understanding of this).

In this labelled voxel space, a sorted list of next best scanner positions $\{l\}_{NBTS}$ is determined by means of a certainty function. This is formulated in probabilistic terms by means of the SE membership probability which, for a voxel, is defined as the probability of it being labelled as a *sensed structural voxel* in the next scan.

As is explained below in more detail, the robot then calculates an obstacle map (OM) and selects the next best scan position from among the former list of candidates. The first free path, according to the global path planning algorithm, is chosen. Finally, the robot moves using its own local planner and reaches its final position. Figure 58.3b shows the thermal models calculated after the first and third scans.

58.4.2 Robot Navigation and Integrated 3D Thermal Model

Assuming that the list of the next best positions $\{l\}_{NBTS}$ has been calculated, we distinguish three principal stages in the robot navigation: the current obstacle map, the best path and the movement of the robot.

The current obstacle map is an image that the robot uses for a safe navigation. The first version is built by performing a top-projection of the horizontal data slice which goes from the ground to the height of the MoPATD. Data above the MoPATD obviously have no influence on the navigation of the robot. On this obstacle map, it is assumed that a black pixel signifies an obstacle and a white pixel represents a free position. Owing to the size of the MoPATD and the security requirements (the robot must be a certain distance from the obstacles), the free space in the first OM version is highly

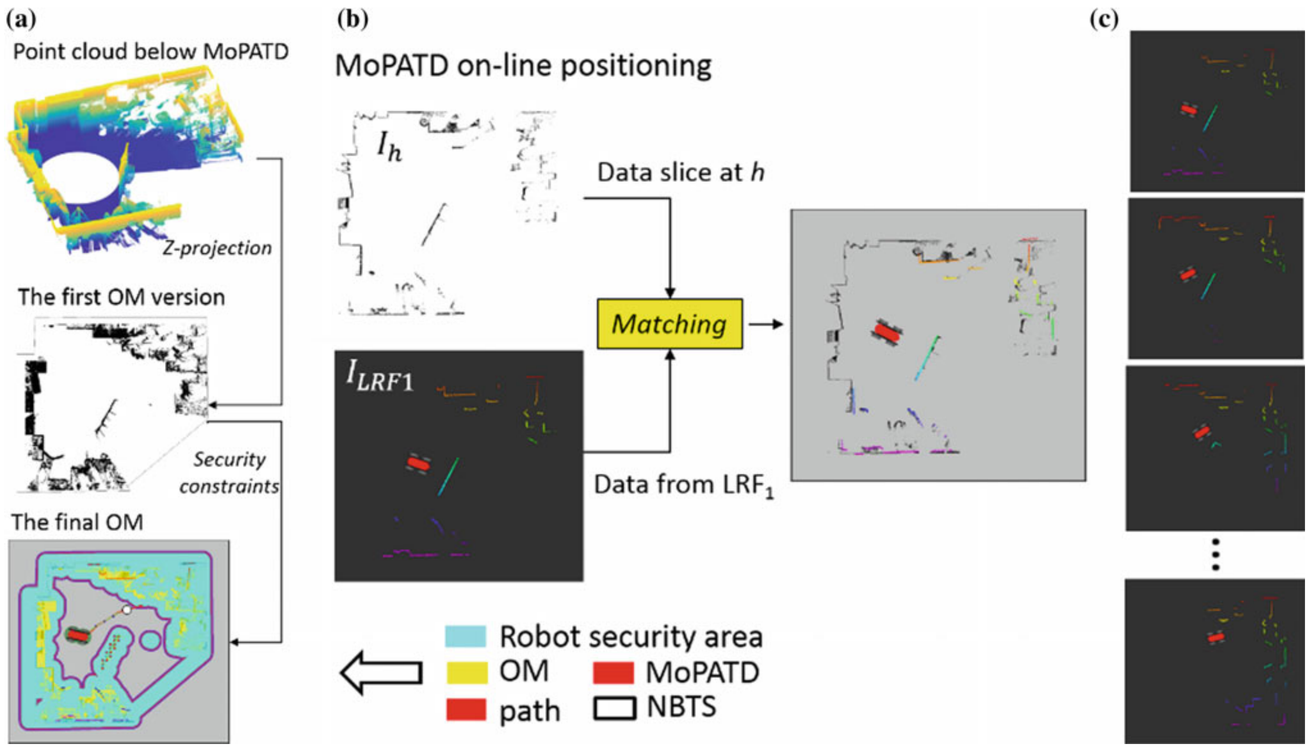

Fig. 58.4 **a** Localizing MoPATD in OM. A view of the data below the height of the MoPATD (left), the initial OM (centre) and the final OM (right). The security regions are shown in cyan and the free positions are in grey. The next best position of the robot and the path calculated by the Navfn planner are included. **b** MoPATD navigation. Result obtained after matching I_h and I_{LRF1} (above). **c** A sequence of images I_{LRF1} from the origin to the end point

reduced to a second version, in which the robot can safely navigate. Taking all this into account, the first candidate in the list $\{l\}_{NBTS}$ that lies in a free region is chosen as the definitive next best position of the scanner (see Fig. 58.4a).

The path from the current to the next position is obtained using the Navfn planner, which runs under ROS (Robot Operating System). This planner uses a costmap to find the minimum cost path from the start point to the end point in a gridded OM. The navigation function is computed using the Dijkstra algorithm.

When the MoPATD moves, a robot positioning algorithm must be run. This signifies that the robot must know, at any moment, its precise position inside the OM. In order to match the information provided by the frontal laser range finder (i.e. LRF1) with the calculated OM, we place LRF1 near the base of the laser scanner, at a certain height h. The information read by LRF1, denominated as I_{LRF1}, can thus be matched to a narrow slice of points at this vertical height h. The map generated by this data slice, which we denote as I_h, is taken as a positioning reference (see illustration in Fig. 58.4b). The robot localizes itself by means of the Adaptive Monte Carlo Localization (AMCL) algorithm.

A new 360-thermal scan must be registered in the world coordinate system, which was established by the first position of the scanner. In order to ensure an efficient registration of a new scan, the odometry of the robot first provides an approximate transformation between the last and the current robot positions. This coarse registration is later refined by using the ICP algorithm.

The scanning process is repeated until a particular stopping criterion is satisfied. The stopping criterion is based on two threshold parameters: the percentage of the SE areas that has been sensed (according to the current RoI) and the increase in the sensed SE area with respect to the last thermal scan. These parameters were set empirically at 90 and 1%, respectively. At the end of this process, the thermal point cloud of the architectural structure of the indoor of the building is generated.

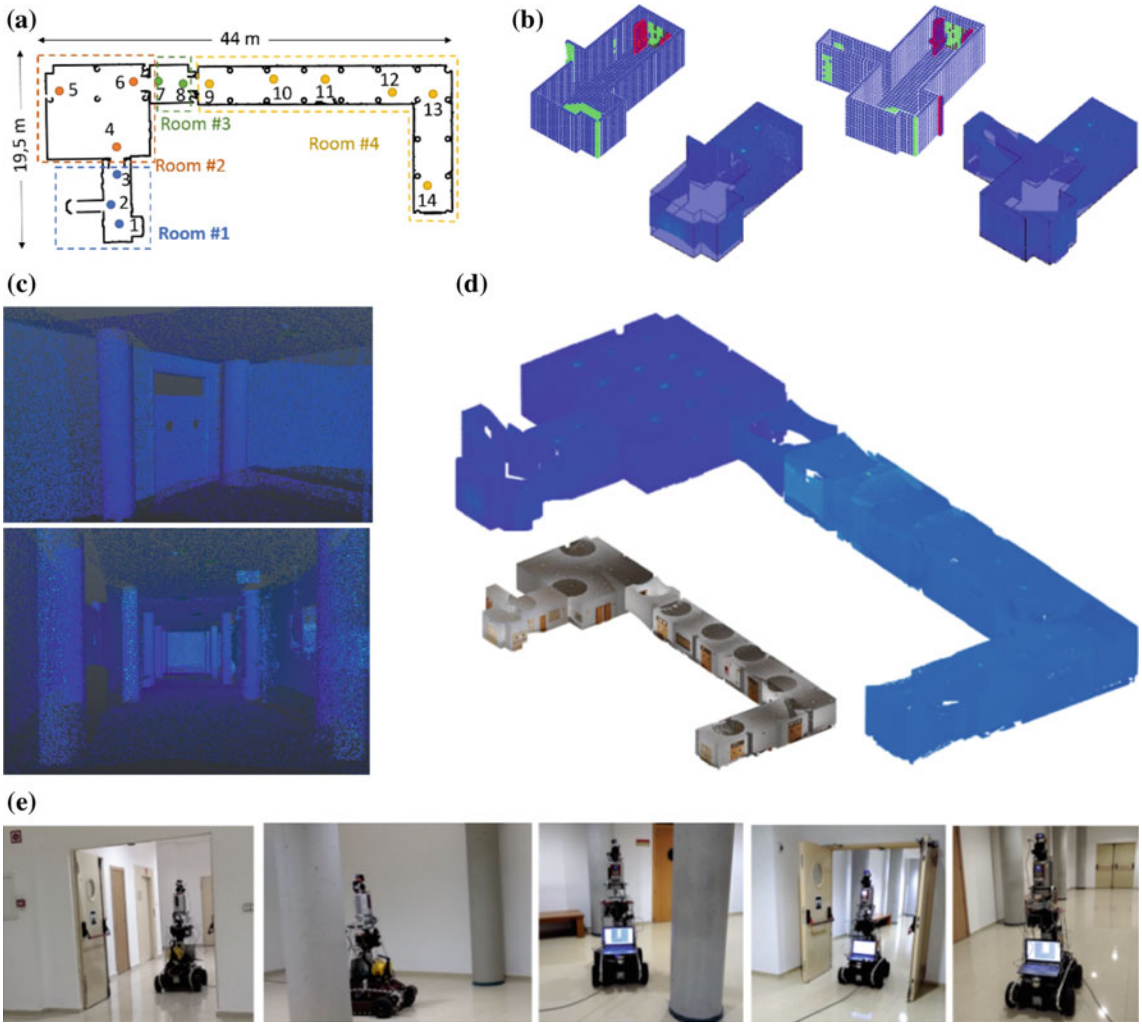

Fig. 58.5 **a** Blueprint of the scene with positions of MoPATD during the scanning session. **b** Evolution of the voxel space and the thermal model in room #1. **c** Some views of the thermal model of the scene. **d** The 3D thermal model. **e** Photos of MoPATD

58.5 Experimental Test

In this section, we present the results obtained for MoPATD on a representative case study. The scene consisted of several rooms in the basement of the Industrial Engineering School at Castilla-La Mancha University, Spain.

The scene is 858 m^2 in size with four lecture halls that are 3.15 m high. The scenario has a large number of columns (24), different kinds of doors (31) and SEs (40). Rooms #2 and #4 are particularly large. MoPATD started scanning this scenario in room #1 and entered the remaining rooms by following the order shown in Fig. 58.5a. In total, the platform stopped in 14 positions and collected 51 million thermal data.

As mentioned in Sect. 58.2, the robot moves until the stopping criteria are verified. At this point of the process, the system runs the door detection algorithm and the platform goes towards the open door that leads to the next room. The robot then stops one meter in front of the door, takes the last scan of the room, passes through the door and stops one meter away from the door. The first scan of the new room is then taken and the process starts again. This is the most critical problem in the whole experiment. Fortunately, the system detected the doors and successfully entered the new room in 100% of the cases. In addition, there was a 95% of successfully identified SEs and a 5% of false negatives.

An example of the evolution of the voxel space and the thermal models calculated in room #1 is illustrated in Fig. 58.5b. Figure 58.5c, d represent some views of the thermal model in rooms and the total thermal model and Fig. 58.5e shows some photos of MoPATD moving in the scenario and passing through doors.

Some interesting time data as regards different steps of the scanning process follows. The scanning session took a total of 1.29 h. The system spent most of the time collecting (43%) and transferring (21.3%) data. The time percentages for the rest of the processes were: identification of outliers (5%), registration (1.3%), RoI (5%), NBTS (15.3%) and the movement of the robot (9.2%).

58.6 Conclusions

This paper presents MoPATD, an autonomous platform that provides a 3D thermal model of the architectural structure of the indoors of a building. The system is able to decide the next best scan position based on the current information of the structure of the building, and navigates from one position to another until a room is completely sensed. MoPATD subsequently moves towards the door of the room, enters the adjoining room and begins the scanning process. This system is one of the few platforms in the world with this degree of autonomy. MoPATD has been successfully tested in real environments.

However, the current version of MoPATD has evident limitations that need to be tackled and some improvements will hopefully be made in the next few months. One of the current problems is that the system takes and processes very-high density point clouds (above one data/cm^2) which, for very large rooms, entails excessive memory and time resources. This high data density is required for the precise detection of doors and, especially, small building components on walls (e.g. sockets, switches and signs), (see [12]). However, thermal maps do not require this degree of resolution and could be constructed faster and with much fewer memory requirements. Another important aspect is that MoPATD moves to an adjoining room only when the door is open. We aim to develop a manipulator robot that will be coupled to MoPATD, and that will be able to open closed doors.

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References

1. Cho, Y.K., Ham, Y., Golpavar-Fard, M.: 3D as-is building energy modeling and diagnostics: a review of the state-of-the-art. Adv. Eng. Inf. **29**, 184–195 (2015). https://doi.org/10.1016/j.aei.2015.03.004
2. Wang, C., Cho, Y.K., Gai, M.: As-is 3D thermal modeling for existing building envelopes using a hybrid LIDAR system. J. Comput. Civ. Eng. **27**, 645–656 (2013). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000273
3. Ham, Y., Golparvar-Fard, M.: An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery. Adv. Eng. Inf. **27**, 395–409 (2013). https://doi.org/10.1016/j.aei.2013.03.005
4. Rangel, J., Soldan, S., Kroll, A., Rangel, J., Kroll, A., Soldan, S., Kroll, A.: 3D Thermal imaging: fusion of thermography and depth cameras. In: International Conference on Quantitative Infra Red Thermography (2014)
5. Armesto, J., Sánchez-Villanueva, C., Patiño-Cambeiro, F., Patiño-Barbeito, F.: Indoor multi-sensor acquisition system for projects on energy renovation of buildings. Sensors (Switzerland) **16**, 1–14 (2016). https://doi.org/10.3390/s16060785
6. Mader, D., Blaskow, R., Westfeld, P., Weller, C.: Potential of UAV-Based laser scanner and multispectral camera data in building inspection. ISPRS Int. Arch. Photogram. Remote Sens. Spat. Inf. Sci. **XLI-B1**, 1135–1142 (2016). https://doi.org/10.5194/isprsarchives-xli-b1-1135-2016
7. Borrmann, D., Nüchter, A., Đakulović, M., Maurović, I., Petrović, I., Osmanković, D., Velagić, J., Maurovic, I., Petrović, I., Osmankovic, D., Velagić, J.: A mobile robot based system for fully automated thermal 3D mapping. Adv. Eng. Inf. **28**, 425–440 (2014). https://doi.org/10.1016/j.aei.2014.06.002
8. Heikkila, J., Silven, O.: A four-step camera calibration procedure with implicit image correction. In: IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pp. 1106–1112 (1997)
9. Blaer, P.S., Allen, P.K.: Data acquisition and view planning for 3-D modeling tasks. In: IEEE IROS, pp. 417–422, San Diego, CA (2007)
10. Potthast, C., Sukhatme, G.S.: A probabilistic framework for next best view estimation in a cluttered environment. J. Vis. Commun. Image Represent. **25**, 148–164 (2014). https://doi.org/10.1016/j.jvcir.2013.07.006
11. Quintana, B., Prieto, S.A., Adán, A., Vázquez, A.S.: Semantic scan planning for indoor structural elements of buildings. Adv. Eng. Inf. **30**, 643–659 (2016). https://doi.org/10.1016/j.aei.2016.08.003
12. Adán, A., Quintana, B., Prieto, S.A., Bosché, F.: Scan-to-BIM for "secondary" building components. Adv. Eng. Inf. **37**, 119–138 (2018)

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59

Productivity Improvement in the Construction Industry: A Case Study of Mechanization in Singapore

Chea Zhiqiang, Gurumurthy Balasubramaniam, and Ruwini Edirisinghe

Abstract

Globally, the construction industry is a key contributor to national economies including Singapore's. However, the industry is a serial productivity underperformer. The literature argues that mechanization, automation and use of advanced technologies help improve construction productivity, but real-world case studies are limited in number. This paper presents a case study of the introduction of mechanization to improve the level of construction productivity in Singapore. The case study under investigation was the production/fabrication of steel gratings, the conventional process of which depends heavily on labor with few workers present on site. The majority of these workers are migrant workers, which contributes to a significant social concern in Singapore. The case study organization introduced a more advanced laser cutting machine to the process. The project team observed the process of using the laser cutting machine, and quantitative and qualitative data were obtained. The researchers observed the processes, both conventional and updated, and recorded the data on both methods. The quantitative data were comparatively analyzed to investigate the relative quality, efficiency and productivity of the two methods. The data revealed that the mechanization process achieved a productivity improvement (or savings) in man-days of at least 78%. Material wastage was reduced, and moreover, less reliance was placed on migrant workers, which helped to mitigate the social concerns created by the influx of foreign workers to Singapore. The findings also shed some light on the positive influence of government incentives to improve the industry's productivity.

Keywords

Construction industry • Productivity • Automation • Mechanization

59.1 Introduction

The construction industry provides a massive contribution to civilization and urbanization, and it is one of the most important industries in the world. The construction industry contributes significantly to the gross domestic product (GDP) of Singapore (5%) [8]. As stated in HOME [7], the construction industry in Singapore depends heavily on manpower, and more than 85% of the total construction workforce is made up of foreign workers. These workers are mostly unskilled and come from developing countries. The number of projects in Singapore is increasing at the same time as wages are rising and a shortage of local workers is making the country more dependent on foreign labor.

As the demand for housing and infrastructure increases, the productivity and efficiency of the construction industry must improve to meet it. The well-being and standard of living of a nation can be affected by the level of productivity in three ways: national competitiveness, real income, and quality of life [11, 12, p. 4]. Domestically produced goods will be less

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competitive if the level of productivity in the country does not increase as fast as in other countries. A nation's real income does not grow if the production of goods and services using the relevant resources is low [11, 12, pp. 3–4].

Productivity is the economic measure of the amount of output produced per unit of input [10]. Construction output is usually measured in length, weight or volume, and the input in man hours or labor. The government of Singapore has set an ambitious target of raising construction productivity by two to three per cent per year to 2020; raising productivity is the only viable route for the construction industry. The use of mechanization and the upgrading of workers' skills will help companies to lower their costs in the long term [3]. Productivity increases also help to improve a country's quality of life. The influx of foreign workers can create social problems, including overcrowding. There are currently 1.32 million foreign workers in Singapore, and this has increased social tensions; the government has received many complaints about overcrowding on trains and buses, for example [16]. Therefore, it is important to address ways to reduce the construction industry's reliance on labor.

59.2 Background

59.2.1 Mechanization to Improve Productivity

The construction industry depends heavily on manpower, especially in Singapore. Until now, Singapore's construction industry has depended a great deal on cheap foreign labor for certain types of work, such as tiling, fabricating steel gratings, plastering etc., and less on advanced technologies. The foreign workers come from nearby developing countries, and anecdotal evidence suggests that most have little or no experience working in the construction industry. Many of these workers have little education and do not have any knowledge or proper skills to work in the industry. With the increase of migrant workers in the industry comes a concern about safety management. Because workers face literacy, comprehension and other language barriers, safety education and training on site are not effective [4]. This not only increases the number of injuries and fatalities, but also decreases the level of construction productivity on sites.

Designs of buildings/structures are becoming more and more complex, and space on construction sites is becoming more and more limited. As a result of this, many countries are trying to adopt different type of advanced technology and mechanization to increase productivity [9, 15, 17]. For example, the Malaysian construction industry, facing problems such as low productivity, labor shortages, decreasing quality, safety issues etc., is trying to adopt innovative technology such as the industrialized building system (IBS) as an alternative to conventional construction methods [17]. Hong Kong's Housing Authority has adopted prefabrication technology for its projects, and this has proven to be beneficial in terms of environmental degradation, material wastage, and productivity [15]. It is recommended that wider adoption be achieved through government regulation and controls, and the provision of incentives. Some construction companies in Nigeria also relied heavily on labor, which caused delays and low quality outcomes. These problems were solved by mechanization [9].

59.2.2 Singapore Initiatives

The Productivity Innovation Project (PIP) Scheme is part of the S$250 million Construction Productivity and Capability Fund (CPCF) introduced by Singapore's government to help the construction industry improve its productivity and capability. The aim of the PIP Scheme is to encourage prefabricators and contractors in Singapore to begin development projects that will improve their site processes and to build up capability to achieve higher on-site productivity. This scheme also helps contractors to adopt labor-efficient technologies, or to re-engineer site processes to improve productivity or reduce the dependency on on-site workers. The types of cost supportable under this scheme include equipment, manpower, professional services/subcontracting, materials and acquisition of intellectual property rights. This financial support is provided on a reimbursement and co-funding basis. Under the standard PIP Scheme, the company can be co-funded up to 50%, capped at S $100 K per application, if the technology could improve productivity or generate savings in man-days of at least 20%. Under the enhanced PIP Scheme, the company can be co-funded up to 70%, capped at S$300 K per application [1].

59.3 Methodology

The case study organization (CSO) is a building and civil engineering company in Singapore registered as grade B2 for general building work and grade C1 for civil engineering work by the Building and Construction Authority (BCA). It employs 175 workers and has an annual turnover of S$20–25 million. The company is involved in public and private building, landscaping and infrastructure projects in Singapore.

The CSO has applied for support under the BCA's PIP Scheme for the use of laser cutting machines for their projects. The present study involved engagement with the experiments related to the introduction of this new machine. This study was carried out to comparatively analyze the productivity of the laser cutting machine in the manufacture of steel drain gratings compared to the conventional manual method. Recently, a laser cutting machine was purchased to take over the work. The machine is able to fabricate various metals, such as steel, aluminium etc. As an experiment, the CSO carried out production of steel gratings using both labor-based (conventional) and the laser cutting machine (new) simultaneously in the fabrication yard.

Data Collection and Test Protocol: The project team observed both the conventional and new processes during the real-time experiments. The project team observed and recorded the fabrication activities. Quantitative and qualitative data relevant to the processes were recorded, for example, the number of steel gratings produced and labor requirements. Figure 59.1 illustrates the experimental setup with conventional, manual (a) and the Bystronic BySprint Pro laser cutting machine-based (b) methods. The activities involved in each method were recorded, and are shown in Table 59.1.

(a) conventional method (b) Bystronic BySprint Pro

Fig. 59.1 Experimental set up

Table 59.1 Activities of conventional, method and the new method using a laser cutting machine

Conventional method (CM)	New method (NM)
Activity 1. Procurement of flat bars to size as per drawings	Activity 1. Procurement of plate to size as per drawings
Activity 2. Cutting of flat bars to the defined size (shearing machine, 1 operator required to feed)	Activity 2. Pre-program (one-off process) sizes/quantities in Computer Numerical Control (CNC) software
Activity 3. Collection of material from shearing machine, moving material to next station to notch and punch holes (multi-function iron worker m/c, 1 operator required)	Activity 3. Cutting of metal plate: place the metal plate on the laser cutting platform and initiate the machine to start the cutting process (1 operator required)
Activity 4. Straightening flat bar-tend to bend in iron worker machine (semi-skilled manpower required)	Activity 4. Laser machine starts to cut plates as required
Activity 5. Grinding grating after assembly in the assembly station. All the processed materials from activity stations 2 to 4 are collected to be ground flat to minimize fabrication tolerance, and this is followed by fitting the flat bars to form a grating as per drawings (1 fitter required)	Activity 5. Assembly work (1 fitter required)
Activity 6. Fabrication process at next station, all assembled/fitted gratings are fully welded and will be sent out for next process, galvanization (1 welder required)	Activity 6. After assembly, cut pieces fully welded to send for galvanization (1 fitter required)
	Activity 7. The completed product is sent to the site for use

59.4 Data Analysis and Results

Observations of the activities discussed in Table 59.1 revealed the following advantages of the new method:

- Wastage of material was minimized (NM: Activity 1 and NM: Activity 2) when procuring the plate of the size compared to the conventional method (CM: Activity 1 and CM: Activity 1). This was because the CNC software can generate cutting patterns which maximize material usage.
- Once the laser cutting is started, the operator was no longer needed (NM: Activity 3), in contrast to the conventional method where the operators presence was needed to feed material to the shearing machine (CM: Activity 2).
- The laser cutter started to cut the plates as required in Activity 4, which removed a number of activities in the conventional method (CM: Activities 1 to 5).
- Assembly work in the new method (NM: Activity 5) could be done without grinding due to the use of more precise high tech cutting technology. This enabled immediate assembly.

The laser cutting machine was able to cut metal sheets and other materials up to 4 × 2 m, and the process is fast and economical. Alignment and nozzle exchange are automated, and this increased autonomy reduces the need for an operator to intervene. The machine possesses the latest piercing and cutting technology, minimizing cutting time and producing good quality with high efficiency across various thicknesses of material. The observations also revealed that the machine was able to reduce noise and smoke emissions compared to the conventional method. Further, the laser cutting machine can also precisely produce different patterns on the steel (Fig. 59.2).

Table 59.2 shows a quantitative and qualitative comparison of the two methods. The total cost savings for labor using the laser cutting machine in comparison to the conventional manual method is S$11.02 per square meter. In terms of area,

Fig. 59.2 Wide variety of patterns cut using laser cutting machine

Table 59.2 Comparison of the two methods

Activity	Conventional fabrication method	Laser cutting fabrication method
Material	It must be in flat bars to start fabrication. Possibility of wastage	Any size of plate can be used; wastage is minimized
Cutting to size with shearing machine using manpower	Required	Not required
Punching and notching with iron working machine using manpower	Required	Not required
Straightening and grinding before assembly of grating using manpower	Required	Not required
Fabrication tolerances	More tolerance required	Less tolerance required
Production per day	18 m^2	60 m^2
Labor hours required	32 man hours	24 man hours
Labor cost per square meter	S$14.22/$m^2$	S$3.20/$m^2$
Output productivity	0.56 m^2/man-hour	2.5 m^2/man-hour
Over-all man-day saving—78%		

productivity is improved from 18 square meters per day to 60 square meters per day which is equal to 78% saving in man day.

The results show that it is more efficient, cost effective and productive to use the laser cutting machine to manufacture steel drain gratings. Only one operator is required during the whole process, and their task is simply to place the materials into the machine. The use of mechanization not only reduces reliance on labor, it also reduces material wastage, simplifies the processes, and more than triples productivity.

Among the findings are also the perceived challenges to implement the new technology. The senior management of the organization perceived some barriers to implementing the new method. The data also revealed that the new method required a significant amount of investment as capital cost. The relatively large amount of space required was also recorded as a challenge for small-medium enterprises (SMEs) in a country like Singapore, where land is scarce. There were also concerns raised about the potentially high electricity demands and the resulting economic challenges due to utility bills. The requirement of a qualified CNC programmer during pre-programming (NM: Activity 2) is also a challenge.

59.5 Discussion and Recommendations

Return on investment over time

The experiments revealed a significant productivity improvement through mechanisation, reduced reliance of labour, wastage minimisation (through the process' greater versatility), and higher quality products. However, due to ongoing barriers to implenentation and operation, mechanization might be more economical for high volume fabrication. Robust research conducted over time with rigorous return-on-investment analysis is needed to verify these observations and to identify suitable applications.

Support Structure for the investment cost

Successful adoption of new technologies depends on the capability and capacity of the construction company in question and on economic factors [13]. The high cost of the machinery and equipment is a major barrier to adoption for contractors. Research suggests that construction project clients should provide financial support to contractors for the purpose of purchasing the required equipment [9]. Government policies and incentives have been argued to be a major motivator for construction innovation [5, 6, 14]. The Singapore government's incentives on [1, 2] were perceived to be a motivator for innovation adoption. Further support though, for example, policies to reduce equipment costs or to provide exemption from duty will encourage mechanized construction.

Raising Awareness

Raising awareness of the benefits of mechanization can influence wider adoption of advanced technologies in the construction industry. Such awareness of mechanized construction allows stakeholders to realize its potential productivity and quality improvements [9]. Local campaigns to inform companies of success stories through BCA's portal and other websites are recommended. Sharing of real-world case studies by academics and the industry also raises international awareness.

Education and Encouragement

Studying previous successes in educating and changing the mind-set of people in the industry are another important way to ensure that the government's initiative will be successful [15]. Although many big and established contractors in Singapore are using advanced technologies for their projects, it is still important to encourage SME contractors to adopt these technologies so that the overall level of productivity in the country is raised.

Potential Technological Advancements

In future, laser cutting machines could be enhanced to cut larger architectural features, such as window frames, gates, doors etc., and the rate of production using the laser cutting machine can be further improved. 3D printing is also becoming increasingly popular and more advanced for the building and construction industry, and it could become the next most important technology for construction companies to adopt. Productivity levels could be improved tremendously if 3D printing can be integrated into laser cutting machines.

Government Role

The literature suggests that successful implementation of advanced technologies depends on existing government policies and incentives, and on the cost of adopting the system in question [13]. The government of Singapore could introduce new policies and provide incentives to encourage stakeholders in the construction industry to mechanize. In addition, the government could take the initiative to encourage and motivate wider adoption of new technology in the industry. Further, government could introduce a merit point system (similar to the current Buildable Design Score, and Constructability Score in Singapore) to contractors who adopt mechanization and advanced technologies for their projects, and these points would provide an advantage in applications to secure future public projects.

Because productivity is critical to the economy, a restructuring exercise was launched in 2014 to bring Singapore to a higher level of growth. The government provided generous monetary grants and tax reduction incentives, such as the Construction Productivity and Capability Fund (CPCF), Capability Development Grant (CDG), and Productivity and Innovation Credit Scheme (PIC) to offset the expenses. All of these call for growth integration. Studies show that the number of locals entering the workforce each year will shrink by 80% (to about 20,000 people), a significant decline [18]. This will lead to a costly labor squeeze. The Ministry of Manpower (MOM) has warned about the daunting difficulties for businesses, and has signaled that practices in work, communication and business are shifting to a totally technology-oriented model.

Industry should also take advantage of the support that the government is providing to up-skill their workforce when re-training for new technologies will enhance productivity. The trend in the direction of a labor crunch should be recognized, and organizations should venture into sophisticated processing machines requiring highly skilled workers. Singapore has the following schemes: Workforce Training and Upgrading (WTU), BCA-Industry Built Environment Undergraduate Scholarship/Sponsorship, Building Information Model (BIM), and the Mechanization Credit (MechC) etc. under the Construction Productivity and Capability Fund (CPCF). These incentive schemes allow the local construction industry to further develop its workforce, engineering capability, and technology adoption. The Investment Allowance Scheme (IAS), administered by the BCA, and the Productivity and Innovation Credit (PIC), administered by the Inland Revenue Authority of Singapore (IRAS), are tax deduction schemes that encourage businesses to improve their productivity [2].

59.6 Conclusions

Construction is an important industry for many countries and it contributes significantly to GDP. Globally in recent years, the focus and attention on construction productivity has been high. Many contractors in Singapore still rely heavily on labor to do the work, as this is a cheaper and more direct option, but this method also hinders the growth of construction productivity. The dependency on labor can also lead to material wastage, as human error is unavoidable. This research investigated the level of productivity and cost saving that adoption of mechanization could provide compared to conventional process in a specific case study organization.

Manual labor can only produce 18 square meters of steel grating per day, while laser cutting machines can produce 60 square meters per day. The number of people required to use a laser cutting machine is only one at any given stage, resulting 78% saving in man-day. This result shows that the level of productivity increased significantly, and that higher cost–savings were achieved when steel gratings were manufactured using a laser cutting machine instead of manual labor. It was also observed that the new method emitted less noise and smoke but improved the quality of production.

The project's relatively short duration prevented the researchers from conducting a comprehensive test and data comparison between the use of conventional cutting methods and mechanization, and this was a limitation of the current project. This could be investigated, together with a return-on-investment analysis of new equipment, in a robust future study.

This research is able to convey and raise awareness of the importance and benefits that productivity can bring to national economies and to the construction industry. It allows construction companies which are still dependent on labor to learn most of what they need to about the technological innovations they can adopt to improve their productivity. This study will also raise awareness of the usefulness of incentives similar to those provided by the government of Singapore and their impact on SMEs through the case study project. Such incentives will relieve the financial burden when adopting mechanization and are expected to motivate firms to adopt similar technologies.

References

1. Building and Construction Authority (BCA): Productivity Innovation Project (PIP), available online https://www.bca.gov.sg/PIP/pip.html (2015a). Accessed 10 Apr 2016
2. Building and Construction Authority (BCA): Construction Productivity and Capability Fund (CPCF), available online https://www.bca.gov.sg/cpcf/cpcf.html (2015b). Accessed 10 Apr 2016
3. Chia, Y.M.: Push to Raise Skills, Productivity in Construction Sector, The Straits Times, 31 October, available online http://www.straitstimes.com/singapore/push-to-raise-skills-productivity-in-construction-sector (2014). Accessed 20 Apr 2016
4. Edirisinghe, R., Lingard, H.: Exploring the potential for using video to communicate safety information to construction workers: case studies of organizational use. Constr. Manage. Econ. **34**(6), 366–376 (2016). (Taylor and Francis)

5. Edirisinghe R., London, K.: Comparative analysis of international and national level BIM standardization efforts and BIM adoption. In: The 32nd International Conference of CIB W78, pp. 800–809. Eindhoven, The Netherlands, 27–29 Oct 2015
6. Gu, N., London, K.: Understanding and facilitating BIM adoption in the AEC industry. Autom. Constr. **19**(8), 988–999 (2010)
7. Home: The Exploitation of Migrant Chinese Construction Workers in Singapore, available online http://www.home.org.sg/wp-content/uploads/2015/07/PRC_MCW_Report_final_2011.pdf (2011). Accessed on Apr 2016
8. Husna, R.: Singapore GDP Annual Growth Rate, Trading Economics, April, available online: http://www.tradingeconomics.com/singapore/gdp-growth-annual, (2016). Accessed on Apr 2016
9. Idoro, G.I.: Sustainability of mechanisation in the Nigerian construction industry. J. Civ. Eng. Manage. **18**(1), 91–105 (2012)
10. Investopedia: Productivity, available online http://www.investopedia.com/terms/p/productivity.asp (2016). Accessed 1 Apr 2016
11. Liew, K.H.: Productivity and Efficiency, Lecture notes distributed in the unit, BUIL 1265, RMIT-SIM University (2016a). Accessed 18 Feb 2016
12. Liew, K.H.: Industries and Authorities on Building and Construction, Lecture notes distributed in the unit, BUIL 1265, RMIT-SIM University (2016b). Accessed 18 Feb 2016
13. Mahbub, R.: Readiness of a developing nation in implementing automation and robotics technologies in construction: a case study of Malaysia. J. Civ. Eng. Archit. **6**(7), 858 (2012)
14. Manley, K., Mcfallan, S.: Exploring the drivers of firm-level innovation in the construction industry. Constr. Manage. Econ. **24**(9), 911–920 (2006)
15. Tam, V.W., Hao, J.J.: Prefabrication as a mean of minimizing construction waste on site. Int. J. Constr. Manage. **14**(2), 113–121 (2014)
16. Tan, A.: 1.32 m foreign workers in Singapore; the bulk in construction and marine sectors, The Straits Times, 6 August 2016, available online http://www.straitstimes.com/singapore/132m-foreign-workers-in-singapore-the-bulk-in-construction-and-marine-sectors (2014). Accessed 1 Apr 2016
17. Waris, M., Liew, M.S., Khamidi, M.F., Idrus, A.: Investigating the awareness of onsite mechanization in Malaysian construction industry. Procedia Eng. **77**, 205–212 (2014)
18. Yong, C: Squeeze to Get Tighter as Local Workforce Growth Shrinks, Asiaone, 10 March, available online www.news.asiaone.com/news/Singapore/squeeze-get-tighter-local-workforce-growth-shrinks (2015). Accessed 10 Apr 2016

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Automated Building Information Models Reconstruction Using 2D Mechanical Drawings

60

Chi Yon Cho, Xuesong Liu, and Burcu Akinci

Abstract

One of the potential benefits of using Building Information Modeling (BIM) for Facility Management (FM) targets enhanced tradespeople performance, facilitated by efficient document management, equipment localization and visualization, and integration of building asset data. However, a major bottleneck towards achieving such a benefit is the lack of BIM. In addition, the owners or the facility managers do not want to invest in generating BIM because manually creating BIM for existing buildings is costly, time-consuming, and requires additional labors with specific skills to maintain. Therefore, the authors aim to build an automated Mechanical, Electrical, and Plumbing (MEP) BIM reconstruction framework that uses 2D building mechanical drawings. In this paper, the authors proposed a new method of generating 3D mechanical objects based on all available information in drawings, such as equipment schedules, symbols and spatial and topological relations amongst objects. The results have shown that the proposed approach could reconstruct more than 70% of the mechanical components among duct, VAV, AHU, FCU, BCU, diffuser, register, and sensor. Even though the authors were not able to achieve 100% success, it was shown that the proposed method reduced the time for generating the mechanical components and it is a major step towards the development of a BIM to support FM tasks associated with MEP components.

Keywords

Building information modeling (BIM) • Facility management (FM) • 3D reconstruction

60.1 Introduction

There are several reasons why building owners or facility managers currently have limited availability of BIMs to be used in FM. First, 80% of existing buildings were constructed based on 2D drawings and does not have BIM [1]. Second, not all MEP contractors are using BIM and hence the MEP BIM could not be delivered to the owner during handover [2, 3]. Third, manually creating BIM for existing buildings is costly, time-consuming, and requires additional labors with specific skills to maintain [4, 5]. Therefore, owners or the facility managers do not want to invest in such efforts [6].

All aspects described above signify a need to create BIMs for existing buildings in a cost- and time- efficient way. To address this need, a wide range of research studies have been conducted using 3D point cloud data (i.e., terrestrial laser-scanned data), photos, or building drawings to reconstruct BIMs but previous studies focused on generation of exterior enclosure or architectural models and did not generate MEP, which typically requires more frequent maintenance than the architectural and structure components in buildings.

Therefore, the authors have been aiming to build an automated MEP BIM reconstruction framework that uses 2D building mechanical drawings. The authors have previously explored graph-based searching methods to obtain closed-loops

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in building mechanical drawings which mostly indicates the duct components [7]. As a result, more than 80% of the ducts were recognized and reconstructed.

In addition, the authors investigated symbol recognition techniques, such as graph matching using semantic relationship [8], template matching using shape context [9], and network of geometric constraints [10], and proposed a vector-based symbol recognition approach to recognize and localize various symbols in mechanical drawings using the vectorial signature matching technique [11–13]. As a result, 75% recognition rate in average was obtained when symbol recognition test was conducted using the vectorial signature matching approach on six different drawings.

In this paper, the authors specifically discuss the developed object generating process which is related to the last step of the reconstruction framework. First, the authors identified all available information in drawings, such as information from equipment schedules, symbols and spatial and topological relations amongst objects that could be used for generating 3D mechanical objects. Second, reasoning rules for each type of relationships between symbols and surrounding parts were defined. Third, region searching technique was utilized to retrieve the related information from the symbols. Lastly, the result of the BIM reconstruction prototype is shown.

60.2 Method

60.2.1 Background Research

The as-built MEP BIM is needed for routine O&M tasks, to response to MEP-related emergencies [14], and to reduce the time for searching for historical records, site location, and related documents when a defect occurs [15]. Thus, many studies were conducted previously to generate BIM automatically as shown in the following Table 60.1.

However, to the best of the author's knowledge, none of the previous studies that attempted to reconstruct MEP BIM utilized the building mechanical 2D drawings along with the equipment schedule document. Thus, most of the previous

Table 60.1 Previous studies related to BIM reconstruction

References	Input	The reason of 3D reconstruction using the input	Output	3D reconstructed or recognized components
[16]	Terrestrial laser scan data	Manual 3D modeling is time-consuming and expensive	3D point model	Pipes were recognized
[17]	Images and point cloud	Images provide more info on the edges and help fix the bounds	As-built 3D model	Industrial site (pipe, equipment) reconstructed as cylinder and boxes
[18]	Terrestrial laser scan data, CAD database, and P&IDs	To use prior knowledge (scene, geometric, and topologic knowledge) from database (P&IDs)	3D model	Industrial instrumentation components
[19]	3D CAD design file and cluttered laser scan data	To automate the search and extraction of the object of interest	As-built pipe spool	Pipe spools (the prefabricated components of a piping system) were recognized
[20]	Laser scan data and pre-knowledge	Pre-knowledge (two ranges of diameter) was used to reduce computational time and cost	Text file (CAD layers)	Pipes and ducts were completely automatically reconstructed from raw point cloud data
[21]	Laser scan data	40% of the total modeling cost is spent on data-processing labor	3D pipeline model	Targeted to generate pipelines including pipes, elbows, and tee pipes

studies are limited to generating the as-built 3D model based on the geometric information. On the other hand, the building mechanical drawing set not only contains the layer of geometric information but the detailed property information in the equipment schedule document. Therefore, utilizing 2D drawings as inputs enables the reconstruction of mechanical equipment such as VAV box, AHU, FCU, etc. However, using 2D drawings and such documents also comes with challenges.

60.2.2 Challenges

Even though the symbols in 2D drawings could be recognized and localized with symbol recognition techniques, reconstructing 3D objects based on the obtained information is still a major challenge. Architectural walls can be simply extruded, but such extrusion method is not applicable for mechanical equipment since they have more complex geometry and connectivity with other components.

In previous studies, several researchers used a predefined 3D object database to link with the result of symbol recognition from drawings. However, based on the authors' case studies, generating these predefined objects (i.e., family objects) is the most time-consuming part of the entire manual modeling process. For example, it takes about 40–50 min to create a VAV unit in Revit. Thus, it is necessary to utilize all the available information from the 2D drawings for reconstructing the mechanical objects and minimize the process of creating the predefined 3D object database.

60.2.3 Available Information by Mechanical Components

In general, information of mechanical components can be obtained from four types of document in the building mechanical drawing set: the 2D drawings, symbol description document, schedule table document, and the section view drawings. The following Table 60.2 gives a summary of available geometric information by mechanical components.

The location of each mechanical components can be recognized through the symbol recognition process on 2D drawings. Recognizing the symbols in building mechanical drawings is essential but defining the relationship between the symbols and the surrounding parts is more important. For example, there can be multiple VAV boxes with different design models in the 2D drawings. Thus, it is required to search the surrounding areas to obtain the correct corresponding property information of each VAV boxes.

Table 60.2 Available information by major mechanical components

Component type	Geometry related information	Information source
Duct	• Physical shape • Dimension • Location	• 2D drawings
VAV	• VAV inlet size • Discharge duct opening size	• Schedule table document
	• Location	• 2D drawings
AHU	• Dimension (length, width, height, weight) • Detail of internal objects • Location (by floor level)	• Schedule table document
	• Location	• 2D drawings
FCU	• Location	• 2D drawings
BCU	• Location	• 2D drawings
Diffuser, register, and grille	• Neck size • Dimension	• Schedule table document
	• Location	• 2D drawings
Sensor	• Location	• 2D drawings

60.2.4 Relationship Between Symbols and the Surrounding Parts

In mechanical drawings, there are several parts such as ducts, annotations, and other symbols that surrounds a symbol. Thus, it is required to define the relationship between the symbols and the surrounding parts which could have meaningful relationship information for BIM reconstruction purpose.

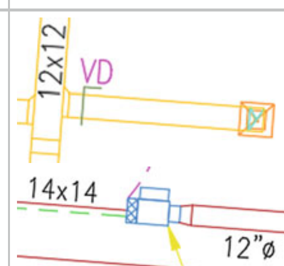
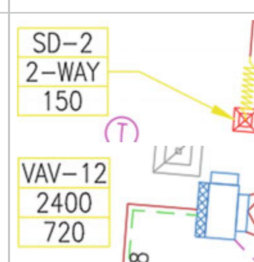
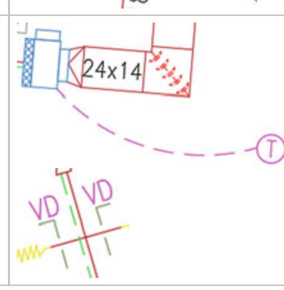
The authors have classified the relationship between symbols and the surrounding parts based on connectivity and location representation. The following Table 60.3 shows the three type of relationships that are presented in the building mechanical drawings.

Relationship between symbols and physically represented component. Many symbols in building mechanical drawings represent an equipment such as VAV, AHU, and diffuser or other components such as transition and damper. This means that symbols that appear in the 2D drawings have a high possibility of being connected to the duct. And this could be further classified into five type of relationships (Table 60.3). For example, there are equipment symbols that are connected at the end of the duct or connected in the middle of a duct. In addition, there are text information nearby regarding the physically represented component.

Relationship between symbols and annotation. Most annotation is connected to a particular symbol using an arrow but some annotation does not have arrows and is simply located near the symbol. Thus, two types of relationship are presented (Table 60.3). Annotations are objects drawn using the LEADER element in AutoCAD and usually placed in the 2D drawings to reference a certain equipment or indicate the dimension of such mechanical component.

Relationship between symbols and other symbols. Some equipment symbols such as VAV and FCU has temperature sensor symbols connected to it with a dashed line. This means that the equipment plays a role regarding the location of the temperature sensor. On the other hand, there are symbols that are placed near the other symbol. For example, the pink text VD (i.e., volume damper) is not connected to the other symbol but it is placed nearby and indicates that the green line symbols are volume dampers.

Table 60.3 Type of relationship between symbols and surrounding parts

Relationship between <>	Type of relationships	Examples
Symbols and physically represented component	• Equipment symbol that are connected at the end of the duct: diffuser, register, and grille • Equipment symbol that are connected in the middle of a duct: VAV, FCU • Component symbols that are connected in the middle of a duct: transition, damper • Component symbols that connects the end equipment and the duct: flexible duct • Surrounding text: dimension	
Symbols and annotation	• Annotation connected with arrow • Annotation connected without arrow	
Symbols and other symbols	• Symbols that indicate the serving location relationship: temperature sensor (T) • Symbols that describes what the other symbol is: volume damper (VD)	

60.2.5 Rules for Reasoning the Relationship

Based on the three type of relationship defined in Sect. 60.2.4, the authors established rules for reasoning each relationship. The following rules are utilized when searching the surrounding parts of the recognized symbols.

Rules for reasoning symbols and physically represented component. First, the dimension information indicates the dimension of the closest duct. But the location of the dimension information could vary. It could be placed above or below the duct or also could be inside the duct. Moreover, it could also have arrows when the surrounding area is compact. Second, the diffuser, register, and grille are located at the end of the duct. In some cases, there could be a flexible duct symbols between them. Third, equipment and components such as VAV box and volume damper are usually located somewhere in between the ducts and not at the end. Furthermore, the size of the inlet and outlet of an equipment should match with the connected duct size.

Rules for reasoning symbols and annotations. If there is an annotation of equipment reference, there is a related equipment symbol nearby. There could be an arrow between the equipment symbol and the equipment reference symbol. Note that there is a possibility that the end point of the arrow does not always align with the equipment symbol and could have disjoint draft errors.

Rules for reasoning symbols and other symbols. There is a dashed line between the temperature sensor and the equipment symbol. However, the carbon dioxide sensor sometimes has no connecting line. In this case, the symbol only provides the location information of the symbol.

60.3 Results

60.3.1 Vision of the Framework

By integrating all the process introduced in this paper and the previous paper [7], the authors proposed an automated BIM reconstruction framework (see Fig. 60.1). The proposed approach interprets three type of input data: 2D drawings, symbol description document, and equipment schedule.

Based on the input data and how the mechanical components are represented, it follows several different steps. If the component is a physically represented component, graph theory is utilized to find the minimum circuit that represents ducts [7]. On the other hand, if the components are represented as symbols, symbol recognition process is conducted using the vectorial signature matching technique.

Then using the retrieved information of the located symbols and the geometric information from the schedule table, the system checks whether if the obtained dimension information is sufficient enough or not to reconstruct BIM. If the information from the original input is not sufficient enough to create BIM, the system searches the web to find the most similar object as possible and retrieves the required information from the web. Finally, BIM can be reconstructed as Industry Foundation Classes (IFC) using the retrieved information from both input data and the web.

60.3.2 Prototype Implementation

Symbol recognition and surrounding region search. The purpose of surrounding region searching is to obtain the dimension information of the mechanical component of interest. Figure 60.2 shows the recognized and localized symbols in blue text labels. The surrounding area of each symbol is searched based on the location of the symbol. For example, equipment reference symbols (i.e., annotation symbol) are nearby the VAV box and supply diffuser symbols. First, the system retrieves the item code (e.g., VAV-03, SD-2, etc.) which is described in the equipment reference symbol. Then, the system further searches the equipment schedule document by using this item code.

If the dimension information is presented in the equipment schedule document, the system will retrieve the dimension information and use it for 3D reconstruction. If not, the object needs to be created based on the boundary information of the symbol itself or the retrieved information from the web.

BIM reconstruction. There is two type of dimension information that is utilized for the 3D reconstruction process. One type is in a form of 'Length x Width x Height' which is retrieved from the equipment schedule document or the web. The other type is in 'Min-x, Min-y, Max-x, Max-y' values which is also a form of a bounding box since some symbols do not

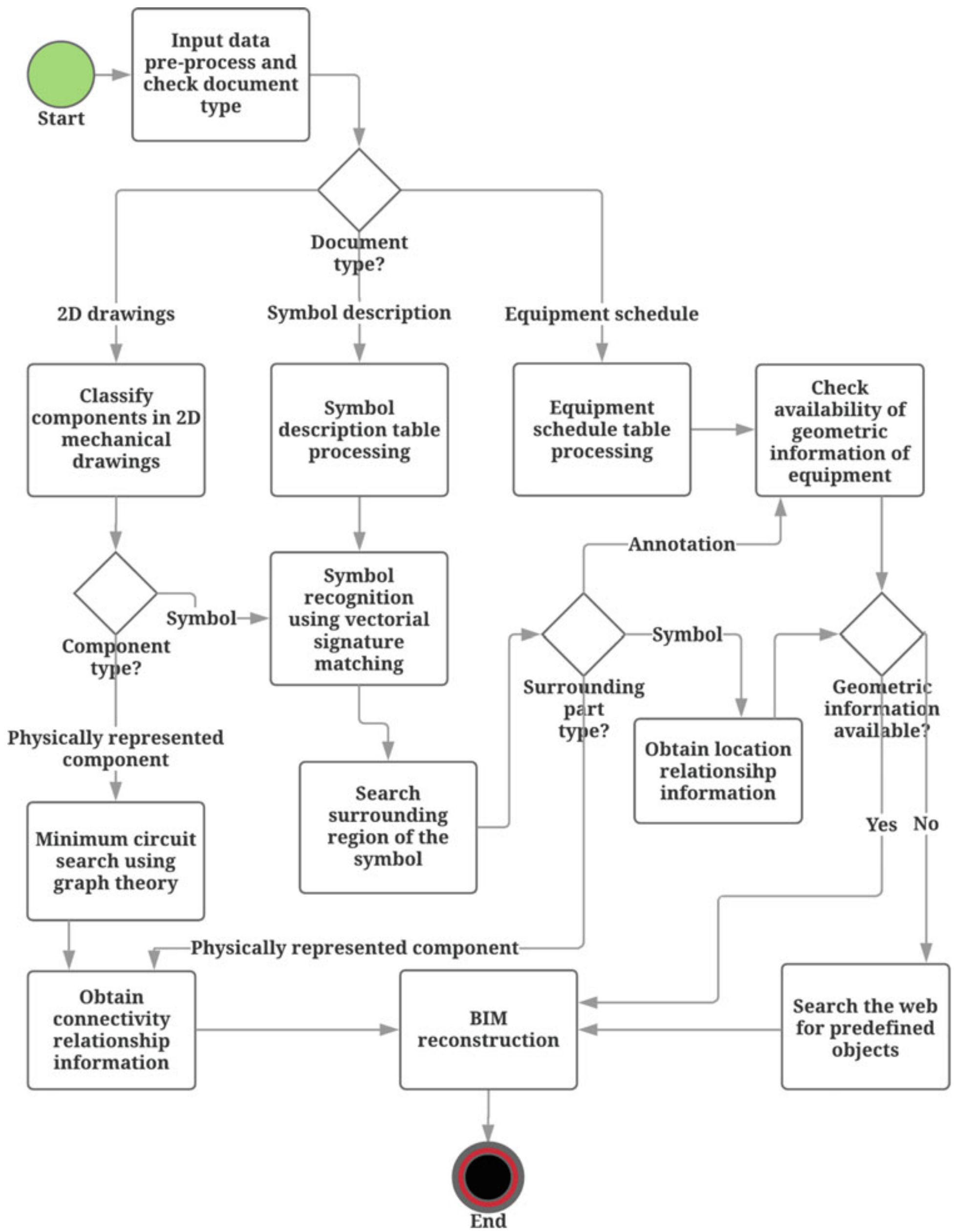


Fig. 60.1 MEP BIM reconstruction process diagram

have the dimension information in the equipment schedule document and require to use the boundary information of the symbol itself.

As a result, the mechanical equipment components are reconstructed as shown in Fig. 60.3. The left image of Fig. 60.3 is the 2D drawing that was used as input and the right image is the reconstructed BIM. The green dashed line indicates the corresponding symbols and reconstructed objects. Although not shown in the figure, note that the VAV object can contain additional information on top of geometric information such as the manufacturer, design model, air flow, and heating coil related information, et cetera which are retrieved from the equipment schedule document.

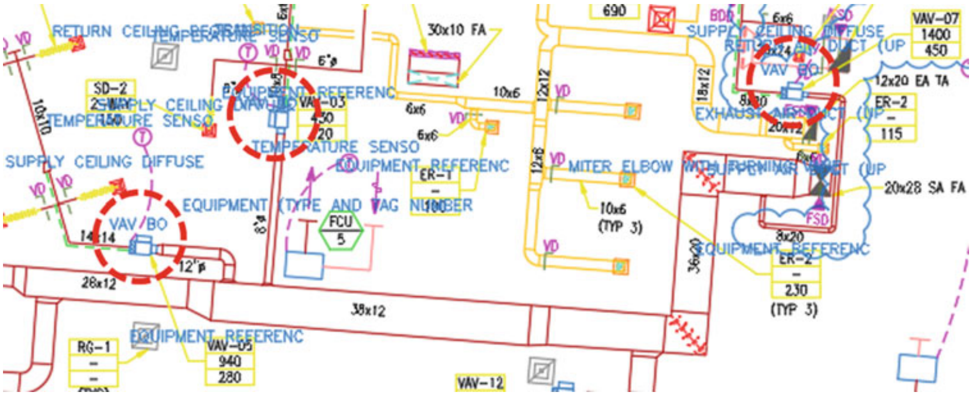


Fig. 60.2 Recognized symbols (VAV BOX highlighted in red dashed circle)

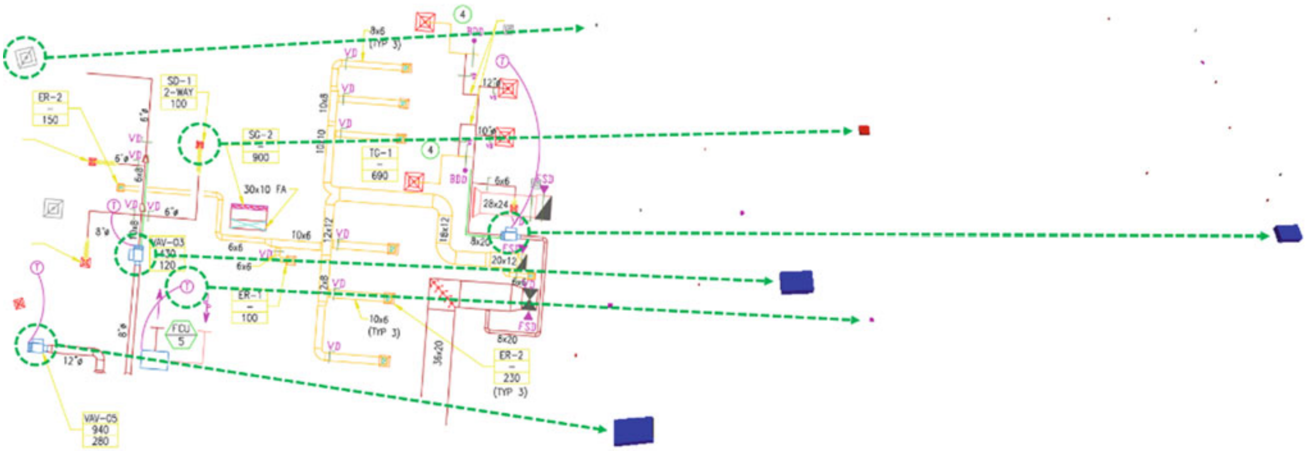


Fig. 60.3 BIM reconstruction result: input (left) and output (right)

60.4 Conclusion

In this paper, the authors have described the overall framework of the MEP BIM reconstruction process using the building mechanical 2D drawings, symbol description document, and the equipment schedule document. The main contribution of this paper is that it proposed a method that could process three type of input documents and connect the information to the mechanical component of interest. Moreover, the paper described the available information that is contained in the input documents along with the relationship and rules that needs to be considered for BIM reconstruction. As a result, 70% of the recognized symbols were reconstructed to BIM using the proposed framework. Future study would include the development of a more sophisticated approach to cover additional mechanical components for reconstruction and experiments on different building mechanical 2D drawing sets.

References

1. Volk, R., Stengel, J., Schultmann, F.: Building information modeling (bim) for existing buildings—literature review and future needs. Autom. Constr. **38**, 109–127 (2014)
2. Hanna, A., Boodai, F., El Asmar, M.: State of practice of building information modeling in mechanical and electrical construction industries. J. Constr. Eng. Manage. **139**(10), 04013009 (2013)

3. Kent, B.J.: Current BIM Practices of Commercial MEP Contractors. All Theses and Dissertations, 4080, https://scholarsarchive.byu.edu/etd/4080 (2014). Last accessed 27 Apr 2018
4. Edirisinghe, R., Kalutara, P., London, K.: An investigation of BIM adoption of owners and facility managers in Australia: Institutional case study. In: COBRA 2016, pp. 1–10. Royal Institution of Chartered Surveyors (2016)
5. Love, P.E., Simpson, I., Hill, A., Standing, C.: From justification to evaluation: building information modeling for asset owners. Autom. Constr. **35**, 208–216 (2013)
6. Korpela, J., Miettinen, R.: BIM in facility management and maintenance—the case of Kaisa library of Helsinki University. In: Proceedings 29th Annual Association of Researchers in Construction Management Conference, ARCOM, pp. 47–56 (2013)
7. Cho, C.Y., Liu, X.: An automated reconstruction approach of mechanical systems in building information modeling (BIM) using 2D drawings. In: Computing in Civil Engineering, pp. 236–244 (2017)
8. Lu, T., Tai, C.L., Su, F., Cai, S.: A new recognition model for electronic architectural drawings. Comput. Aided Des. **37**(10), 1053–1069 (2005)
9. Belongie, S., Malik, J., Puzicha, J.: Shape matching and object recognition using shape contexts. IEEE Trans. Pattern Anal. Mach. Intell. **24**(4), 509–522 (2002)
10. Ah-Soon, C., Tombre, K.: Architectural symbol recognition using a network of constraints. Pattern Recogn. Lett. **22**(2), 231–248 (2001)
11. Dosch, P., Lladós, J.: Vectorial signatures for symbol discrimination. In: International Workshop on Graphics Recognition, pp. 154–165. Springer, Berlin, Heidelberg (2003)
12. Schettini, R.: A general-purpose procedure for complex graphic symbol recognition. Cybern. Syst. **27**(4), 353–365 (1996)
13. Zhang, W., Liu, W.: A new vectorial signature for quick symbol indexing, filtering and recognition. In: Document Analysis and Recognition. ICDAR 2007. Ninth International Conference on vol. 1, pp. 536–540. IEEE (2007)
14. Hu, Z.Z., Tian, P.L., Li, S.W., Zhang, J.P.: BIM-based integrated delivery technologies for intelligent MEP management in the operation and maintenance phase. Adv. Eng. Softw. **115**, 1–16 (2018)
15. Kang, T.W., Choi, H.S.: BIM perspective definition metadata for interworking facility management data. Adv. Eng. Inform. **29**(4), 958–970 (2015)
16. Kawashima, K., Kanai, S., Date, H.: Automatic recognition of a piping system from large-scale terrestrial laser scan data. Int. Arch. Photogram. Remote Sens. Spatial Inform. Sci. **XXXVIII**, 38–45 (2011)
17. Rabbani, T., Van Den Heuvel, F.: 3D industrial reconstruction by fitting CSG models to a combination of images and point clouds. Int. Arch. Photogram. Remote Sens. Spatial Inform. Sci. (ISPRS) **35**(B5), 2 (2004)
18. Son, H., Kim, C., Kim, C.: 3D reconstruction of as-built industrial instrumentation models from laser-scan data and a 3D CAD database based on prior knowledge. Autom. Constr. **49**, 193–200 (2015)
19. Czerniawski, T.: Automated Pipe Spool Recognition in Cluttered Point Clouds. Master's thesis, University of Waterloo, UWSpace, http://hdl.handle.net/10012/10451 (2016). Last accessed 27 Apr 2018
20. Ahmed, M., Haas, C.T., Haas, R.: Autonomous modeling of pipes within point clouds. In: Proceedings of the 30th ISARC, Montréal, Canada, pp. 1093–1100 (2013)
21. Lee, J., Son, H., Kim, C., Kim, C.: Skeleton-based 3D reconstruction of as-built pipelines from laser-scan data. Autom. Constr. **35**, 199–207 (2013)

61 Architectural Symmetry Detection from 3D Urban Point Clouds: A Derivative-Free Optimization (DFO) Approach

Fan Xue, Ke Chen, and Weisheng Lu

Abstract

Symmetry is a fundamental phenomenon in not only nature and science but also cities and architectures. Architectural symmetry detection (ASD) from 3D urban point clouds is an essential step in understanding the architectures as well as creating a semantic city/building information model (CIM/BIM) to enable various applications for a smart and resilient future. However, manual segmentation and recognition of 3D urban point clouds are too time-consuming, tedious, and costly, and automatic ASD is very challenging. This paper presents a derivative-free optimization (DFO) approach for automatic ASD from 3D urban point clouds. In this paper, we formulate the problem of ASD as a nonlinear optimization problem by extending the mathematical definition of geometric symmetry with architectural styles. We develop a 'divide-and-detect' process to detect the symmetry hierarchy based on the formulation and apply the state-of-the-art DFO algorithms. A pilot study was conducted on a case of the rooftop of a neoclassical building. The proposed approach detected the global reflection from 1.4 million points in 23.5 s, and the whole symmetry hierarchy of reflections in about ten minutes. The detected symmetry hierarchy was applied to a regularity-based rooftop modeling method. The contribution of this paper is twofold. First, this paper exposes the problem of ASD to many mathematical methods through an innovative problem formulation. Secondly, the proposed DFO approach is accurate, efficient, and capable of processing large-scale 3D urban point clouds for semantic CIMs/BIMs.

Keywords

Symmetry detection • Architectural symmetry • Derivative-free optimization (DFO) • Point cloud • Semantic enrichment • Urban semantics • City information model (CIM) • Building information model (BIM)

61.1 Introduction

From quarks to animals to galaxies, symmetry is a fundamental phenomenon in nature and science. The presence of various symmetries makes an impact on not only our perceptions and recognition but also our understandings, responses, and artifacts [1]. In architecture, symmetry always finds its fundamental position across eras, continents, and cultures [2], in examples including the Parthenon of Greece, the Great Wall of China, the Taj Mahal of India, the Sydney Opera House, and 'The Gherkin' in London. Types of architectural symmetries include reflection, translation, rotation, uniform scaling, and their combinations. Architectural symmetries are not accidental but often result from considerations of function, mechanics, economics, manufacture, and aesthetics [3], e.g., for cleaner massive prefabrication and better buildability.

A semantic *city/building information model* (CIM/BIM) of these artificial architectures can enable various applications, such as architectural design, computer vision, construction management, heritage conservation, for a smart and resilient future of cities [4, 5]. Nowadays, 3D point cloud is a fashionable, affordable, and accurate data source of CIM/BIM [5]. *Architectural symmetry detection* (ASD) that reveals geometric fundamentals is an essential step in understanding the point

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clouds of architectures. However, many existing methods for processing point clouds to CIM/BIM fail to utilize ASD in enriching the semantic information (e.g., in surface optimization and component determination) and the overall hierarchy. As a result, the resulting CIM/BIM is often inaccurate, semantically impoverished, and unrecognizable by computers [6], e.g., symmetric beams or windows often become position and size-asymmetric in models. One reason for the absence of ASD in the methods is that automatic ASD remains very challenging, particularly in large-scale point clouds [7].

Derivative-free optimization (DFO) is a class of nonlinear optimization in mathematics and computer science [8]. It is well-known that the derivatives of a function contain information vital to finding the best values in mathematical problems. However, in many real-world complicated science and engineering problems, such as predicting protein folding, optimizing aircraft wings, as well as ASD, the derivatives the objective functions are often unavailable, unreliable, or impractical to obtain [9, 10]. DFO algorithms have shown successful records to carry out optimization under such circumstances [8, 9]. Examples of DFO applications are *general pattern search* for protein structure prediction [11] and *covariance matrix adaptation evolution strategy* (CMA-ES) [12] for as-built BIM generation from 2D images and 3D point clouds [10, 13].

This paper aims to apply state-of-the-art DFO algorithms to the problem of ASD from 3D urban point clouds. We first formulate the problem of ASD of a single symmetry to a nonlinear optimization problem by extending the definition of general symmetries. The symmetry hierarchies, including all the global and local symmetries and their relationships in a 3D urban point cloud, can thereafter be established in a ‘divide-and-detect’ process. Then, we apply a well-known DFO algorithm CMA-ES (see [12]) to the formulated problems to detect the symmetries and the symmetry hierarchies automatically. As far as is concerned, this paper is the first attempt of applying up-to-date DFO algorithms, such as CMA-ES, to the problem of ASD from 3D urban point clouds.

The remainder of the paper is structured into four sections. Section 61.2 revisits the related methods in the literature. Section 61.3 presents the proposed DFO approach. Section 61.4 describes the experimental tests on a pilot case of a dense point cloud. Conclusion and recommendations for future research are given in Sect. 61.5.

61.2 Background

61.2.1 Symmetry

In geometry and group theory, symmetry is an affine transformation that preserves points, straight lines, and planes on the 3D Euclidean space $\mathbb{R}^3$. Symmetry detection is the process of finding the symmetry group G of a geometric object [14], e.g., a 3D point cloud $\mathcal{C}$ in this research:

$$\begin{aligned} G &= \langle \mathcal{T}, \circ \rangle, \\ \mathcal{T} &= \left\{ T | T(\mathcal{C}) = \mathcal{C}, T \text{ is affine on } \mathbb{R}^3 \right\}, \\ \mathcal{C} &= \{p_1, p_2, \ldots, p_n\} \subset \mathbb{R}^3, n > 0, \end{aligned} \tag{61.1}$$

where $\mathcal{T}$ is the set of all global symmetries, $\circ$ is the function composition defined on $\mathcal{T}$, i.e., $(g \circ f)(x) = g(f(x))$, and n is the cardinality (number of points) of $\mathcal{C}$. An affine transformation T is called a *global symmetry* if $T(\mathcal{C}) = \mathcal{C}$ [15], i.e., a global symmetry keeps $\mathcal{C}$ invariant as a whole while permuting its parts. Alternatively, T is called *local* (or *partial*) if $\exists \mathcal{C}' \subset \mathcal{C}$ such that $T(\mathcal{C})' = \mathcal{C}'$. Usually, the point cloud of a real object inevitably has instrumental, environmental, and calibration errors. Thus, the ideal global (or local) symmetry condition is often approximately relaxed to some quantitative descriptors [16, 17], such as:

$$\text{PCR} = \frac{1}{n} |T(\mathcal{C}) \cap \mathcal{C}| > 1 - \varepsilon, \tag{61.2}$$

$$\text{MSE} = \frac{1}{n} \sum_{p \in \mathcal{C}} \| T(p) - N(T(p), \mathcal{C}) \|^2 < \varepsilon d^2, \tag{61.3}$$

where $0 \leq \varepsilon \ll 1$ is a small threshold of error tolerance, d is the diagonal of $\mathcal{C}$, and $N(T(p), \mathcal{C})$ denotes the nearest point to the transformed point $T(p)$ in $\mathcal{C}$. A high *point correspondence ratio* (PCR) in Eq. (61.2) means that almost all points still belong to $\mathcal{C}$ after transformation T; Eq. (61.3) is the *mean square error* (MSE).

61.2.2 Symmetry Detection Methods

Researchers have developed different approaches for detecting general symmetries, including architectural symmetries, from 3D point clouds. These approaches can be broadly categorized by their methodology into three types, i.e., (i) pairwise voting-clustering based on *all* pairwise correspondences, (ii) heuristic feature matching based on heuristic (*a priori* or trained) rules, and (iii) parameter optimization based on optimization models over the parameter space.

Pairwise voting-clustering approaches are primarily based on Eq. (61.2). The core technique is the collection of *votes* for symmetry parameters in a Hough-like transform parameter space [15]. There are $n(n-1)/2$ pairwise correspondences between n points. Each correspondence 'votes' for a grid in the parameter space. The most voted grids represent the approximate parameters of the symmetries. The correspondence can be between 3D points for architectural models and symmetrization-based design [15, 16] and other geometry such as wavelet convolution [18]. However, voting-clustering approaches have limitations in processing urban point clouds, e.g., the inherited bias and proneness to the noise of the Hough-like transform [19] and ineffective recognition of local symmetries due to loss of correlation information during voting [21].

Heuristic feature matching approaches involve matching a collection of local geometric features. A feature such as a line, plane, or sphere can infer the locations and tilts of the dual symmetries, e.g., a planar rectangle naturally has two reflection symmetries. Examples of approaches include iterative closest points, boundary-tracing, matching of feature points, feature lines, and their repetitive patterns, e.g., [20, 21]. The most popular methods in this category are the variants of *random sample consensus* (RANSAC) for detecting planes, spheres, and other pre-defined features [22]. Some variants (e.g., RAPter [23]) have considered preliminary regularities for buildings, e.g., emphasizing the angles of 90 and 60 between adjacent planes to improve the results of RANSAC. However, feature matching approaches often have inevitable errors inherited from the feature detection process [22] and rely heavily on a priori rules of the point clouds and availability of an abundance of suitable and regular features [24].

Parameter optimization approaches, in contrast, focus on optimizing the parametric symmetries (e.g., the location and tilt of a reflection axis) for a satisfactory condition (see Eqs. 61.2 and 61.3). Early work in this category began with finding symmetries from 2D images, e.g., using eigenvectors of the similarity matrix [25]. In processing 3D models and point clouds to detect the symmetries and symmetry group, [17] exploited *fast Fourier transform* (FFT) and formalize the optimal axis of rotational symmetry; [26] presented a parameter optimization method for non-rigid 3D objects in general. In fact, some advanced feature matching methods, e.g., RAPter [23], also partially incorporate parameter optimization to take advantage of modern mathematical methods, though the parameters are strictly confined to the matching results of the prerequisite features.

In summary, parameter optimization approaches can detect all types of symmetries in satisfactory conditions in reasonable time. However, the optimization problem can become very complicated and expensive (time-consuming) in the dense point clouds (e.g., $n > 10^6$) of real architectures; as a result, many derivative-based mathematical methods cannot be implemented. This dilemma has given rise to attempts to develop a DFO approach in this paper.

61.3 Methodology

The set $\mathcal{T}_A$ of all architectural symmetries, as a subset of $\mathcal{T}$, can be defined on Eq. (61.1) and the style A of a known architecture:

$$\begin{aligned} &\mathcal{T}_A = \{T | \mathcal{A}(T) = \mathcal{A}_g(T) + \mathcal{A}_t(T) < \varepsilon_A, T \in \mathcal{T}\} \subseteq \mathcal{T}, \\ &\mathcal{A}_g(T) \geq 0, \\ &\mathcal{A}_t(T) \geq 0, \end{aligned} \tag{61.4}$$

where $\mathcal{A}_g$ measures the violations of the geometric regularity defined in the architectural style A, $\mathcal{A}_t$ measures the violations of the defined topology, and ε_A represents a small threshold of error tolerance. The global and local architectural symmetries can thereafter be similarly defined. For each symmetry, the problem of ASD can thus be formalized as a general form of nonlinear optimization with a weighted sum objective function:

$$\begin{array}{lll} min & f(x) = f_{\mathcal{C}}(x) + w\mathcal{A}(x) & \\ s.t. & x = \{x_1, x_2, \ldots, x_m\} \in \mathbb{R}^m, & \\ & f_{\mathcal{C}} : \mathbb{R}^m \mapsto \mathbb{R}^+ \cup \{0\}, & \text{see Eq.}(61.2\text{--}61.3), \\ & \mathcal{A} : \mathbb{R}^m \mapsto \mathbb{R}^+ \cup \{0\}, & \text{see Eq.}(61.4), \\ & w \in \mathbb{R}^+ \cup \{0\}, & \end{array} \quad (61.5)$$

where f is the objective function comprising of the penalty $f_{\mathcal{C}}(x)$ from the point cloud and $\mathcal{A}(x)$ from the architectural style, x a parametric transformation with m parameters, ω is the relative weight of $\mathcal{A}$. In Eq. (61.5), the violations of the soft constraints of the architectural style are converted to a weighted penalty. Equation (61.5) is general and can be applied to all architectural symmetries, such as reflection, translation, rotation, uniform scaling, and their combinations.

Because Eq. (61.5) only formulates the detection of one single symmetry, DFO algorithms must solve separately to obtain the optimal symmetries for each type of global symmetries such as reflection, rotation, translation, and scaling. The local symmetries can be detected in a 'divide-and-detect' process as follows. Every newly found symmetry splits its input $\mathcal{C}_{\text{input}}$ into three parts: the source $\mathcal{C}_{\text{src}}$ of correspondence, the destination $\mathcal{C}_{\text{dest}}$, and the non-corresponded remaining points $\mathcal{C}_{\text{rem}}$. With the formulation (Eq. 61.5) and DFO algorithms, the ASD can continue on each part by substituting $\mathcal{C}_{\text{input}}$ with $\mathcal{C}_{\text{src}}, \mathcal{C}_{\text{dest}}$, and $\mathcal{C}_{\text{rem}}$, respectively. This 'divide-and-detect' process ceases when a termination criterion, such as a maximum level or too small fragments, is met. All the detected architectural symmetries can form a family of symmetry hierarchies according to the relationships between the parts of cloud $\mathcal{C}$.

61.4 Experimental Results on a Pilot Case

A pilot study was conducted to find the reflection symmetries of a university building. The Hung Hing Ying Building at the University of Hong Kong is a two-storey neoclassical redbrick building (see Fig. 61.1a). The authors took a series of 250 aerial photos with a drone (model: DJI Inspire 1) (see Fig. 61.1b) and constructed a dense cloud of 1, 413, 211 points (over 2, 000 points/m^2) of the rooftop from the photos using the photogrammetry function provided by Autodesk ReCap 360 (see Fig. 61.1c). According to neoclassicism, we assumed the planes of the reflections on rooftops (i) must be perfectly vertical on the rooftop and (ii) prefer perpendicularity and parallelity of geometric regularity with other reflections. We defined the parameters of the vertical plane of a 3D reflection as a 2D line on the horizontal polar coordinate system L (see [16]), so that each (ρ, φ) on L represents a plane with a distance $\rho \geq 0$ to the pole O and an angle $\varphi \in (-\pi, \pi]$ of the heading direction. In fact in geometry, the point (ρ, φ) is the foot of the perpendicular from the pole O to the reflection axis on L. Due to the assumption (i), we can reduce the computational load of verifying f by partitioning the whole cloud $\mathcal{C}$ into 177 horizontal slices ($\mathcal{C}_1, \mathcal{C}_2, \ldots, \mathcal{C}_{177}$, height = 0.05 m), as shown in Fig. 61.1d.

We then formulated a nonlinear optimization problem for the reflection symmetries based on the general form of Eq. (61.5):

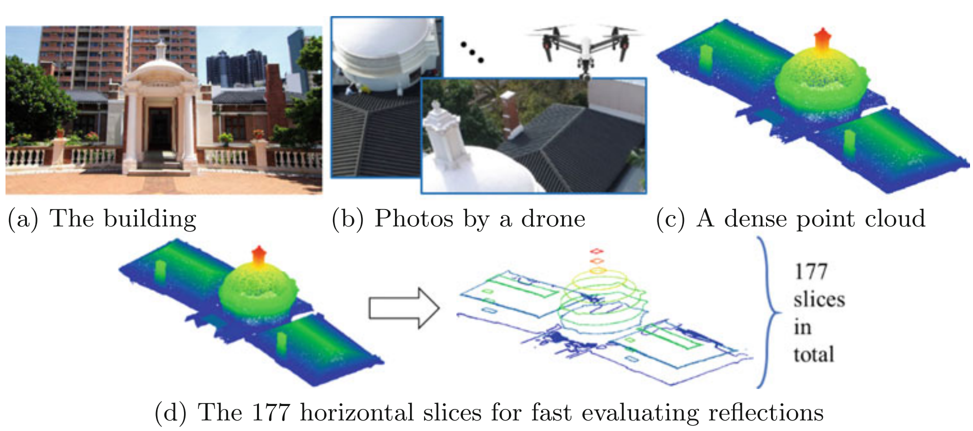


Fig. 61.1 A pilot case: The Hung Hing Ying building at the University of Hong Kong

$$\begin{aligned} min \quad & f(x) = f_{\mathcal{C}}(x) + 10\mathcal{A}(x) \\ s.t. \quad & x = \{\rho, \varphi\}, \\ & \rho \in \mathbb{R}^{+} \cup \{0\}, \varphi \in (-\pi, \pi], \\ & f_{\mathcal{C}}(x) = \frac{1}{n}\sum_{i=1}^{177} |\mathcal{C}_i| \mathrm{MSE}_{\mathcal{C}_i}(x), \\ & \mathcal{A}(x) = min\_radius\_to\_perp\_or\_para(x), \end{aligned} \tag{61.6}$$

where x represents a possible vertical plane of reflection axis, $|\mathcal{C}_i|$ stands for the cardinality of $\mathcal{C}_i$, $f_{\mathcal{C}}$ is MSE (Eq. 61.3), $\mathcal{A}$ measures the minimum angular error (in radian) to the perpendicularity or parallelity against the parent symmetry, and the relative weight ω was set to 10 (e.g., a penalty $\mathcal{A}$ = 0.01 in architectural style was amplified to 0.1 in *f*).

We applied a C++ version of CMA-ES (*libcmaes*, version 0.9.5), a well-known DFO algorithm, to solve the formulated Eq. (61.6). The tests were conducted on a workstation (Intel Xeon E5-2690 v4 2.6 GHz, 64 GB memory, Ubuntu 16.04, single-threading), with the *point cloud library* (version 1.8.1) and *fast library for approximate nearest neighbor* (FLANN, version 1.8.4) for efficient point cloud processing. We set the number of iterations of CMA-ES to 200 and other parameters to default. Figure 61.2 shows the process of detecting the global reflection symmetry, where the objective value quickly descended from over 18 to less than 0.1 in about a minute. In the viewport of parameter space, ρ and φ quickly converged to the most voted (dark color) grid; while in the point cloud viewport, the optimal global reflection symmetry was found by CMA-ES in less than 100 s, as shown in Fig. 61.2. The time was furthermore reduced to 23.5 s on the test machine by enabling multi-threading parallel computing.

The proposed DFO approach was compared with a point-based pairwise voting-clustering [16] and a wavelet convolution-based voting method [18]. The feature matching methods were not included due to the error-prone feature detection in uncontrolled real-world scenes [22]. The feature matching Table 61.1 lists the comparisons, including PCR (Eq. 61.2), MSE (Eq. 61.3), plane equation, and computational time, of the three methods on the pilot case. According to the PCR and MSE, one can confirm the success of finding the target reflection, and evaluate the performances of different methods. The proposed DFO approach won in both accuracy (PCR = 93.7%, MSE = 0.086 m^2) and efficiency (98.7 s), while the point-based voting-clustering found a slightly less accurate and efficient result (PCR = 90.7%, MSE = 0.091 m^2, in 140.7 s), and the wavelet convolution-based voting was only with local symmetries.

The 'divide-and-detect' process continued for local reflections till the remaining clouds were too small (less than *n*/20). All the global and local reflections, as shown in Fig. 61.3a, were detected in 641.8 s in total; Fig. 61.3b shows the hierarchy of the reflections. It was found that the whole hierarchy of reflections was also symmetric to the plane of the global reflection. The symmetry hierarchy was applied to a RANSAC-based automatic rooftop modeling process to rectify the planar and spherical primitives [6]. As shown in Fig. 61.3c, a symmetry-guided rooftop model was created and attached to the 'box' model of the building. In summary, the pilot study preliminarily endorsed the feasibility and soundness of the proposed DFO approach.

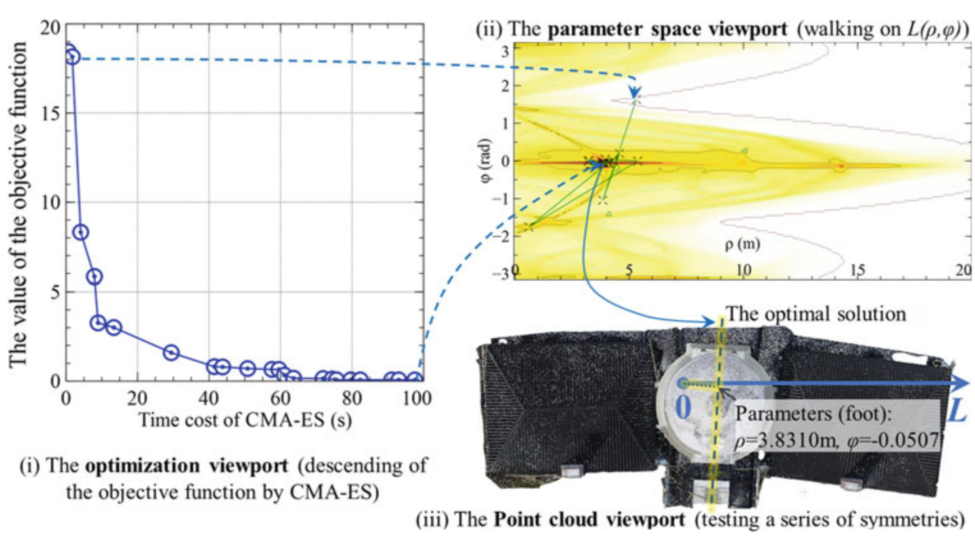
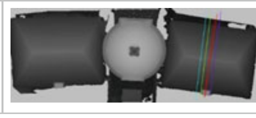
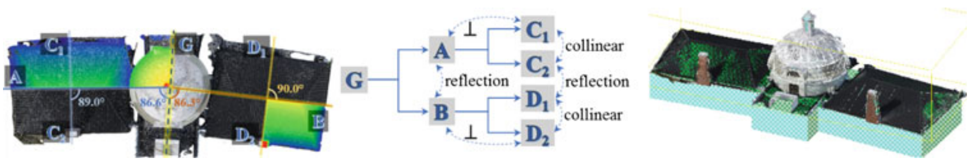


Fig. 61.2 Illustrations of ASD by the proposed DFO approach in three viewports

Table 61.1 A comparison of the results of detecting the global reflection symmetry

	Mitra and Pauly [16]	Cicconet et al. [18]	The DFO approach
Type	Voting-clustering	Voting-clustering	Parameter optim.
PCR[a]	90.7% (grid center)	9.77% (the best one)	**93.7%**
MSE[a](m^2)	0.091	19.164	**0.086**
Plane	$19.983X - Y = 78.033$	$7.914X - Y = 71.718$	$19.708X - Y = 75.596$
Correct?[a]	**Yes**	No (local only)	**Yes**
Time[a] (s)	140.7	837.7	**98.7**
Top view			

[a]Best values in bold



(a) The detected reflections (b) Symmetry hierarchy (c) A symmetry-guided model

Fig. 61.3 The hierarchy and an application of the detected symmetries

61.5 Conclusion

This paper presents a DFO approach for automatic ASD from 3D urban point clouds for creating CIM/BIM. In this approach, the symmetries and symmetry hierarchies can be formulated to nonlinear optimization problems, that concerns both the geometric symmetry condition and architectural style, and solved by DFO algorithms. The results of experiments on a pilot case, i.e., the best accuracy (both PCR and MSE) and efficiency (time cost)in detecting the global reflective symmetry, preliminarily confirmed its technological feasibility. The symmetry hierarchy was also validated in generating a symmetry-guided as-built rooftop model.

The contribution of this paper is twofold. First, the problem formulation in this approach exposes the problem of ASD from 3D urban point clouds to DFO algorithms and other mathematical methods. Secondly, The accurate and efficient DFO approach for ASD can be applied to the processing of large-scale 3D urban point clouds for enriching the urban semantics in CIM/BIM. Given the background of the boomingly available 3D urban point clouds and the demands of semantic CIM/BIM, the presented approach, and the enriched CIM/BIM at large, may enable various applications in heritage conservation, smart city development, architectural morphology, computational geometry, computer vision, and location-based services for a smart and resilient future.

Although the proposed DFO approach has many merits, the proposed approach relies on domain knowledge (architectural styles) in the formulation and only works with the clouds of uniformly distributed points. The experiments in this paper were also preliminary, e.g., focusing on reflections only. Possible future research directions include: (i) collecting, formulating, and compiling the typical architectural styles in urban areas, (ii) adopting, gauging, and fine-tuning state-of-the-art DFO algorithms, and (iii) integrating and applying the symmetries and symmetry hierarchy into popular CIM/BIM software platforms.

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References

1. Thompson, D.W.: On Growth and Form. Cambridge University Press, Cambridge (1961)
2. Fletcher, B., Fletcher, B.F.: A history of architecture on the comparative method, 5th edn. Agnew, & Co., London, Bradbury (1905)
3. Mitra, N.J., Pauly, M., Wand, M., Ceylan, D.: Symmetry in 3D geometry: extraction and applications. Comput. Graph. Forum **32**(6), 1–23 (2013). https://doi.org/10.1111/cgf.12010
4. Eastman, C.M., Eastman, C., Teicholz, P., Sacks, R.: BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors, 2nd edn. Wiley, Hoboken, NJ (2011)
5. Tang, P., Huber, D., Akinci, B., Lipman, R., Lytle, A.: Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques. Autom. Constr. **19**(7), 829–843 (2010). https://doi.org/10.1016/j.autcon.2010.06.007
6. Chen, K., Lu, W., Xue, F., Tang, P., Li, L.H.: Automatic building information model reconstruction in high-density urban areas: augmenting multi-source data with architectural knowledge. Autom. Constr. **93**, 22–34 (2018). https://doi.org/10.1016/j.autcon.2018.05.009
7. van Kaick, O., Zhang, H., Hamarneh, G., Cohen-Or, D.: A survey on shape correspondence. Comput. Graph. Forum **30**(6), 1681–1707 (2011). https://doi.org/10.1111/j.1467-8659.2011.01884.x
8. Conn, A.R., Scheinberg, K., Vicente, L.N.: Introduction to derivative-free optimization. SIAM, Philadelphia, PA (2009)
9. Rios, L.M., Sahinidis, N.V.: Derivative-free optimization: A review of algorithms and comparison of software implementations. J. Global Optim. **56**(3), 1247–1293 (2013). https://doi.org/10.1007/s10898-012-9951-y
10. Xue, F., Lu, W., Chen, K.: Automatic generation of semantically rich as-built building information models using 2D images: a derivative-free optimization approach. Comput. Aided Civil Infrastruct. Eng. in press (2018). https://doi.org/10.1111/mice.12378
11. Nicosia, G., Stracquadanio, G.: Generalized pattern search algorithm for peptide structure prediction. Biophys. J. **95**(10), 4988–4999 (2008). https://doi.org/10.1529/biophysj.107.124016
12. Hansen, N., Ostermeier, A.: Completely derandomized self-adaptation in evolution strategies. Evol. Comput. **9**(2), 159–195 (2001). https://doi.org/10.1162/106365601750190398
13. Xue, F., Lu, W., Chen, K., Zetkulic, A.: From 'semantic segmentation' to 'semantic registration': a derivative-free optimization-based approach for automatic generation of semantically rich as-built building information models (BIMs) from 3D point clouds. J. Comput. Civil Eng., under review (2018)
14. James, G.D.: The Representation Theory of the Symmetric Groups. Springer, New York (1978)
15. Mitra, N.J., Guibas, L.J., Pauly, M.: Partial and approximate symmetry detection for 3D geometry. ACM Trans. Graph. **25**(3), 560–568 (2006). https://doi.org/10.1145/1179352.1141924
16. Mitra, N.J., Pauly, M.: Symmetry for architectural design. In: Advances in Architectural Geometry. pp. 13–16. (2008). http://www.architecturalgeometry.org/aag08/aag08proceedings-papers_and_poster_abstracts.pdf
17. Kazhdan, M.: An approximate and efficient method for optimal rotation alignment of 3D models. IEEE Trans. Pattern Anal. Mach. Intell. **29**(7), 1221–1229 (2007). https://doi.org/10.1109/TPAMI.2007.1032
18. Cicconet, M., Birodkar, V., Lund, M., Werman, M., Geiger, D.: A convolutional approach to reflection symmetry. Pattern Recogn. Lett. **95**, 44–50 (2017). https://doi.org/10.1016/j.patrec.2017.03.022
19. Brown, C.M.: Inherent bias and noise in the Hough transform. IEEE Trans. Pattern Anal. Mach. Intell. **5**(5), 493–505 (1983). https://doi.org/10.1109/TPAMI.1983.4767428
20. Berner, A., Bokeloh, M., Wand, M., Schilling, A., Seidel, H. P.: A graph-based approach to symmetry detection. In: Volume Graphics, 40, pp. 1–8. ACM (2008). https://doi.org/10.2312/vg/vg-pbg08/001-008
21. Bokeloh, M., Berner, A., Wand, M., Seidel, H., Schilling, A.: Symmetry detection using feature lines. Comput. Graph. Forum **28**(2), 697–706 (2009). https://doi.org/10.1111/j.1467-8659.2009.01410.x
22. Andreopoulos, A., Tsotsos, J.K.: 50 years of object recognition: directions forward. Comput. Vis Image Underst. **117**(8), 827–891 (2013). https://doi.org/10.1016/j.cviu.2013.04.005
23. Monszpart, A., Mellado, N., Brostow, G.J., Mitra, N.J.: RAPter: rebuilding man-made scenes with regular arrangements of planes. ACM Trans. Graph. **34**(4), 103 (2015). https://doi.org/10.1145/2766995
24. Lipman, Y., Chen, X., Daubechies, I., Funkhouser, T.: Symmetry factored embedding and distance. ACM Trans. Graph. **29**(4), 103 (2010). https://doi.org/10.1145/1778765.1778840
25. Chertok, M., Keller, Y.: Spectral symmetry analysis. IEEE Trans. Pattern Anal. Mach. Intell. **32**(7), 1227–1238 (2010). https://doi.org/10.1109/TPAMI.2009.121
26. Raviv, D., Bronstein, A.M., Bronstein, M.M., Kimmel, R.: Full and partial sym-metries of non-rigid shapes. Int. J. Comput. Vis. **89**(1), 18–39 (2010). https://doi.org/10.1007/s11263-010-0320-3

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Sequential Pattern Analyses of Damages on Bridge Elements for Preventive Maintenance

62

Kowoon Chang, Soram Lim, Seokho Chi, and Bon-Gang Hwang

Abstract

For the safety and serviceability of aging bridges, it is important to understand how the current conditions of the bridges will deteriorate in the future as time goes by. The primary goal of this research is to analyze sequential patterns of damages on the bridge elements that are normally recorded through site inspections and managed by the bridge management system (BMS). To achieve the research goal, the research team first discovered a number of bridge clusters with distinguished characteristics by using a data clustering algorithm. Sequential pattern mining was then utilized to extract types and sequences of damages on bridge elements frequently seen in each cluster. The data used for the analyses was collected from BMS managed by the Korea Institute of Civil Engineering and Building Technology. This BMS includes the general, structural, traffic, and weather information of 6773 bridges (i.e., the total of 127 attributes) and contains 834,815 site inspection records of the bridge elements. A preliminary test was performed by using a dataset of 1542 Pre-Stressed Concrete I-shape type bridges for the validation purpose. The results of this study showed application potential to estimating future condition changes of the bridges based on the past inspection records for preventive bridge maintenance.

Keywords

Bridge management system (BMS) • Preventive maintenance • Big data analytics • Damage patterns • Sequential pattern mining

62.1 Introduction

In recent years, the number of aging bridges has rapidly increased all over the world, including South Korea. Almost 40% of bridges in the U.S. became older than 50-year-old in 2017 [1] and the number of aging bridges over 20 in South Korea is expected to increase up to three times higher in 2026 [2]. To ensure the safety and serviceability of the aging bridges, it is important to understand how the current structural and visual conditions of the bridges will deteriorate in the future as time goes by.

In response to the importance, the bridge management system (BMS) has been developed as a strategic tool in order to forecast future bridge conditions for better planning of maintenance, rehabilitation, and replacement. BMSs have established

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traditional deterioration models that explain condition rating changes of bridge elements, such as individual decks of the superstructure, by using multi-regression or Markovian transition probabilities with significant deterioration parameters (e.g., bridge age, deck material, deck length, and ADT) [3–5]. For more reliable deterioration prediction, the applications of big data analytics into bridge maintenance have been proposed to discover meaningful knowledge from a big size of bridge data. Kim et al. [6] examined the massive National Bridge Inventory (NBI) dataset to identify the deterioration trends and develop a corresponding model in the U.S. by utilizing both deterministic and probabilistic analyses including two-factor analysis of variance. Similarly from the NBI database, Huang and Chen [7] discovered factors and association rules of bridge deck deterioration by applying clustering, classification, and association rule data mining algorithms. Although such models showed potential benefits for preventive maintenance, they had limitations in understanding the complex relationship between various damages on bridge elements, such as water leakage to the expansion joint accelerating the corrosion of adjacent girders which lead to weakened bearing [8], and exploring hidden damage mechanism of bridge elements [9, 10].

Sequential pattern is one of useful knowledge that can be derived from data analyses. Sequential pattern mining is a technique to discover patterns of ordered events. It has been widely applied to identify sequential relationship between events and predict posterior events based on the historical patterns in the retail and medicine industries [11, 12]. Since BMS data are periodically recorded and updated, such sequential analyses seem to be applicable to find sequential patterns of damages on bridge elements and estimate future condition changes based on the historical damage patterns. Such sequential patterns can explain damage mechanism between different bridge elements while enhancing prediction performance of structural deterioration of bridges.

Thus, the primary goal of this research is to analyze sequential patterns of damages on the bridge elements. The sequential pattern analysis in the research is summarized as two objectives: (1) determination of structural and environmental characteristics of bridges that cause similar damage patterns, for instance Bridge I and Bridge II follow similar deterioration patterns, and (2) investigation of sequential damage mechanisms such that Damage II has occurred after Damage I. The result of this research will contribute to estimating the future condition changes of the bridges based on the past inspection records for preventive bridge maintenance.

The data used for the analyses was collected from BMS managed by the Korea Institute of Civil Engineering and Building Technology and data mining algorithms for clustering and sequential pattern mining were applied to extract patterns. This paper proposed research methodology for sequential pattern analyses and a preliminary test was performed with a dataset of Pre-Stressed Concrete I-shape type bridges for the validation purpose.

62.2 Research Methodology

To achieve the research goal, the research methodology was organized into three main processes. First, this research collected and preprocessed the data of BMS. Second, the research selected a set of features and performed cluster analysis to discover a number of bridge clusters with distinguished characteristics. Third, sequential pattern mining was utilized to extract types and sequences of damages on bridge elements frequently seen in each cluster. The methodology was developed and implemented by R software version 3.3.2.

62.2.1 Data Collection

The collected BMS data were composed of two structured table datasets: bridge information and bridge inspection records. The bridge information included general, structural, traffic, and weather information of 6773 bridges (i.e., the total of 127 attributes) located in provinces of Korea except Seoul, which were built from 1966 to 2015 (see Table 62.1). Another dataset, the bridge inspection records, contained 834,815 inspection records of the bridge elements. The records were manually entered by inspectors from 1994 to 2015 through 9775 detailed inspections and 900 precise safety diagnoses periodically performed every two to six years. The inspection records included six attributes (i.e., Inspection Bridge Code, Span or Support Code, Inspection Date, Inspection Element, Damage Type, and corresponding Condition Grade). The condition grade was divided into five grades as “A” (best condition), “B”, “C”, “D”, and “E” (worst condition), of which grades “C”, “D”, and “E” meant damaged grades to be repaired (see Table 62.2) [13].

Table 62.1 Sample of bridge information dataset

General information (47 attributes)			Structural information (51 attributes)			Traffic information	Weather information (28 attributes)	
Bridge code	Total length (m)	Total width (m)	Deck type	Deck depth (m)	Girder type	Avg. truck traffic volume (veh./day)	Avg. humidity (%)	Avg. rainy days (/year)
0001	125.2	19.5	RC	20	PSCI	7228	67.7	107
0006	43.8	19.5	RC	60	PSCI	5796	62.4	110
0011	40.8	19.5	RC	23	PSCI	6924	69.2	120

Table 62.2 Sample of bridge inspection records dataset

Inspection bridge code	Span (or support) code	Inspection date	Inspection element	Damage type	Condition grade
0001	01	2006-06-18	Deck	Crack	B
0001	01	2006-06-18	Pavement	Porthole	C
0001	01	2006-06-18	Expansion joint	Corrosion	B
0001	02	2006-06-18	Deck	Crack	B

62.2.2 Data Preprocessing

The research conducted preprocessing before analyses to minimize negative effects of original BMS data on the analyses, which were recorded manually thus included some human errors. Two kinds of preprocessing approaches were applied to a bridge information table. First, the research omitted tuples which contained attributes with missing values to enhance the completeness of dataset, and thus the information of 560 bridges was deleted. Second, the continuous attributes (e.g., traffic volume, length of span, and temperature) were normalized into normal distribution (i.e., mean with zero and standard deviation with one) to avoid the problems caused by different measurement scales on each attribute [14].

The bridge inspection records were also preprocessed by cleaning and reorganizing the attributes. First, the research deleted inspection records with input errors of condition grades such as “F” and “|” instead of “A” to “E”. In addition, the records with condition grade of “A” or “B” were also removed since this research only focused on damaged bridge elements: “C”, “D”, and “E”. Second, a new attribute, “Bridge Inspection ID”, was made by combining the bridge code and the span or support code. For inspection date, only inspection year was recorded because detailed inspection or safety diagnose is performed only once a year. Consequently, “Inspection year”, “Inspection Element”, and “Damage Type” were considered for each “Bridge Inspection ID”.

62.2.3 Cluster Analysis

Cluster analysis is an unsupervised method to partition a dataset by considering multiple attributes. The key steps include: Feature selection, Clustering algorithm design, and Result interpretation. The research team generated a subset of features from the total 127 attributes of the bridge information table. Then, the clustering algorithm named PAM (Partitioning Around Medoids) was utilized to group bridges with similar features into the same cluster. Finally, the researchers interpreted and discussed clustering results.

PAM introduced by Kaufman and Rousseeuw is one of the most commonly used k-medoids clustering algorithms [15, 16]. The k-medoids algorithm is a clustering approach for partitioning a dataset into k clusters but less sensitive to outliers than a k-means clustering method because each cluster is represented by one of data points of the cluster. These points are named medoids. The k-medoids algorithm needs to specify k, the number of clusters to be generated. In this study, the “pam” function in the “cluster” package on R software was utilized and the optimal k was determined by the silhouette method.

PAM algorithm was proceeded by following steps [16, 17]. Particularly, the study calculated the Gower’s dissimilarity matrix which is applied for mixed data types with continuous, ordinal, or categorical attributes at the same time [18].

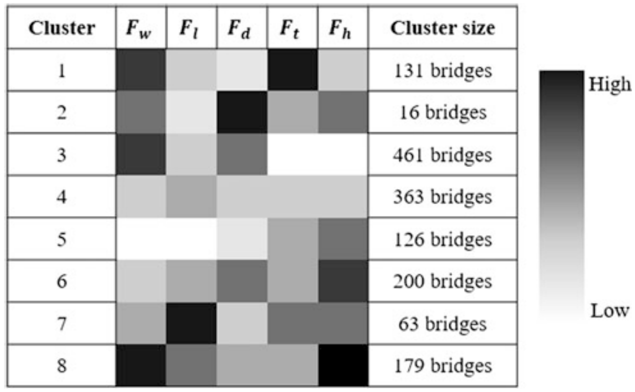

Fig. 62.1 Distinctive characteristics of the features by each cluster

Table 62.3 Example of transaction database based on the bridge inspection records

Bridge inspection ID	Inspection year	Damage types on bridge elements
0001_01	2006	(Damage A, Damage B, Damage C)
0001_01	2010	(Damage B, Damage D)
0001_01	2014	(Damage A, Damage E)
0001_02	2006	(Damage B, Damage C)
0001_02	2010	(Damage A, Damage C, Damage D)

1. Select k objects to become the medoids.
2. Calculate the dissimilarity matrix.
3. Assign every object to its closest medoid.
4. For each cluster, search if any of the object of the cluster decreases the average dissimilarity coefficient.
5. If at least one medoid has changed, go to step 3, else end the algorithm.

62.2.4 Sequential Pattern Mining

Sequential pattern mining (SPM) is a data mining technique to identify patterns of ordered events within transaction database [11]. The bridge inspection records had a large transaction database, where each transaction consisted of three fields: “Bridge Inspection ID” corresponding to the subject of the transaction; “Inspection Year” as transaction time; and “Damage Types on Bridge Elements” as items associated with the transaction (see Table 62.3).

Let $\mathrm{I} = (i_1, i_2, \ldots, i_m)$ be a set of items. A sequence s is an ordered list of item sets. It is denoted by $\mathrm{s} = \langle s_1, s_2, \ldots, s_n \rangle$, where $s_j, j \in 1, 2, \ldots, n$, is an item set, for example $\langle (\mathrm{A, B, C}), (\mathrm{B, D}), (\mathrm{A, E}) \rangle$. Another sequence $s' = \langle (A), (B), (E) \rangle$, which means Damage B has been produced after Damage A, and subsequently Damage E has occurred, is a subsequence of sequence s since $(\mathrm{A}) \subseteq (\mathrm{A, B, C}), (\mathrm{B}) \subseteq (\mathrm{B, D}), (E) \subseteq (\mathrm{A, E})$. The support of sequence s' means the proportion of data-sequences which contain s' as subsequence. A minimum support value can be set to decide whether a sequence is frequent or not [6, 19].

SPADE (Sequential Pattern Discovery using Equivalent classes) algorithm introduced by Zaki is one of potential SPM methods. It transforms horizontal transaction database into a vertical id-list database format, which is a list of items consisting of all the IDs and transaction times when the item occurs. This algorithm makes it efficient to reduce database scans in the case of large database such as BMS [20]. The “arulesSequences” package on R software provides an interface to the c++ version of cSPADE.

62.3 Preliminary Test

To validate the proposed research methodology, preliminary test was conducted by using a dataset of 1542 Pre-Stressed Concrete I-shape type (PSCI) bridges with 147,268 inspection records of the superstructure elements. The target elements included expansion joint, deck pavement, deck, girder, and cross beam. After filtering and preprocessing, 31,733 inspection records of the damaged elements were aligned to 3163 PSCI Bridge Inspection ID.

For cluster analysis, five features were selected: effective deck width(F_w), maximum span length(F_l), deck depth(F_d), average truck traffic volume per day(F_t), and average humidity(F_h), which have been known to cause superstructure damages by previous studies [7, 21, 22]. As a result, PSCI bridges were partitioned into eight clusters and the distinctive characteristics of each cluster are illustrated in Fig. 62.1. For example, the bridges in Cluster 1 had high average truck traffic volume per day and thin deck depth compared to the bridges in Cluster 3 which had low average truck traffic volume per day and relatively thick deck depth.

To derive distinct sequential patterns of element damages from each cluster, the authors applied sequential pattern mining algorithms. Different damage types and sequences with 0.03 minimum support were extracted from eight clusters. The minimum support means the ratio of the number of Bridge Inspection IDs that contain such damage types or patterns to the total number of Bridge Inspection IDs within the cluster.

Table 62.4 explains examples of damage types found from Cluster 2 and Cluster 7. The types of severe element damages (e.g., exposed reinforcing steel, breakdown, and deformation) were more frequently discovered in Cluster 2 than Cluster 7. The bridges in Cluster 2 have shorter span length and thicker deck depth than the bridges in Cluster 7, those structural characteristics often explain the bridges are strong against a vertical load but have severe damages instead of common damages such as cracks.

Next, the sequences of damage occurrence were also examined and Table 62.5 shows an example list of the most frequently found sequences within Cluster 7 (long spans and thinner deck depth) in the order by support. Sequence #1 explained same damages can be repeated and similarly Sequence #3 showed the pavement damage could be deteriorated from the crack to the porthole. Sequence #2 examined that the crack of a deck could cause possible leakage from the deck

Table 62.4 Sample damage types on bridge elements seen in Cluster 2 and Cluster 7

Cluster	Damage type on bridge element	Support
2	Exposed reinforcing steel and corrosion of a deck	0.4146
	Concrete efflorescence of a deck	0.2195
	Exfoliation of a girder	0.2195
	Breakdown of a girder anchorage	0.1707
	Deformation of expansion joint	0.0976
7	Crack of a deck	0.2683
	Corrosion of a expansion joint	0.2317
	Exposed reinforcing steel and corrosion of a deck	0.1220
	Crack of pavement	0.1098
	Crack of a cross beam	0.0854

Table 62.5 The most frequently found sequences of Cluster 7

Sequence number	Sequence on bridge elements	Support
1	<(Corrosion of expansion joint), (Corrosion of expansion joint)>	0.2195
2	<(Crack of a deck), (Corrosion of expansion joint)>	0.0854
3	<(Crack of pavement), (Porthole of pavement)>	0.0488
4	<(Rubber-breakdown on expansion joint), (Crack of a cross beam)>	0.0366
5	<(Corrosion of expansion joint), (Exposed reinforcing steel and corrosion of a deck)>	0.0366
6	<(Breakdown of a deck), (Exposed reinforcing steel and corrosion of a deck)>	0.0366

while leading to the second damage of corrosion of expansion joint. Last, Sequence #5 showed that the heavy weight due to long spans could result in weakened expansion joints which then cause severer damages step by step: corrosion of the joint, exposed reinforcing steel, and corrosion of a deck.

62.4 Conclusions

This research aims to analyze sequential patterns of damages on the bridge elements. For the primary goal, the research proposed a research methodology including cluster analysis for discovering bridge clusters with distinguished characteristics and sequential pattern mining for investigating sequential damage causation mechanisms. As preliminary results, PSCI bridges were partitioned into eight clusters and the different sequences of element damages were extracted from each cluster with 0.03 minimum support.

The results showed application potential to estimating future condition changes of the bridges based on the past inspection records for preventive bridge maintenance. However, there are still improvement opportunities. The cluster analysis with more elaborate feature selection needs to be applied to monitor condition changes of the bridges, for instance newly built bridges would follow the deterioration patterns of the aging bridges in the same cluster. In addition, the current research does not explain causal relationships among damage patterns; thus further empirical and statistical analyses need to be conducted to explain damage causation mechanism built on top of the discovered sequential patterns. The further improvement also includes the verification of the pattern-extracting methodology by applying it to other bridges with more various structural types.

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References

1. American Society of Civil Engineers (ASCE): Report Card for America's Infrastructure, https://www.infrastructurereportcard.org. last accessed 10 Jan 2018
2. Ministry of Land: Infrastructure, and Transport of Korea: Yearbook of road bridges and tunnels (2016)
3. Agrawal, A.K., Kawaguchi, A., Chen, Z.: Deterioration rates of typical bridge elements in New York. J. Bridg. Eng. **15**(4), 419–429 (2010). https://doi.org/10.1061/(ASCE)BE.1943-5592.0000123
4. Morcous, G.: Performance prediction of bridge deck systems using Markov chains. J. Perform. Constr. Facil. **20**(2), 146–155 (2006). https://doi.org/10.1061/(ASCE)0887-3828
5. Huang, Y.H.: Artificial neural network model of bridge deterioration. J. Perform. Constr. Facil. **24**(6), 597–602 (2010). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000124
6. Kim, Y.J., Queiroz, L.B.: Big Data for condition evaluation of constructed bridges. Eng. Struct. **141**, 217–227 (2017). https://doi.org/10.1016/J.ENGSTRUCT.2017.03.028
7. Huang, R.Y., Chen, P.F.: Analysis of influential factors and association rules for bridge deterioration using national bridge inventory data. J. Mar. Sci. Technol. **20**(3), 336–344 (2012)
8. Sianipar, P., Adams, T.: Fault-tree model of bridge element deterioration due to interaction. J. Infrastruct. Syst. **3**(3), 103–110 (1997). https://doi.org/10.1061/(ASCE)1076-0342
9. Creary, P.A., Fang, F.C.: The data mining approach for analyzing infrastructure operating conditions. Procedia. Soc. Behav. Sci. **96**, 2835–2845 (2013). https://doi.org/10.1016/J.SBSPRO.2013.08.316
10. Liu, K., El-Gohary, N.: Semantic modeling of bridge deterioration knowledge for supporting big bridge data analytics. In: Proceedings of the 2016 Construction Research Congress. pp. 930–939. ASCE Press, San Juan, Puerto Rico (2016)
11. Agrawal, R., Srikant, R.: Mining sequential patterns. In: the 11th International Conference on Data Engineering. pp. 3–14. IEEE Comput. Soc. Press, Taipei, Taiwan (1995)
12. Wright, A.P., Wright, A.T., McCoy, A.B., Sittig, D.F.: The use of sequential pattern mining to predict next prescribed medications. J. Biomed. Inform. **53**, 73–80 (2015). https://doi.org/10.1016/J.JBI.2014.09.003
13. Lim, S., Chung, S., Chi, S., Song, J.: A framework for developing an estimation model of damages on bridge elements using big data analytics. In: the 33rd International Association for Automation and Robotics in Construction. pp. 241–249. I.A.A.R.C., Auburn, AL (2016)
14. Elhag, T.M.S., Wang, Y.M.: Risk assessment for bridge maintenance projects: neural networks versus regression techniques. J. Comput. Civ. Eng. **21**, 402–409 (2007). https://doi.org/10.1016/(asce)0887-3801
15. Kaufman, L., Rousseeuw, P.J.: Finding groups in data: an introduction to cluster analysis Title. Wiley, United States (1990)
16. Kassambara, A.: Practical Guide to Cluster Analysis in R: Unsupervised Machine Learning. STHDA, United States (2017)
17. Park, H., Jun, C.: A simple and fast algorithm for K-medoids clustering. Expert Syst. Appl. **36**(2), 3336–3341 (2009). https://doi.org/10.1016/j.eswa.2008.01.039

18. Podani, J.: Extending gower's general coefficient of similarity to ordinal characters. Int. Assoc. Plant Taxon. (IAPT) **48**(2), 331–340 (1999)
19. Masseglia, F., Poncelet, P., Teisseire, M.: Incremental mining of sequential patterns in large databases. Data Knowl. Eng. **46**(1), 97–121 (2003). https://doi.org/10.1016/S0169-023X(02)00209-4
20. Zaki, M.: SPADE: an efficient algorithm for mining frequent sequences. J. Machine Learning **42**, 31–60 (2001). https://doi.org/10.1023/A:1007652502315
21. Morcous, G., Rivard, H., Hanna, A.M.: Modeling bridge deterioration using case-based reasoning. J. Infrastruct. Syst. **8**(3), 86–95 (2002). https://doi.org/10.1061/(ASCE)1076-0342
22. Huang, R., Mao, I.S., Lee, H.K.: Exploring the deterioration factors of RC bridge decks: a rough set approach. Comput. Civ. Infrastruct. Eng. **25**(7), 517–529 (2010). https://doi.org/10.1111/j.1467-8667.2010.00665.x

63

Sound Event Recognition-Based Classification Model for Automated Emergency Detection in Indoor Environment

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Abstract

Prompt emergency detection and response in indoor environments is a significant issue due to the difficulties in detecting indoor emergency events. However, current indoor monitoring tasks are mainly carried out by manual observations of occupants and such human-dependent methods generally have limitations in taking actions against emergency events. Many researchers have made much effort to develop automated indoor monitoring systems using wearable sensing device technologies and computer vision. While these methods have various advantages, there still remain challenges to be addressed for detecting indoor emergency events; for instance, wearable sensors need to be attached to a human body and occlusions make it hard to recognize the emergencies. To overcome those deficiencies, this paper proposes a sound event recognition (SER)-based indoor event classification (e.g., emergency and normal event) method with a convolutional neural network (CNN). The research consists of four main steps. First, the sound types of indoor events are determined as four emergency sounds (explosion, gunshot, glass break, and scream) and one normal sound (sleeping). Second, 692 sound data of identified events are collected from online sound data sharing services, and the preprocessing is performed. Third, SER model is developed through CNN algorithm with log-scaled mel-spectrogram features. Finally, model performance is evaluated using 5-fold cross validation. The experimental results showed that the sounds caused by indoor emergency events could be automatically recognized by the proposed method with F-score of 77.32%, which demonstrates its applicability for real emergency situations.

Keywords

Indoor environment • Emergency event • Sound event recognition • Convolutional neural network

63.1 Introduction

Emergency detection and response system has been demanded due to the spatial characteristics of indoor environments. As the indoor environment usually involves a confined area separated from the outside, numerous indoor incidents are usually identified by occupants in the building. Moreover, the interior space consists of building components (e.g., floors, walls, windows, and doors), which obstruct the line of sight [1] and emergency detection can be delayed or neglected as a result.

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However, the indoor emergency monitoring is largely dependent on manual observations and responses by occupants. As this approach is subject to missing or overlooking the accidents in indoor environments [2], there remains a need for developing indoor monitoring systems that automatically recognize and respond to emergencies.

A number of supplementary methods have been studied such as wearable sensing device technologies (e.g., radio frequency identification and inertial measurement unit) [1, 3, 4] and computer vision [2, 5, 6]. Although the information (e.g., location and action type) of occupants tagged with sensors can be obtained by wearable device-based methods, detection of non-tagged people is not available. Moreover, the occlusions by indoor obstacles make it hard to detect emergency events with computer vision.

To overcome such deficiencies, sound recognition from the indoor events can be an alternative way for the following reasons. First, it is possible to recognize various events in a space with a few acoustic sensors, not to be tagged on every occupant. Second, within an effective detection range, the events can be detected without occlusions. Finally, it is possible to classify indoor events by extracting distinct sound patterns from each event. Thus, the purpose of this paper is to develop a sound event recognition (SER)-based classification model to distinguish emergency events from normal daily events and classify emergency types using convolutional neural network (CNN).

63.2 Preliminary Study

63.2.1 Sound Types of Indoor Emergencies

In recent years, firearm accidents and terrorism have become global issues. According to national vital statistics reports in U. S. [7], 36,562 people died from injuries caused by firearms in 2015. Moreover, 25,621 people were killed by terrorism and 54% of attack types were bombing and explosion around the world in 2016 [8]. While these events can occur both in indoor and outdoor environments, there are practical challenges in the indoor emergency detection caused by spatial characteristics of indoor environments. For instance, indoor obstacles, such as floors and walls, obscure the view for emergency detection in occlusion area. To mitigate the problems, it is required to identify the emergency events and analyze the corresponding characteristics (e.g., distinct sounds) in indoor emergencies.

The emergencies can be divided into primary events and secondary events. The primary events are directly involved with dangerous situations and they cause the secondary events. In the case of firearm accidents and terrorism, gunshot and bomb explosion are categorized into the primary events and people's screaming and window break, which are subsequently caused by the primary events, can be classified into the secondary events.

Since these events have unique sound patterns distinct from other events, the sounds of indoor events can be classified as emergency sounds, including primary and secondary events, and normal sounds. In previous research, 7 types of sound events were analyzed [9], 3 for alarming sounds (glass break, screams, and dishes sounds) and 4 for usual sounds (door clapping, ringing phone, step sounds, and door lock). In the study of [10, 11], the categories of sounds were comprised of normal sounds and critical sounds related to distress situation. In this paper, the sound types of indoor events were determined as emergency sounds (explosion, gunshot, glass break, and scream) and normal sound.

63.2.2 Sound Event Recognition

Sound event recognition (SER), the main methodology of this paper, has been recently studied in the field of sound recognition behind speech recognition and music recognition. In contrast to the other two research fields, SER aims to capture non-stationary and random sounds in daily life [12, 13] which have large variations of frequencies.

In order to recognize specific events using SER, distinct sound characteristics are extracted in terms of frequency and magnitude, which is called features. Also, various features can be selected depending on the types of the sounds (e.g., long-term/short-term and stationary/nonstationary). Then these features are fed into classification models and the models are optimized by machine learning techniques.

Previous research on the SER has been addressed for the purpose of monitoring such as surveillance system [14]. In addition, for health monitoring of elderly people, falling accident was detected using one-versus-all classifiers with nearest neighbor, support vector machine, and Gaussian mixture model [15] and sound classification and localization methods were studied [16]. However, few researchers have focused on emergency monitoring in indoor environments. To the best of the authors' knowledge, this research is the first attempt to apply a sound recognition method to emergency monitoring in construction domain.

63.3 Research Framework

The research framework illustrated in Fig. 63.1 is comprised of four main steps: preprocessing, feature extraction, model development, and evaluation. First, the preprocessing is carried out to improve quality of the original sound data by eliminating non-sound intervals, applying normalization, and splitting into several sound clips with same durations. Second, log-scaled mel-spectrograms are extracted from the preprocessed data as features which represents the patterns of sound signal across time and frequency. Third, the SER model is developed by training the extracted features with CNN. Finally, the proposed model is evaluated using 5-fold cross validation method. The details of each step are explained in the following sections.

63.3.1 Preprocessing

The data preprocessing was carried out to improve quality of original sound data before extracting the features. First, non-sound intervals irrelevant to the characteristics of sound events were manually trimmed in order to prevent performance degradation of the model. Second, to address scale effects (i.e., different amplitude ranges) resulting from different recording conditions (e.g., environments), the amplitudes of sound data were normalized between −1 to 1. Finally, the original sound data was split into several sound clips that have same duration in order to fit a specific size of spectrogram in the next step.

63.3.2 Feature Extraction

Log-scaled mel-spectrogram was extracted from a sound clip through following steps [17]. First, short time Fourier transform was applied to convert a sound clip from time domain to frequency domain. Second, the transformed sound clip was represented as spectrogram with mel-scaled frequency bands and log-scaled magnitudes that are perceptual scales of the human auditory system. Finally, the corresponding delta of log-scaled mel-spectrogram was added as a feature, building two channels. An example of the original sound wave and extracted feature is illustrated in Fig. 63.2.

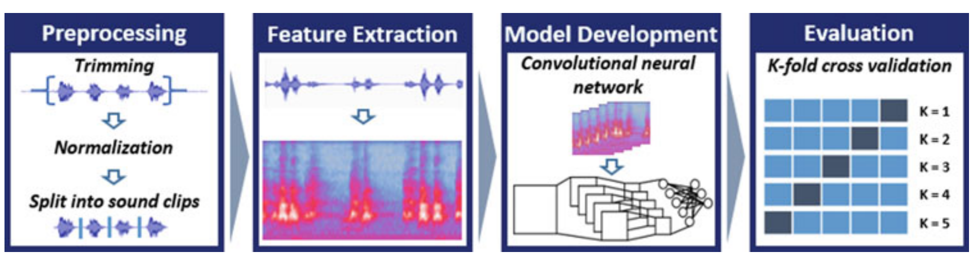

Fig. 63.1 Research framework

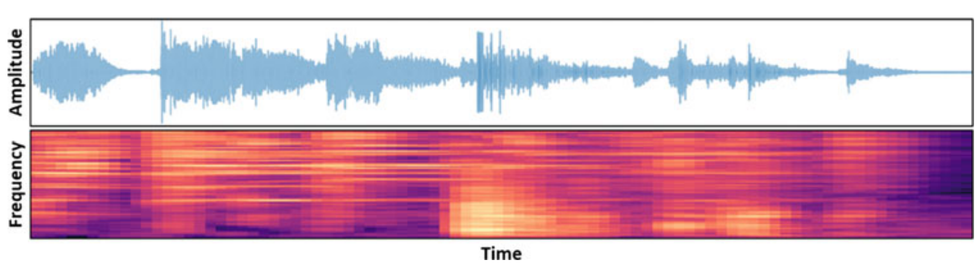

Fig. 63.2 An example of sound wave and log-scaled mel-spectrogram

63.3.3 Model Development

Convolutional neural network (CNN) was proposed as the classification model in this study, which has demonstrated outstanding performance in image recognition [18]. The typical architecture of CNN consists of convolutional layers, pooling layers, and fully-connected layers as well as input and output layers.

As it is possible to transform a sound signal to the form of two-dimensional spectrogram through the feature extraction method described in the Sect. 63.3.2, sound data can be fed as input features into CNN; a shape of input in CNN usually consists of three-dimensional data, which is a 2D matrix with channels. In addition, previous research has shown high performance of CNN in the field of SER [17, 19, 20]. The authors concluded that CNN would be an effective classifier in the sound recognition field as well as image recognition.

63.3.4 Evaluation

The procedure of model training and testing was implemented using 5-fold cross validation and the test results were represented as accumulated confusion matrix. To quantify the performance of the proposed classification model, F-score was calculated based on the precision and recall. The evaluation metrics are defined as Eq. (63.1–63.3), where the true positive (TP) is the number of cases that types of events are correctly predicted; the false positive (FP) is the number of cases that the other events are incorrectly predicted as the target events; and the false negative (FN) is the number of cases that the target events are incorrectly predicted as the other events. The precision indicates the reliability of predictions and the recall represents the ratio of correct predictions without omission. The F-score is harmonic mean of the precision and the recall. For obtaining the average precision, recall, and F-score, the micro-average method was applied to address imbalance of the number of sound clips in each class.

$$Precision = TP/(TP + FP) \tag{63.1}$$

$$Recall = TP/(TP + FN) \tag{63.2}$$

$$Fscore = 2 \cdot Precision \cdot Recall/(Precision + Recall) \tag{63.3}$$

63.4 Experiment and Result

63.4.1 Data Collection

In order to train and evaluate the SER model, total five classes were selected, including two classes (explosion and gunshot) for representing primary events in emergencies (e.g., terrorism and firearm accident), other two classes (glass break and scream) for secondary events corresponding to the primary events, and the other one class for normal event (sleeping) irrelevant to emergency events. Thus, four emergency sounds and one normal sound were determined as the classes for the model.

Then, 692 sound data was collected from online sound data sharing services, including Freesound.org and Youtube. These sound data were evenly distributed into five folds of each class for cross validation, three folds for training, one for validation, and the other one for test. Total numbers and durations of each class are as follows.

- Explosion: 54 data (287.98 s) was split into 1155 clips
- Gunshot: 354 data (447.19 s) was split into 1407 clips
- Glass Break: 140 data (471.06 s) was split into 1822 clips
- Scream: 89 data (398.24 s) was split into 1583 clips
- Normal: 55 data (508.44 s) was split into 2103 clips.

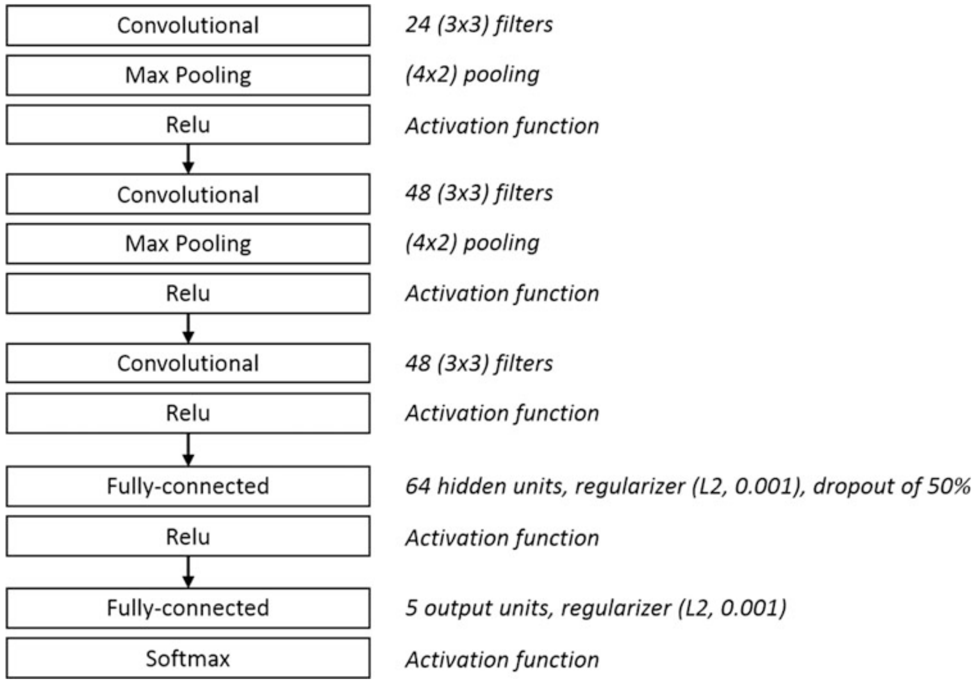

Fig. 63.3 Model configuration

63.4.2 Experiment Setup

Features. In this study, each sound clip has 0.46 s duration with the sampling rate of 22050 Hz, which has 41 overlapping frames with window size of 2048 and hop length of 256. As described in the Sect. 63.3.2, log-scaled mel-spectrogram features were extracted with three-dimensional array (120 × 41 × 2), which means 120 bands, 41 frames, and 2 channels respectively.

Model Configuration and Implementation. The model is comprised of five layers: three convolutional layers with pooling layers and two fully-connected layers. For the implementation, the research team built upon an open source code [21], which refers to the research paper [17] and [20]. Detailed information of each layer and parameters for training setup are described in Fig. 63.3. The proposed model was trained with 50 epochs and batch size of 32.

63.4.3 Results and Discussions

The accumulated confusion matrix is represented in Table 63.1. From the confusion matrix, the precision, recall, and F-score of each class and micro-average of total classes were obtained as shown in Table 63.2.

The lowest F-score of 68.67% was measured from the classification results of the normal sound class, which might have been caused by the insufficient amount of normal sound data to reflect large variation of its sound patterns. In the case of the

Table 63.1 Accumulated confusion matrix from 5-fold cross validation (unit: sound clips)

Event		Predicted label				
		Explosion	Gunshot	Glass break	Scream	Normal
True label	Explosion	1366	130	477	7	133
	Gunshot	70	1823	85	44	80
	Glass break	326	111	1432	154	86
	Scream	169	119	300	1549	33
	Normal	236	213	317	102	1261

Table 63.2 Results of precision, recall and F-score

Event	Precision (%)	Recall (%)	F-score (%)
Explosion	81.62	79.22	80.40
Gunshot	75.76	90.41	82.44
Glass break	77.82	71.08	74.30
Scream	78.29	89.77	83.64
Normal	74.65	63.58	68.67
Micro-average	77.32	77.32	77.32

explosion and glass break classes, 41% of FP in explosion class was related to the false predictions that predicted glass break class as explosion class. Similarly, 40% of FP in glass break class was caused by false predictions that predicted explosion class as glass break class. The reason of these results can be inferred that the explosion sounds that are often accompanied with glass broken sounds made it difficult to distinguish between the two classes.

Based on the evaluation and results analyses, the trained model provided high performance with the average F-score of 77.32%, while the error rate of emergency detections that classifies the emergency events as normal events need to be decreased as it would be fatal in real emergencies. Additionally, the developed model can be utilized to detect the emergency sounds from various sound mixtures with environmental noise; for example, several event classes can be selected if they have higher presence probabilities than predetermined threshold values.

63.5 Conclusions

This study proposes a SER-based emergency classification method using CNN. To implement the proposed method, emergency sounds and normal sounds data were collected and preprocessed, log-scaled mel-spectrograms were extracted as features, and the model was trained by CNN. For evaluating the proposed model, 5-fold cross validation with 5 classes was implemented and the average F-score of 77.32 was obtained. The experiment results showed that the emergency events in indoor environments can be automatically identified with the proposed method and demonstrated its potential to real life applications. Nevertheless, the proposed method still has improvement opportunities. This study assumed that one type of sound event occurs at a time, which is called single-label classification. The approach of multi-label classification is required to consider real emergencies in which various sound events can occur simultaneously. Future study will be conducted focusing on additional conditions for emergency detection such as polyphonic sound event detection with multi-labels to be applied in real life.

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References

1. Cillis, F. De, Simio, F. De, Faramondi, L., Inderst, F., Pascucci, F., Setola, R.: Indoor positioning system using walking pattern classification. In: 22nd Mediterranean Conference on Control and Automation. pp. 511–516. IEEE, Palermo, Italy (2014)
2. Gómez, M.J., García, F., Martín, D., de la Escalera, A., Armingol, J.M.: Intelligent surveillance of indoor environments based on computer vision and 3D point cloud fusion. Expert Syst. Appl. **42**(21), 8156–8171 (2015). https://doi.org/10.1016/J.ESWA.2015.06.026
3. Dirafzoon, A., Lokare, N., Lobaton, E.: Action classification from motion capture data using topological data analysis. In: 2016 IEEE Global Conference on Signal and Information Processing (GlobalSIP). pp. 1260–1264. IEEE, Washington, DC (2016)
4. Spadacini, M., Savazzi, S., Nicoli, M.: Wireless home automation networks for indoor surveillance: technologies and experiments. EURASIP J. Wirel. Commun. Netw. **2014**, 6 (2014). https://doi.org/10.1186/1687-1499-2014-6
5. Tran, D.-D., Le, T.-L., Tran, T.-T.-H.: Abnormal event detection using multimedia information for monitoring system. In: 2014 IEEE Fifth International Conference on Communications and Electronics (ICCE). pp. 490–495. IEEE, Danang, Vietnam (2014)
6. Foroughi, H., Aski, B.S., Pourreza, H.: Intelligent video surveillance for monitoring fall detection of elderly in home environments. In: 2008 11th International Conference on Computer and Information Technology. pp. 219–224. IEEE, Khulna, Bangladesh (2008)
7. Murphy, S.L., Xu, J., Kochanek, K.D., Curtin, S.C., Arias, E.: National vital statistics reports. (2017). https://www.cdc.gov/nchs/data/nvsr/nvsr66/nvsr66_06.pdf
8. Statista Homepage. https://www.statista.com/. Last accessed 17 Apr 2018

9. Istrate, D., Vacher, M., Castelli, E., Nguyen, C.-P.: Sound processing for health smart home. In: 2nd International Conference on Smart homes and health Telematic. Amsterdam, Singapore (2004)
10. Abdoune, L., Fezari, M.: Everyday life sounds database: telemonitoring of elderly or disabled. J. Intell. Syst. **25**(1), 71–84 (2016). https://doi.org/10.1515/jisys-2014-0110
11. Abdoune, L., Fezari, M.: A sound database for health smart home. In: 2014 World Congress on Computer Applications and Information Systems (WCCAIS). pp. 1–5. IEEE, Hammamet, Tunisia (2014)
12. Chachada, S., Kuo, C.-C.J.: Environmental sound recognition: a survey. APSIPA Trans. Signal Inf. Process. **3**, 1–15 (2014). https://doi.org/10.1017/ATSIP.2014.12
13. Cowling, M., Sitte, R.: Comparison of techniques for environmental sound recognition. Pattern Recognit. Lett. **24**(15), 2895–2907 (2003). https://doi.org/10.1016/S0167-8655(03)00147-8
14. Nguyen, Q., Choi, J.S.: Matching pursuit based robust acoustic event classification for surveillance systems. Comput. Electr. Eng. **57**, 43–54 (2017). https://doi.org/10.1016/j.compeleceng.2016.11.007
15. Popescu, M., Mahnot, A.: Acoustic fall detection using one-class classifiers. In: 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. pp. 3505–3508. IEEE, Minneapolis, MN, USA (2009)
16. Goetze, S., Schroder, J., Gerlach, S., Hollosi, D., Appell, J.-E., Wallhoff, F.: Acoustic monitoring and localization for social care. J. Comput. Sci. Eng. **6**(1), 40–50 (2012). https://doi.org/10.5626/JCSE.2012.6.1.40
17. Piczak, K.J.: Environmental sound classification with convolutional neural networks. In: 2015 IEEE 25th International Workshop on Machine Learning for Signal Processing (MLSP). IEEE, Boston, MA, USA (2015)
18. Krizhevsky, A., Sutskever, I., Hinton, G.E.: ImageNet classification with deep convolutional neural networks. In: Advances in neural information processing systems. pp. 1097–1105 (2012)
19. Zhang, H., McLoughlin, I., Song, Y.: Robust sound event recognition using convolutional neural networks. In: 2015 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). pp. 559–563. IEEE, Brisbane, QLD, Australia (2015)
20. Salamon, J., Bello, J.P.: Deep convolutional neural networks and data augmentation for environmental sound classification. IEEE Signal Process. Lett. **24**(3), 279–283 (2017). https://doi.org/10.1109/LSP.2017.2657381
21. Github of Jaron Collis. https://github.com/jaron. Last accessed 17 Apr 2018

Improved Window Detection in Facade Images

64

Marcel Neuhausen and Markus König

Abstract

A variety of applications require detailed geometric information about a building's hull. In particular, windows are of high interest in this context. However, common 3D models only roughly outline existing buildings' geometrical outward appearance. The field of application is, thus, severely limited by now. In this paper, we propose an approach to the automatic detection of windows in facade images complementing common building models by information derived from detected windows to enable new opportunities and widen the spectrum of applications. Therefore, we apply a soft cascaded classifier to identify windows in patches of facade images. Moreover, a postprocessing is applied to the detections. We initially refine their dimensions and alignment on the facade. From these we infer so far non-detected windows. With an overall detection rate of 95 and 97% precision our proposed detection system yields sufficient results for complementing existing 3D building models by information of the detected windows.

Keywords

Window detection • Cascaded classifier • Urban environments • 3D building reconstruction

64.1 Introduction

In recent years, 3D models of existing buildings have become prominent in several application areas. In entertainment industry these are used to create high immersive virtual sceneries of realistic cities for movies and video games. Online map services integrate 3D urban models into their maps for an improved navigation experience. Such models also proved suitable in various civil engineering tasks. In urban planning, the administration of cities and their infrastructures benefit from georeferenced virtual buildings as well as the management of inner city construction sites and related logistics. Beyond visualization purposes, detailed geometric information about a building's hull can be used to support the automation of planning and assessment tasks or to enable simulations. The spectrum of applications demanding such information of existing buildings is manifold. In this context, especially windows often are of high relevance. As these constitute thermal bridges, windows are a necessary feature in energy efficiency rating. Moreover, windows mainly affect a facade's stiffness so that Earthquake simulations and risk analyses for settlement induced damages demand these to determine a building's stability.

However, 3D building models which are publicly available from land registry offices or web services like OpenStreetMaps often lack relevant details. These commonly only comprise georeferenced geometrical information of buildings in form of coarse block models which are sometimes extended by simplified roof shapes (see Fig. 64.1). Complementing existent building models by windows, thus, is inevitable to facilitate further applications. Hence, we propose an approach to

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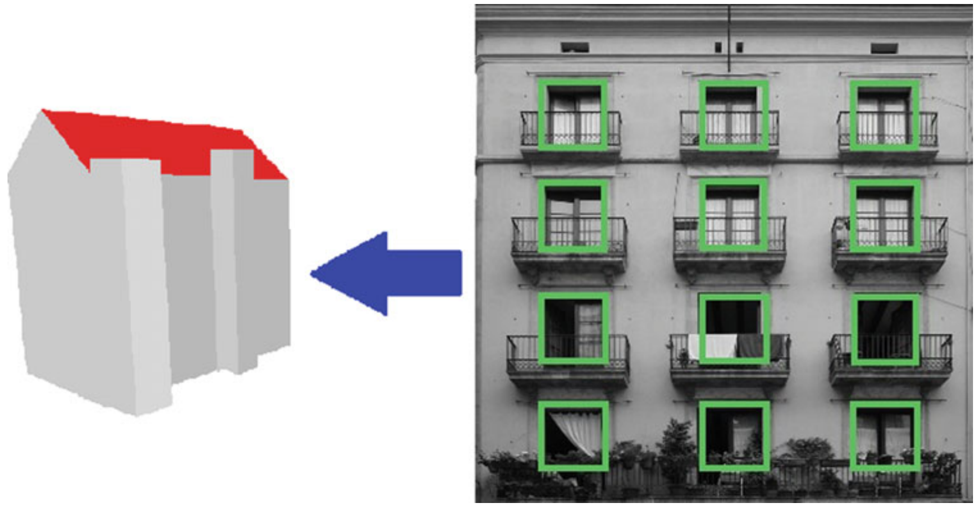

Fig. 64.1 3D block model of a building as commonly provided by public services. Complementing these with window information may facilitate various applications

window detection in facade images sufficiently supplementing such models to facilitate the automation of civil engineering tasks like energy efficiency ratings. We show that our detection system based on a soft cascaded classifier yields reliable results despite the windows' poorness of features. For this, we train the classifier on a set of windows taken from facade images of buildings in different countries and calibrate it towards a low false positive rate. For detection, we apply a sliding window approach which scans a facade image and passes patches to the classifier. To reduce the windows' variety in appearance emerging from perspective distortion due to different camera angles, we operate on rectified images for classifier training as well as for detection. We subsequently improve our results via a postprocessing based on the set of obtained detections. Therefore, we initially refine the geometry of detected windows by adjusting their dimension towards actual edges in the facade image. Ensuing, we cluster them regarding size and appearance. We align the windows within the clusters in a grid-like manner to infer potential positions of so far non-detected windows from this refined set. At these positions, we apply a second classifier which is calibrated less conservatively to also identify windows possessing less clear evidence.

We evaluate our detection system on rectified facade images of buildings from different countries. We and that our detector itself already yields adequate results to provide an initial assessment of a building. Nevertheless, the geometrical accuracy as well as the provided detection rate are too low to complement given models with the detected windows to a meaningful extent. Though, by refining the detections and inferring further windows, we can increase both detection rate and accuracy so that complementing such models by the resulting windows becomes reasonable.

64.2 Background

Building reconstruction in general became a wide field of research in the last decades and a large body of literature arose around it. Nevertheless, window detection as a subtopic has, by now, sparsely been addressed and still remains a challenging task.

Many applications such as simulations or analyses focus on several buildings in a city district. Thus, input data for detection has to be available for large areas. Aerial imagery and laser scans which are often used in building reconstruction satisfy this need but are impractical for window detection due to the oblique top view and spatial resolution. Becker and Haala [4] proposed an approach relying on terrestrial LiDAR point clouds. Exploiting that emitted light of the LiDAR sensor passes through glas, they identify windows by no-measurement areas in the facade's plane. Due to reflections of the laser on window panes, Ali et al. [1] improved this method by an adaptive distance threshold of adjacent measurements. Although, LiDAR based approaches o er reasonable detection methods for windows, point clouds are not publicly available for large areas yet and ought to be acquired at first. Albeit StreetMapper [3] may facilitate data gathering of point clouds for urban areas, it remains to be costly and involves high effort.

For this reason, ground view images qualify best for our purpose as they are already available from web services for most regions or, elsewise, can be gathered at low costs and effort. Grammar based approaches split facade images taken from ground view perspective into increasingly smaller semantic units to detect windows. Formal grammars are applied to subdivide a facade according to symmetries and repetitions [10, 11]. Teboul et al. [12], alternatively, developed a shape grammar including semantic relationships between facade components into the subdivision process. These approaches yield sufficient results on highly regular facades as they depend on symmetries and uniformity. Another approach superimposes histograms of horizontal and vertical edges [7] so that resulting peaks indicate the windows' locations. Haugeard et al. [6] advanced this by superimposing histograms separately for each potential row of windows. However, Meixner et al. [8] found that such approaches perform well if facades are plain and regular but will fail as soon as facades' complexity increases due to irregular window patterns or extensions like balconies and awnings.

Yang et al. [14] proposed an approach to identify windows by their inherent characteristics regardless of the facades' appearance. For this, they apply a randomized decision forest and evaluate the suitability of various image features. Ali et al. [2] proposed a similar approach applying a Viola-Jones detector [13] to facade images. However, their reported detection rates are ineligible for 3D building model enrichment. In related work [9] the cascaded classifier of the Viola-Jones detector is substituted by a soft cascaded approach [5]. Although this improves the detection rate, results are still not applicable for our purpose.

64.3 Methodology

In this paper, we propose a window detection system providing reasonable results to enable accurate 3D building model enrichment. Our system comprises three main components as illustrated in Fig. 64.2. First, we preprocess the facade images to reduce variability in the input images. We, then, apply our detector scanning an image and passing image patches to the soft cascaded classifier for identification. Overlapping detections are eventually merged to a single window hypothesis. Finally, a postprocessing is applied which initially refines current detections. Potential further window positions on the facade are, then, inferred based on the alignment of the refined detections. Ensuing, we investigate the inferred regions more closely to also detect less recognizable windows. In the following we describe the three components in more detail.

Although the soft cascaded classifier in general is robust with respect to high variability of positive examples [5], in combination with the windows' poorness of image features, the detection is highly complicated. An elimination of unnecessary variability beforehand is, hence, reasonable. Different camera angles immensely contribute to the variation due to the perspective distortion. Thus, a normalization of the windows' appearance improves the detection results [9]. For this, we semi-automatically rectify the facade images before detection such that windows are ensured to be of rectangular shape.

For detection, we apply a sliding window approach as proposed by Viola and Jones [13]. A sub-window slides across the entire image in multiple scales and step sizes. After each run through the image the sub-window is scaled by a factor of 1.25. Depending on this, the shifting step size starting with $\Delta = 1.0$ scales by $\lfloor s\Delta + 0.5 \rfloor$, where s denotes the current sub-window's scale. As windows are of various shapes, different kinds of sub-windows are required. We found that using two rectangular sub-windows—one upright and one lying—in addition to a squared sub-window allow to sufficiently cover most window shapes occurring on common urban facades. At each sub-window's position the underlying image patch is passed to the classifier resolving the presence of a window in each patch. For this, we apply a soft cascaded classifier which is composed of serially connected weak classifiers. Since a window mainly consist of a transparent pane and a frame, an identification by the frames' edges and changes in brightness between frame and pane seems reasonable. Thus, we consider to use thresholded Haar-like features as weak classifiers in our setup. Positively classified regions in the image are collected and treated as window hypotheses. Since the classifier is insensitive to small translations and changes in scale, there may be

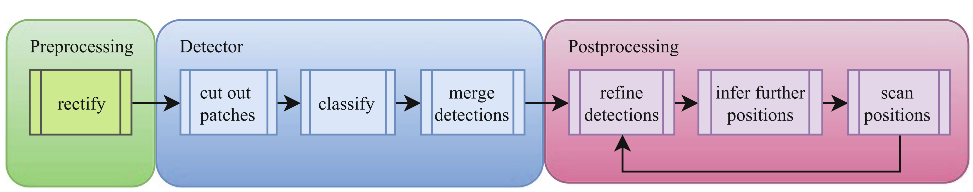

Fig. 64.2 Concept of the entire detection system proposed in this paper. Facade images are initially rectified. Then, the detector is applied. Finally, we refine the detections and search for further windows

Fig. 64.3 Dirac comb (blue) shifted by an offset (red) to match the windows' centers (yellow crosses)

multiple overlapping detections around the actual windows' locations. Similar occurs if actual windows are aligned in close proximity. To distinguish between different windows but at the same time aim for only one detection per window, we subsequently merge detections which at least overlap to 60%. Position and size of such overlapping detections are averaged resulting in a single window hypothesis.

The postprocessing serves a dual purpose. On the one hand, we refine the dimensions of the current window hypotheses and, on the other hand, we search for further windows in the facade image which have not been detected so far. Due to the detection method, the detector's results match the actual windows edges only approximately. To provide precise detections, we refine the hypotheses' dimensions towards actual edges in the image. As proposed by Lee and Nevatia [7] we perform a one dimensional search for supporting image edges for each side of a window hypothesis. For this, we generate a candidate edge from each hypothesis' side. While we translate these edges pixelwise in orthogonal direction, we search for best evidence. Supporting evidence consists of line segments which confirm the generated line's position. These segments are projected onto the candidate edge and the particular coverages are summed up to an evidence score. By this refinement based on a single window scope, the detections become more accurate. Non-window edges on the facade may, though, interfere a more exact adjustment. Considering the appearance of windows which are of the same kind and their alignment on the facade, allows to further refine the hypotheses' dimensions and position. For this purpose, hypotheses are clustered regarding their texture and size as proposed by Lee and Nevatia [7]. After clustering, the sizes of the hypotheses are adjusted by averaging their dimensions within each cluster. Following, we align each clusters' elements in rows and columns by repositioning elements which are arranged similarly in horizontal and vertical direction, respectively.

By the previous refinement similar detections are identified which are grouped into rows and columns. This enables to find missing windows of the same size in the spaces between current detections of each row or column. The windows' alignment on a facade can be described by a Dirac comb shifted by an offset as shown in Fig. 64.3. Irregularities in the alignment as well as false detection may hinder determining optimal function parameters. To properly estimate o set and period of the Dirac comb, we use a RANSAC algorithm. The positions obtained by the resulting functions' peaks reveal potential further windows. On common urban facades windows may occur which break the periodical pattern. Thus, we only consider potential windows if their regions do not overlap with previously detected windows whereas potential windows overlapping each other do not require a special treatment.

Since we cannot assume a facade to be regular, the presence of a window has yet to be proven based on evidence in the image despite that it has not been detected before. There are two major reasons for the detector missing a window. First, the sliding window might not have hit the window precisely enough through its step size. Second, image features responses might be too low so that they did not reach the weak classifiers' thresholds. From the previous step, we received precise information about positions and sizes of potential windows so that we can scan these regions more specifically. To overcome the second reason, the image patches are classified by a less strict soft cascade which tolerates lower feature responses. As a consequence, it is also more prone to yield false positive detection so that it should only be applied on certain small image regions.

The inferred positions determined by the RANSAC algorithm depend on the current set of detections and subdivision into rows and columns. Windows found while postprocessing may, thus, give new hints for further potential window positions by constituting new rows in the windows' alignment. As a consequence, we iteratively repeat the proposed postprocessing until no new window hypothesis is found anymore.

64.4 Experiments

In the following experiments we investigate the quality of our proposed detection system. At first, to verify the improvement of using a soft cascaded classifier on rectified facade images over the Viola-Jones detector approach proposed by Ali et al. [2], we contrast their reported results with the performance of our detector without postprocessing. In a second experiment we evaluate the benefit of our proposed postprocessing. For this, we compare the results of our detector obtained in the first experiment to the detection results of our entire system on the same facade images.

As comparability between the detection results has to be ensured, the evaluation metrics proposed in [2] are used for both experiments. Since precision with regard to the windows' size and position plays a major role for our application purposes, more specifically, we use the single window evaluation method. Accordingly, a detection is only marked as true positive if it is found inside a ground truth labeled region or at maximum overlaps it by 5 pixels in each direction. The detection, in addition, has to cover the bounding box of the ground truth label at least to a certain fraction. Again, owed to the required precision we allow a minimum coverage of 75%. A detection is marked as false positive if it covers less than 5% of a ground truth label.

The classifier used in our approach for these experiments is trained and calibrated on the dataset described in Sect. 64.4.1. Although our approach consists of two differently strict acting classifiers, it succes to train only one soft cascaded classifier. Differences in the classifiers' behavior can be achieved afterwards by distinct calibrations. For the detector component, we calibrate the classifier to a false positive rate of 2%. This ensures a reasonable detection rate while false positives per image are sufficiently few to not impair the postprocessing immoderately. For the postprocessing component, a calibration to 10% false positives is sufficient, allowing to identify windows with lower feature responses without falsely classifying most facade patches.

64.4.1 Dataset

We use the Ecole Central Paris Facades Database [12] which is one of the most prominent datasets. It provides a variety of facade images from different countries also allowing to investigate the general applicability of a detection approach. The dataset consists of 478 rectified facade images taken in 10 cities in Europe and the US. We cut out 4000 randomly chosen windows from 410 facade images and distribute them equally to the training and calibration of the classifier. Negative samples are generated from image patches of the same facades not containing windows. In the remaining 68 images ground truth was labeled manually. We excluded shop windows from labeling as their appearance is generally too different so that covering these would require another explicitly trained classifier.

Fig. 64.4 Window hypotheses obtained by our detector. Hypotheses are of different sizes and are slightly larger than the actual windows

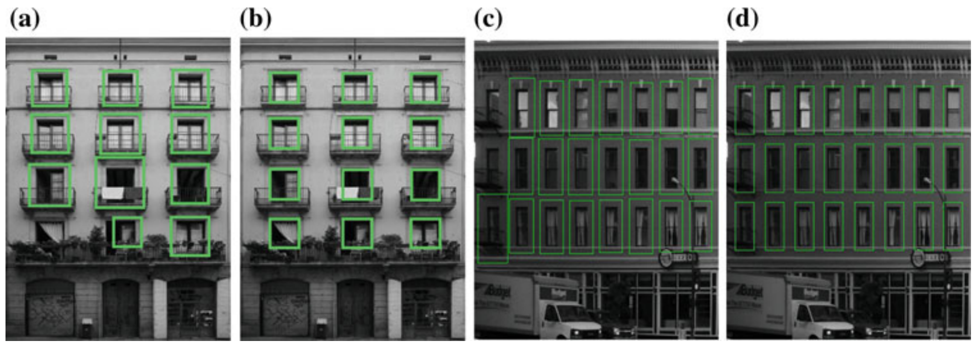

Fig. 64.5 Illustration of postprocessing results in (**b**) and (**d**) in comparison to detector results in (**a**) and (**c**)

64.4.2 Results

In the first experiment, we apply our detector without postprocessing to 68 rectified facade images of the Ecole Central Paris Facades Database. As can be seen in Fig. 64.4 detected regions are of different sizes and slightly larger than the actual windows dimensions. On this dataset our detector yields a detection rate of 84:9% and a false positive rate of 2:1%. This is a significant improvement over the Viola-Jones detector as stated by Ali et al. [2] reporting a maximum detection rate of 57% while 7% of the detections are false positives by means of the same evaluation metrics.

In the second experiment, the detector's results of the first experiment are fed into the postprocessing proposed in this paper. Figure 64.5 illustrates the improvements made by the refinement. By this, detected regions are well adapted and match the actual windows' dimensions much more precisely. Moreover, with a detection rate of 95:2% and 2:5% false positives the detection of further windows by inferring potential positions from current detections leads to a high increase of identified windows while insignificantly increasing false detections.

64.4.3 Discussion

The findings of Neuhausen et al. [9] already indicate an improvement of the soft cascaded classifier over the Viola-Jones detector on window detection. With the achieved detection rate of 84:9% we gain an increase of more than 27% with regard to the best detection results reported by Ali et al. while having a slightly lower false positive rate. Combining the findings with the results of our experiment allows to conclude that the soft cascaded classifier outperforms the conventional Viola-Jones detector on this task. Beyond this, the decrease in variation of the windows' appearance by rectifying the facade images beforehand leads to a further improvement of the detection results.

The second experiment clearly demonstrates the postprocessing's capability of improving the detector's results. We showed that its use increases the true positive rate of our detector by more than 10%. Addition finally, the resulting false positive rate could be kept similarly low. The increase is yet dependent on false positives obtained by the detector. Detected false positives may multiply exponentially if the initial rate is too high. Thus, keeping the false positive rate of the detector as low as possible is a prerequisite. As the experiment shows, a rate of about 2% fulfills this requirement.

Concluding, the entire detection system as proposed in this paper achieves a recall of 95:2% with a precision of 97:4%. Furthermore, the detections' bound aries match the actual windows very precisely. These results are sufficient to complement existing building models with precise window information to facilitate a variety of simulation and assessment tasks in civil engineering.

64.5 Conclusion

Building models can be used to simulate a building's behavior so that buildings can be assessed and compared with regard to their characteristics. However, publicly available 3D models usually lack relevant details. Models have, thus, to be complemented by other data.

Referring to an approach detecting windows using a cascaded classifier, in this paper we proposed a detection system improving the stated results. Our system consists of a preprocessing which rectifies facade images before detection to eliminate unnecessary variability in the windows' appearance. Afterwards, a detector scans the image and passes relevant image patches to a soft cascaded classifier. Resulting detections are finally postprocessed. On the one hand, the detections' borders are refined and, on the other hand, further windows are detected. Comparing the results of our detector to these of the Viola-Jones detector highlights that the soft cascade classifier outperforms the conventional cascade on the window detection task. Furthermore, we showed that applying a proper postprocessing to the window hypotheses obtained by our detector tremendously increases detection quality. With a resulting recall of 95:2% and a precision of 97:4% our entire detection system yields suitable results to successfully supplement existing building models by windows.

However, future work has to be done in terms of shop window detection. Moreover, the results of our system could be further improved if false positive hypotheses obtained by our detector were sorted out before postprocessing.

References

1. Ali, H., Ahmed, B., Paar, G.: Robust window detection from 3d laser scanner data. In: Proceedings of the Congress on Image and Signal Processing, pp. 115–118 (2008)
2. Ali, H., Seifert, C., Jindal, N., Paletta, L., Paar, G.: Window detection in facades. In: Proceedings of the Conference on Image Analysis and Processing, pp. 837{842 (2007). https://doi.org/10.1109/iciap.2007.4362880
3. Barber, D., Mills, J., Smith-Voysey, S.: Geometric validation of a ground-based mobile laser scanning system. ISPRS J. Photogramm. Remote Sens. **61**(1), 128–141 (2008)
4. Becker, S., Haala, N.: Renement of building facades by integrated processing of lidar and image data. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. **36**, 7–12 (2007)
5. Bourdev, L., Brandt, J.: Robust object detection via soft cascade. In: Proceedings of the Conference on Computer Vision and Pattern Recognition, pp. 236–243 (2005)
6. Haugeard, J., Philipp-Foliguet, S., Precioso, F., Lebrun, J.: Extraction of Windows in facade using Kernel on Graph of Contours. In: Proceedings of the 16th Scandinavian Conference on Image Analysis, pp. 646–656. Springer, Berlin Heidelberg, Germany (2009)
7. Lee, S.C., Nevatia, R.: Extraction and integration of window in a 3d building model from ground view images. In: Proceedings of the Conference on Computer Vision and Pattern Recognition, pp. 106–113 (2004)
8. Meixner, P., Leberl, F., Bredif, M.: Interpretation of 2d and 3d building details on facades and roofs. In: Proceedings of the Conference on Photogrammetric Image Analysis, pp. 137–142. ISPRS (2011)
9. Neuhausen, M., Martin, A., Obel, M., Mark, P., König, M.: A cascaded classifier approach to window detection in facade images. In: Proceedings of the International Symposium on Automation and Robotics in Construction (2017)
10. Ripperda, N.: Grammar based facade reconstruction using rjmcmc. Photogramm. Fernerkundung Geoinf. **2**, 83–92 (2008)
11. Ripperda, N., Brenner, C.: Application of a formal grammar to facade reconstruction in semiautomatic and automatic environments. In: Proceedings of the AGILE Conference on Geographic Information Science (2009)
12. Teboul, O., Simon, L., Koutsourakis, P., Paragios, N.: Segmentation of building facades using procedural shape priors. In: Proceedings of the Conference on Com-puter Vision and Pattern Recognition, pp. 3105–3112 (2010)
13. Viola, P., Jones, M.J.: Robust real-time face detection. Int. J. Comput. Vis. **57**(2), 137–154 (2004). https://doi.org/10.1023/b:visi.0000013087.49260.fb
14. Yang, M.Y., Förstner, W., Chai, D.: Feature evaluation for building facade images—an empirical study. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. **39**(B3), 513–518 (2012)

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Path Planning of LiDAR-Equipped UAV for Bridge Inspection Considering Potential Locations of Defects

65

Neshat Bolourian and Amin Hammad

Abstract

Over the past decades, several bridges have collapsed causing many losses. To keep bridges in a fully functional condition, a good maintenance system should be implemented. Although several new techniques have been developed and used recently to detect bridge defects, annual visual inspection remains the main approach for detecting surface defects, such as cracks. An Unmanned Aerial Vehicle (UAV), equipped with Light Detection and Ranging (LiDAR) scanner, can fly to reach all parts of a large structure. This equipment is capable of scanning the inaccessible surfaces of the bridges at a closer distance, which improves safety, accuracy, and efficiency. Using his method in structural inspection is attracting attention in research, and recent advancements have been made to automate and optimize the path planning of the UAV. However, the difference between the criticality levels of sections is not reflected in these methods. This paper proposes a path planning method of LiDAR-equipped UAV for bridge inspection using Genetic Algorithm (GA) and A* to solve Traveling Salesman Problem (TSP) considering the potential locations of surface defects such as cracks. The objective is minimizing time-of-flight to achieve acceptable visibility.

Keywords

Bridge inspection • LiDAR • UAV • Path planning • TSP • A*

65.1 Introduction

Over the past decades, several bridges have collapsed causing many losses [1]. To keep bridges in a fully functional condition, a good maintenance system should be implemented. Although several new techniques have been developed and used recently to detect bridge defects, visual inspection remains the main approach in detecting surface defects, such as cracks and corrosion. However, a higher inspection frequency might be required depending on the conditions noted in previous inspections, type and configuration of the bridge, and traffic volume [2]. Therefore, many researchers have shifted their focus to increasing the efficiency, safety, and accuracy of inspection. Traditionally, visual inspection relies mainly on the data collected manually using non-equipped eyes, which is subjective and time-consuming. Recently, camera-based and laser scanner-based methods have been employed in order to improve the accuracy of the inspection results by collecting images and point clouds, respectively. Moreover, accessing all parts of the surface puts the inspector at the risk of falling [3]. Unmanned Aerial Vehicle (UAV), equipped with Light Detection and Ranging (LiDAR) scanner or/and camera [4], can fly to reach all parts of a large structure. This equipment is capable of scanning the inaccessible surfaces of the bridges at a closer distance, which improves safety, accuracy, and efficiency. Using his method in the structural inspection is becoming increasingly popular, and recent advancements have been made to automate and optimize the path planning of the UAV [4].

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LiDAR scanners are able to generate point clouds, which can then be used in detecting the location and depth of surface defects [5]. In addition to minimizing the flight time of a collision-free path for the UAV, it is crucial to ensure that all critical surfaces of the bridge are covered more than once from near perpendicular view. Several parameters can influence the accuracy of the data, such as the incidence angle of the laser beam and the distance between the scanner and the structure. Small incidence angles and minimum distances are required to achieve high-quality data and to avoid missing some high-risk defects. Running a structural analysis before path planning provides a good perspective about the high-risk spots. The proposed method extends available path planning methods to consider the level of criticality of different areas and collect more accurate data from these areas.

In the previous research of the authors, a framework for bridge inspection using LiDAR-equipped UAV has been developed, which includes three main phases: path planning, data collection, and data analysis. The focus was mainly on the calculation of the visibility of the surfaces of the bridge in the planning phase [5]. Extending the previous framework, this paper aims to develop the path planning method for bridge inspection considering the potential locations of defects. The structure of the paper is as follows: first, the related research works are reviewed. Then, the proposed method is introduced, and the feasibility and benefits of the proposed method are demonstrated using a case study. Finally, the conclusions of the paper and of the future work are presented.

65.2 Literature Review

Researchers have explored new visual inspection technologies (e.g. cameras and LiDAR scanners) in order to increase the efficiency of inspection. The LiDAR-based methods collect point clouds and analyze the collected data without the need of any information related to the equipment [6]. The application of these methods to the surface defect detection has been studied by many researchers [3, 6, 7]. For example, Guldur and Hajjar [7] used a well-established point cloud processing to detect the location of defects and collect quantitative information of a collapsed bridge (e.g. large cracks, spalling and misalignment).

The ability to access most parts of the structure helps the UAV to collect a denser set of points from a closer distance with a near perpendicular view of the damaged surfaces. Moreover, this unmanned method eliminates safety risks posed to inspectors [8]. Although remote control is available to control the flight path of the UAV, having an automated path planner can lead to the optimal flight path. The main objective of path planning of the LiDAR-equipped UAV is finding an optimal collision-free path taking into account the minimum time of flight and maximum visibility of the surface of the inspected structure.

Several motion planner algorithms are able to calculate the optimal or feasible path, such as A* [9], Bug [10], Rapidly-exploring Random Tree (RRT) [11], and RRT* [12] algorithms. Unlike the first two algorithms (A* and Bug), RRT and RRT* are applicable to the cases with many Degrees of Freedom (DoFs). On the other hand, RRT generates a zigzag path due to picking random seeds. RRT* tries to eliminate zigzag paths from the tree and generate a smoother path compared to RRT. Moreover, according to Zammit and Van Kampen's research, A* generates a shorter path compared to RRT for UAV path planning [13]. The main goal of these algorithms is to find a feasible collision-free path from the start point to the end point. However, these algorithms do not guarantee high visibility during the inspection.

There are several Coverage Path Planning (CPP) methods which guarantee full coverage of the area of interest. Solving Traveling Salesman Problem (TSP) as a non-deterministic polynomial time (NP)-hard problem is another approach to find the shortest path passing through View Points of Interest (VPIs) [14]. Meanwhile, Art Gallery Problem (AGP) solvers can be used for finding the smallest set of VPIs. The main criteria of an effective path planning for the inspection of a structure are obstacle avoidance, maximum coverage, the minimum time of flight, and the best set of VPIs while considering all the constraints.

Recently, several efforts have been made to use automated structural inspection systems using a UAV equipped with a vision-based sensor. Bircher et al. [4] proposed a path planning algorithm using Lin-Kernighan-Helsgaun heuristic (LKH) TSP solver. Their method is based on a mesh representation of the environment. One VPI is sampled for each triangle in the mesh considering sensor limitation. Then, the cost of moving from one point to another is computed and RRT* is used in case of the presence of an obstacle between two VPIs. Based on the cost matrix, the initial path is found using LKH. In their method, the short inspection path is computed using an alternating two-step optimization algorithm. In each iteration, the new set of VPIs is selected in order to minimize the path length and the rotation duration. Another solution of the inspection problem was suggested by Phung et al. [15]. Like the previous study, the path planning of a camera-equipped UAV for structural inspection was done based on TSP solver. However, to cover the whole surface of the inspected structure, VPIs were sampled with respect to Field of View (FoV), focal length, sensor size and overlapping percentage. Instead of RRT* and LKH, A* and Particle Swarm Optimization (PSO) were used in this research, respectively. On the other hand, Freimuth et al. [16] proposed an inspection method for buildings using camera-equipped UAV. In their method, A* algorithm was used in order to provide the flight path between start and end points around the building. Using a simulation software from Dronecode Foundation helped to take some factors into account, such as UAV speed and wind effects.

65.3 Proposed Method

In the proposed method, the risk-prone areas are defined using structural analysis. Then, critical areas are determined, and Importance Values (IVs) corresponding to the level of criticality (low, medium, and high) are assigned to them. IV is assigned to the created cells on the surface of the bridge. Then, VPIs, which the UAV should pass through, are determined. The VPIs help the scanner to collect the data of the corresponding locations from the shortest allowable distances and near perpendicular angles. In this method, the surface visibility from the VPIs is calculated using ray tracing. The optimal path is found in two steps: (1) A Genetic Algorithm (GA) is used to solve the TSP considering all the VPIs, and (2) A* is used to find a collision-free path between two VPIs that have an obstacle in between. The objective function for evaluation of the optimal path is the minimum time-of-flight with an acceptable visibility. Figure 65.1 represents the proposed framework for planning the obstacle-free path with maximum coverage and minimum time-of-flight considering the potential locations of defects. Time-of-flight is the summation of the time of changing the position and the rotation. In this paper, the rotation time is not considered. So, the time-of-flight is equal to the path length divided by the UAV speed.

The proposed method includes the following steps: (a) The bridge structure is modeled in a structural analysis software. (b) The structural analysis is done based on the applied loads on the bridge. (c) Based on the calculated stresses on the bridge surface, the level of criticality is determined. Higher stress shows the potential locations of defects and a risk prone zone. Three zones are determined: low-, mid- and high-risk zones. (d) Before dividing the bridge surface into cells, their size is calculated. It should be proportional to the resolution of the scanner and small enough to achieve high accuracy. As shown in Fig. 65.2, the minimum size of cells, which is equal to minimum scan spacing, can be calculated by the following equation [6]:

$$\Delta_{\min} = \frac{d_{\min} \times \alpha_R}{\cos(\alpha_1)} \tag{65.1}$$

where $\Delta_{\min}$: minimum scan spacing (m); $d_{\min}$: scan distance between the structure surface and the scanner (m); α_R: angular resolution (rad); and α_1: incidence angle (degree).

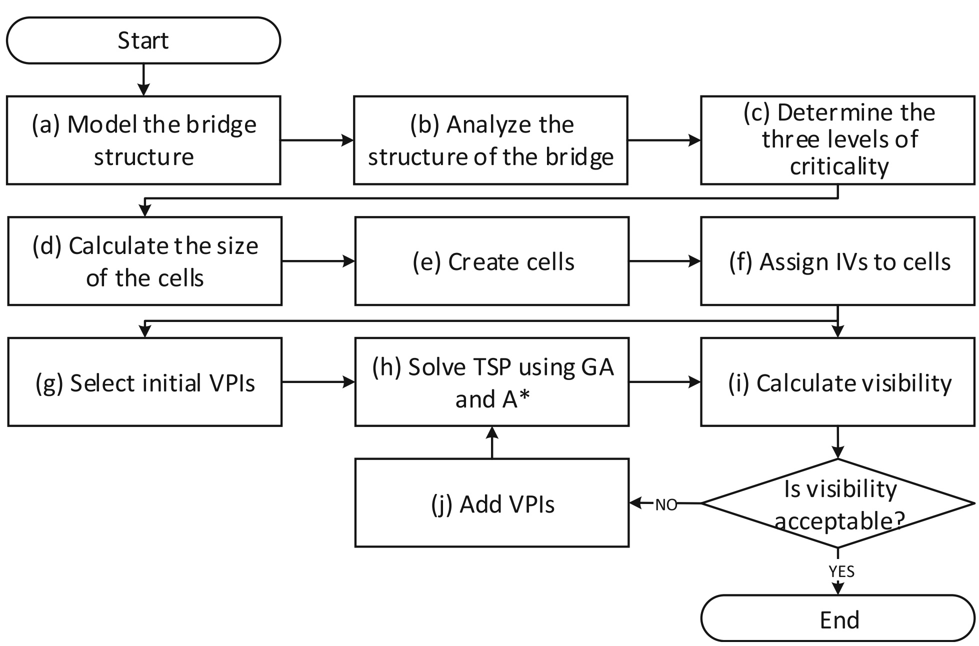

Fig. 65.1 Proposed method

(e) Then, the surface of the bridge (e.g. the lower surface of the deck) is divided into equal cells. (f) The cells in each zone will inherit the IV of the zone that they belong to. Figure 65.3 shows a bridge with divided cells, which are categorized into three groups: high-risk, mid-risk and low-risk zones and represented by red, yellow, and green, respectively.

(g) Solving TSP starts with generating a set of VPIs, which the path should pass through only once. In the proposed method, the following factors are considered for this step to improve the accuracy of the result: (1) The VPIs should have perpendicular view of the inspected surface as much as possible (Fig. 65.4). (2) The LiDAR may not completely scan the surface of the defects because of the existence of obstacles. In addition, scanning all the covered surface with a perpendicular view is not necessary for low-risk zones. Consequently, selecting more VPIs corresponding to the high-risk zones leads to more accurate detection of the defect size. In case that a perpendicular view is not possible or time-consuming, overlapping views in high-risk zones can be used to increase the accuracy of the inspection. Figure 65.5a shows how the non-perpendicular view and the existence of an obstacle lead to misestimating the size of a defect. As shown in Fig. 65.5b, scanning defects from more than one VPI results in a better estimation of the defect size. The hatched areas represent the missing area of the defect.

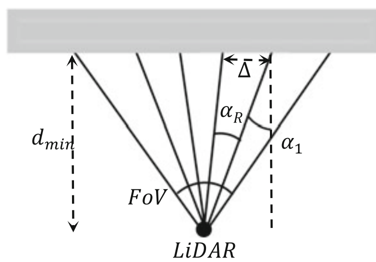

Fig. 65.2 Calculating the minimum size of cells

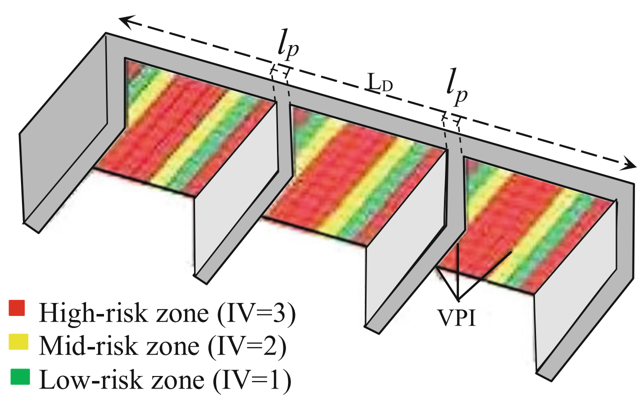

Fig. 65.3 Assigning the IVs to the created cells under the bridge

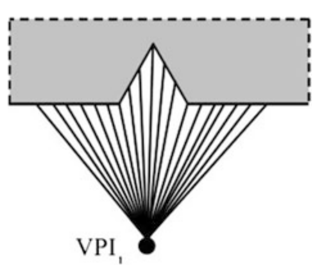

Fig. 65.4 Scanning the surface from VPI with perpendicular view

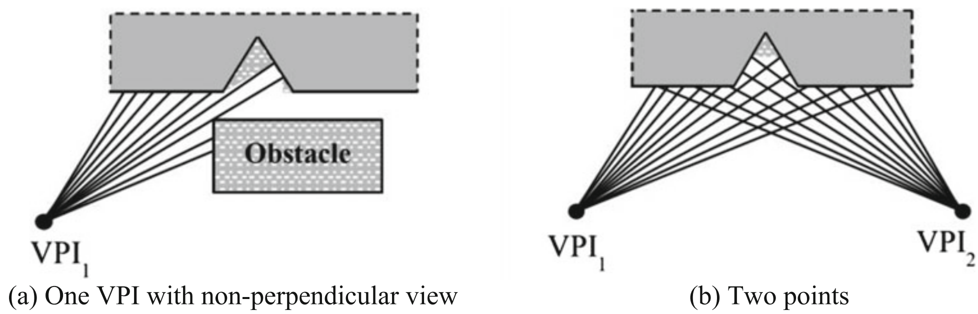

Fig. 65.5 Scanning the surface different VPIs

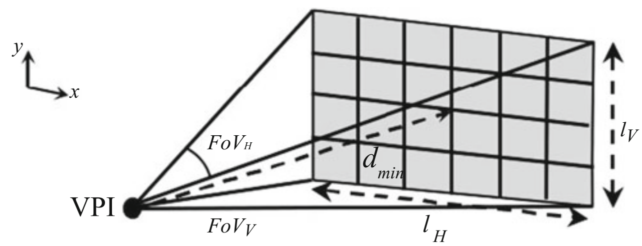

Fig. 65.6 Maximum visible area from VPI located at minimum distance from the surface

As shown in Fig. 65.6, the maximum visible area from a view located at minimum distance ($d_{\min}$) is equal $l_H \times l_V$, where l_H and l_V are computed based on Eqs. 65.2 and 65.3, respectively.

$$l_H = 2d_{\min}\tan(FoV_H/2) \tag{65.2}$$

$$l_V = 2d_{\min}\tan(FoV_V/2) \tag{65.3}$$

where FoV_H and FoV_V are horizontal and vertical FoVs, respectively.

VPIs are distributed based on the following rules: (1) In order to provide the full coverage in x-direction, VPIs are located on several rows, which are considered along the length of the deck (x axis) with a distance of l_H. The number of rows (P_x) can be calculated using Eq. 65.4, where L_D, a, and L_p are the length of the deck, one abutment and the piers, respectively.

$$P_x = \left(L_D - a - L_p\right)/l_H \tag{65.4}$$

(2) The number and distance of the VPIs in y-direction is selected based on the criticality level of the corresponding row. If the row is located in high-risk zones, 50% overlap is considered for VPIs with perpendicular view. Consequently, the distance between VPIs should be $l_v/2$ and each cell is viewed at least twice from different angles. In mid-risk and low-risk zones, full coverage without overlapping with near perpendicular view is considered. Therefore, the distance between VPIs is V in the y-direction.

Figure 65.7 shows how VPIs are distributed under a bridge deck.

The number of VPIs in each row (P_y) and total number of VPIs (P_{all}) can be computed based on Eqs. 65.5 and 65.6, respectively, as shown in Fig. 65.3.

$$P_y = \begin{cases} \textit{High risk zone}: & 2W_D/l_V \\ \textit{Mid and low risk zone}: & W_D/l_V \end{cases} \tag{65.5}$$

$$P_{all} = \sum\nolimits_1^{p_x} P_y \tag{65.6}$$

where W_D is the width of the deck.

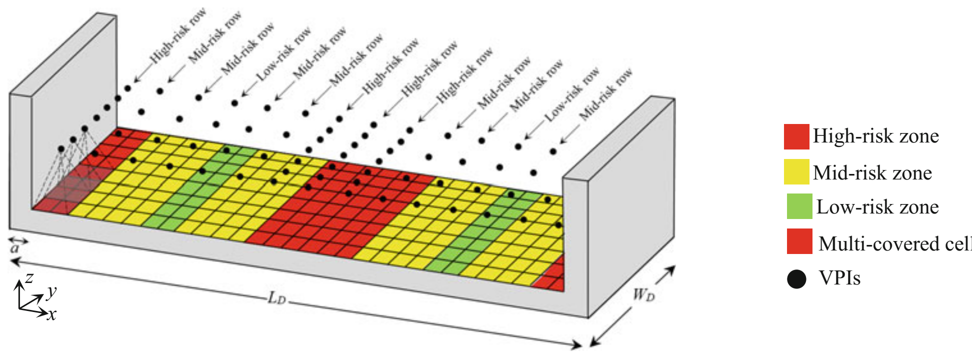

Fig. 65.7 Selecting VPIs based on the criticality level

(h) In (Fig. 65.7) the proposed method, path planning is based on TSP which is solved using GA and A*. A near optimum path which passes through VPIs is found using GA. In case of an obstacle existence between two points, A* is used for planning an obstacle- free path between those VPIs. (i) The visibility calculation using ray tracing method provides the total coverage of the LiDAR-equipped UAV considering the IV of cells [5]. (j) In case of inadequate visibility, new VPIs should be added to the low risk zone and the path should be updated

65.4 Case Study

In this paper, the implementation is based on a hypothetical three-span bridge and focused on the lower surface of the bridge deck. The aim is to find the optimal path with maximum coverage of lower surface of the bridge deck and the shortest path considering the potential location of defects. A Matrice 100 equipped by a Hokuyo UTM-30LX was considered as the prototype equipment. Hokuyo UTM-30LX is an affordable light 2D laser scanner, which can be used in collecting 3D point clouds using a servo [17]. The constraints are determined based on the characteristics of the equipment. For instance, the height of the Matrice 100 plus all mounted equipment is almost 50 cm. In order to have a safe flight, the minimum distance in the y direction ($d_{min,y}$) is considered 5 m. $d_{min,x}$, and $d_{min,z}$ were estimated based on the size of the UAV arms and the space that it needs to rotate around, equal to 60 cm. is selected as 0.25° degree.

A three-span bridge is modeled with box girder slab in CSiBridge 2017 [18], a structural bridge design software. The bridge has 4 lanes with 2 sidewalks, which results in a 15 m width and 60 m length. The moment (M) and shear (V) of the sections were calculated based on the applied loads. The result is shown in Fig. 65.8.

Based on the potential location of the cracks and the calculated bending moment and shear, three levels of criticality are determined as follows:

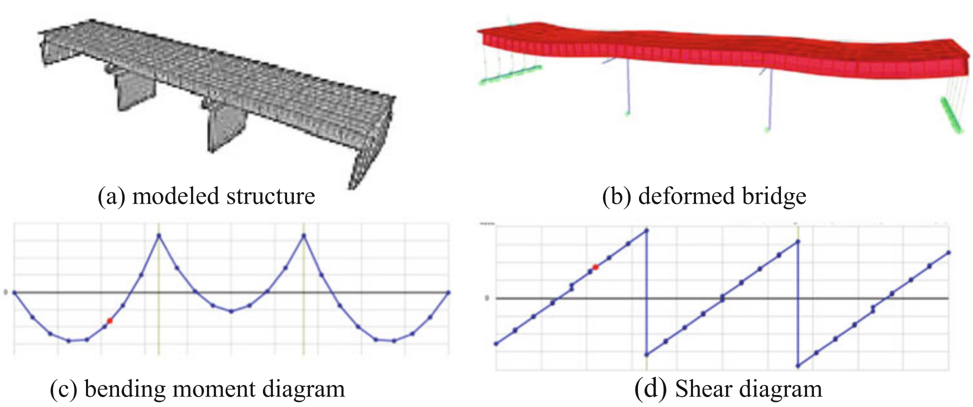

Fig. 65.8 Analyzing the bridge structure in CSiBirdge 2017

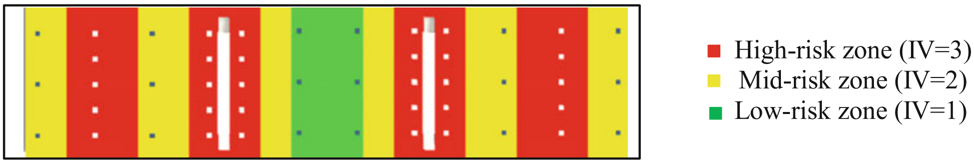

Fig. 65.9 Level of criticality of each section the surface under the bridge deck and the VPIs

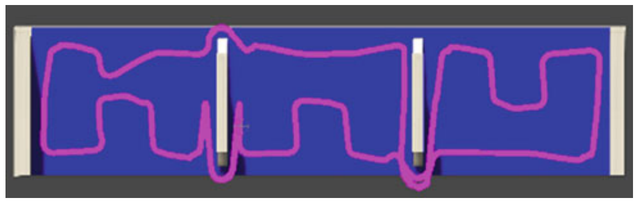

Fig. 65.10 Visual representation for the calculated path

Table 65.1 Calculated overlapping counter and visibility for different FoVs

FoV (°)	Overlapping counter				Visibility (%)
	High-risk zone	Mid-risk zone	Low-risk zone	Average	
30	2.0	0.2	1.3	1.1	98
40	2.4	1.0	1.0	1.4	100
50	3.2	2.4	1.2	2.3	100
60	4.0	3.7	2.2	3.3	100
70	5.4	5.3	4.2	5.0	100

$$\begin{cases} 0 \le M \le 2500\ \text{kN.m} & : \text{low risk zone} \\ 2500\ \text{kN.m} \le M < 5000\ \text{kN.m} & : \text{mid risk zone} \\ 5000\ \text{kN.m} \le M & : \text{high risk zone} \end{cases} \quad \begin{cases} 0 \le V < 812\ \text{kN} & : \text{low risk zone} \\ 812\ \text{kN} \le V < 1624\ \text{kN} & : \text{mid risk zone} \\ 1624\ \text{kN} \le V & : \text{high risk zone} \end{cases} \tag{65.7}$$

Based on the criticality level, the IVs are assigned to the sections. Figure 65.9 shows the level of criticality of the sections under the bridge and their corresponding IVs. In the path planning phase, Revit 2017 works as an intermediate software between CSiBridge and Unity 3D [19]. The bridge structure is imported into Revit 2017 [20] in *.rvt format, and then exported as an *.fbx file in order to use in Unity 3D. It will also be used in the next phase, data analysis, in order to make the BrIM model and store information in Industry Foundation Classes (IFC) [5].

The minimum size of the cells should be at least 0.2 cm based on Eq. 65.1. In order to speed up the calculations, the surface under the bridge is divided into 0.5 × 0.5 m^2 cells. Consequently, the IVs are assigned to the created cells following the rules explained in step *f*. Based on Eqs. 65.4–65.6, 48 VPIs are defined considering 60° FoVs, 50% overlaps for high-risk zones, no overlaps for mid- and low-risk zones (Fig. 65.9).

The GA was used in order to solve TSP and find a path passing through all VPIs, and in case of the existence of an obstacle (e.g. the piers of the bridge) A* was used. The initial result considering 48 VPIs is a path with 186 m length and 100% visibility considering the IVs. Figure 65.10 represents the calculated path. Adding too much points in the first round may cause longer path with unnecessary overlapping in low-risk zone.

Overlapping counter expresses how many times a cell is seen from different angles of view during the scanning. As shown in Table 65.1, increasing FoV leads to increasing overlapping. However, too much overlapping is not necessary and may cause more errors.

65.5 Conclusion and Future Work

This paper proposed a path planning method of LiDAR-equipped UAV for bridge inspection using GA and A* to solve TSP considering the potential locations of surface defects such as cracks. The objective function is finding the path with the minimum time-of-flight and acceptable visibility. Although the result of this method is not optimal, it is near-optimal, time-effective and reliable. The proposed method is able to consider the potential locations of the bridge surface defects in calculating the visibility by using IV. Moreover, the initial VPIs are selected with respect to the potential locations of surface defects with perpendicular view. The VPIs provide overlapping views, which lead to higher accuracy in detecting the size of the cracks.

In future work, the study will be extended to provide a two-objective optimization model, which includes minimizing the time-of-flight and maximizing the visibility.

References

1. Ghadiri Mohghaddam, D.: Framework for Integrating Bridge Inspection Data with Bridge Information Model. Master of Science, Concordia University, Montreal, Canada (2014)
2. Transport Canada.: Canadian Aviation Regulations (CARs) and Standards. 603.06 (2017)
3. Kim, M., Sohn, H., Chang, C.: Localization and quantification of concrete spalling defects using terrestrial laser scanning. J. Comput. Civ. Eng. **29**(6), 04014086 (2014)
4. Bircher, A., Kamel, M., Alexis, K., Burri, M., Oettershagen, P., Omari, S., Mantel, T., Siegwart, R.: Three-dimensional coverage path planning via viewpoint resampling and tour optimization for aerial robots. Auton. Robots **40**(6), 1–6 (2015)
5. Bolourian, N., Soltani, M.M., Albahria, A. and Hammad, A.: High level framework for bridge inspection using LiDAR-equipped UAV. In: Proceedings of the International Symposium on Automation and Robotics in Construction, vol. 34, pp. 1–6. Taipei, Taiwan (2017)
6. Laefer, D.F., Truong-Hong, L., Carr, H., Singh, M.: Crack detection limits in unit based masonry with terrestrial laser scanning. NDT and E Int. **62**(1), 66–76 (2014)
7. Guldur, B., Hajjar, J.F.: Automated classification of detected surface damage from point clouds with supervised learning. In: Proceedings of the International Symposium on Automation and Robotics in Construction, vol. 33, pp. 1–7. Auburn, Alabama (2016)
8. Metni, N., Hamel, T.: A UAV for bridge inspection: visual serving control law with orientation limits. Autom. Constr. **17**(1), 3–10 (2007)
9. Hart, P.E., Nilsson, N.J., Raphael, B.: A formal basis for the heuristic determination of minimum cost paths. IEEE Trans. Syst. Sci. Cybern. **4**(2), 100–107 (1968)
10. Lumelsky, V.J., Stepanov, A.A.: Path-planning strategies for a point mobile automaton moving amidst unknown obstacles of arbitrary shape. Algorithmica **2**(1), 403–430 (1987)
11. LaValle, S.M., Kuffner Jr., J.J.: Randomized kinodynamic planning. Int. J. Rob. Res. **20**(5), 378–400 (2001)
12. Nasir, J., Islam, F., Malik, U., Ayaz, Y., Hasan, O., Khan, M., Muhammad, M.S.: RRT*-SMART: A rapid convergence implementation of RRT. Int. J. Adv. Rob. Syst. **10**(7), 299 (2013)
13. Zammit, C. and Van Kampen, E.: Comparison between A* and RRT algorithms for UAV path planning. In: 2018 AIAA Guidance, Navigation, and Control Conference, pp. 1846. (2018)
14. Helsgaun, K.: An effective implementation of the Lin-Kernighan traveling salesman heu-ristic. Eur. J. Oper. Res. **126**(1), 106–130 (2000)
15. Phung, M.D., Quach, C.H., Dinh, T.H., Ha, Q.: Enhanced discrete particle swarm optimization path planning for UAV vision-based surface inspection. Autom. Constr. **81**, 25–33 (2017)
16. Freimuth, H., Müller, J. and König, M.: Simulating and executing UAV-assisted inspections on construction sites. In: 34th International Symposium on Automation and Robotics in Construction and Mining, pp. 647–655 (2017)
17. Nasrollahi, M., Bolourian, N., Zhu, Z. and Hammad, A.: Designing LiDAR-equipped UAV platform for structural inspection. In: 35th International Symposium on Automation and Robotics in Construction (ISARC 2018), vol. 1, Berlin, Germany (2018)
18. Computers and Structures Inc.: CSiBridge (2018), https://www.csiamerica.com/products/csibridge, last accessed 2018
19. Unity Technologies: Unity 3D Game Engine, https://unity3d.com, last accessed 17 Dec 2017
20. Autodesk Revit: Autodesk Revit online document, https://www.autodesk.com/products/revit/, last accessed 2017

66 Automatic Annotation of Web Images for Domain-Specific Crack Classification

Peter Cheng-Yang Liu and Nora El-Gohary

Abstract

Manual visual crack detection and classification for inspection of civil infrastructure is time-consuming and labor-intensive. Many automatic crack detection and classification algorithms have, thus, been developed in the past decade, several of which achieved acceptable performance results for specific applications and using large datasets for training. However, developing training data for automatic crack classification is not an easy task. It requires a large dataset in terms of quantity and variability, as well as well-trained professionals to label the dataset. Hence, there is a need for efficient ways to develop well-labeled datasets that could not only reduce human effort, but also adapt to diverse inspection contexts for improved classification performance. To address this need, this paper proposes a data retrieval and annotation method to automatically retrieve and label crack images from the Web. The dataset can be used as pseudo training data for supervised machine learning-based crack classification algorithms. The proposed method incrementally retrieves and labels crack images. A weak Convolutional Neural Network classifier first learns from a limited set of Web images, and then acts as a machine annotator and further labels a larger size of data. The proposed method was able to retrieve and label a set of images with 95% labeling recall, which shows that the proposed approach is promising.

Keywords

Crack classification • Machine learning •
Convolutional neural networks • Automatic training data generation •
Image retrieval • Image annotation

66.1 Introduction

Cracks are a common type of distress for civil infrastructure. Manual visual inspection for crack detection is time-consuming and costly, and can put inspectors at a safety risk. Automatic crack detection and classification is, thus, necessary to reduce human involvement. Crack detection has been well studied in the past decades [1]. Many automatic crack detection algorithms have been developed, and achieved acceptable performance results. However, automatic crack classification is still an open research area. Different types of cracks lead to different structural deterioration risks. For example, fatigue cracks, also known as alligator cracks, might cause disintegration of the surface, and become potholes [2]. Identifying the types of detected cracks is, thus, critical for deterioration detection/prediction and maintenance decision making.

In the computer vision domain, supervised learning is still the state-of-the-art approach for image classification problems [3]. In this case, a labeled dataset is essential for training. However, two problems exist in this regard. First, on one hand, training data for crack classification tasks are not easily available/accessible. On the other hand, developing training data for automatic

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https://doi.org/10.1007/978-3-030-00220-6_66

Fig. 66.1 Comparison between images from a fixed setting acquisition system and a natural scene. The left image is acquired by a system with video cameras mounted on a car [7]. The right image is an arbitrary image downloaded from the Web [9]

crack classification is not an easy task. It requires a large dataset in terms of quantity and variability, as well as well-trained professionals to label the dataset. Second, current crack detection datasets that could be used for classification training are not suitable for training sufficiently adaptive classification models. Existing inspection approaches are moving towards using more general and dynamic platforms. For example, in bridge inspection, unmanned aerial vehicles (UAVs) are used for inspecting deck surfaces and building 3D models of the entire structures [4–6]. Images collected from such platforms contain varied heights and noisy objects in the scene. Current crack detection datasets, however, include images that are taken from specific mobile platforms with fixed settings (e.g., a vehicle with a fixed camera) [7, 8] (Fig. 66.1 shows a comparison between an image taken in a fixed setting and another in a natural setting). Classification models trained on such datasets are, thus, not adaptive to varying, non-ideal settings (e.g., with high levels of noise). Hence, there is a need for efficient ways to develop well-labeled datasets that could not only reduce human effort, but also adapt to diverse settings for improved classification performance.

To address this need, this paper proposes a data retrieval and annotation method to automatically retrieve and label crack images from the Web. The proposed method incrementally retrieves and labels diverse crack images. A weak Convolutional Neural Network (CNN) classifier first learns from a limited set of Web images, and then acts as a machine annotator and further labels a larger size of data. Most of the images retrieved from the Web are natural scene images—they are from different sources, taken from different angles, contain noisy objects in the scene, etc.

66.2 Related Work

66.2.1 Crack Detection and Classification

Many computer vision-based automatic crack detection algorithms have been developed in the past decades, which can be classified into three approaches: crack image thresholding, patch-based classification, and depth-based methods [8]. For example, Chambon and Moliard [7], Oliveira et al. [10], Zou et al. [11], and Salman et al. [12] took an image thresholding approach; they assumed that a crack is darker locally and tried to find the local intensity minimum. Zhang et al. [1] and Varadharajan et al. [13] took a patch-based classification approach; they cropped images into patches and used machine learning methods to check if each region contained cracks. Mertz [14], Yamada et al. [15], and Yu et al. [16] took a depth-based approach; they extracted cracks from depth information.

In addition to detecting cracks in road surface images, analyzing defects and classifying crack types also received research attention. For example, Byoung and Hosin [17] implemented three neural networks—image-based neural network, histogram-based neural network, and proximity-based neural network—to classify images into crack types: alligator, block, longitudinal, and transverse cracks. More recently, Saar and Talvik [18] improved the performance by extracting potential crack pixels before classifying them. Recent work (e.g., Radopoulou and Brilakis [19]) tried to distinguish more defects such as potholes. Hoang and Nguyen [20] compared different feature sets with multiple machine learning algorithms—support vector machines, artificial neural networks, and random forest—for crack type classification. Despite the importance of existing efforts, the majority of these efforts used experimental datasets that were taken in a fixed setting or from a close look at the surface.

66.2.2 Crack Types

A number of state and federal authorities developed standards and guidelines that describe different crack classes to assess pavement conditions. For example, the Washington State Department of Transportation (DOT) [21] divided cracks into alligator, longitudinal, transverse, block, and rigid cracks, according to width, length, pattern, and appearance frequency features. The American Association of State Highway and Transportation Officials [22] introduced more crack classes, such as joint reflection cracks from PCC slab. Most recently, the U.S. DOT [23] developed their Distress Identification Manual for the Long-Term Pavement Performance Program.

66.2.3 Convolutional Neural Networks

The Convolutional Neural Networks (CNN) algorithm is a neural network machine learning algorithm, which does feature learning and classification in one shot. Instead of conventional hand-crafted features, CNN is proven to be more effective and accurate in learning image features directly from training data [24]. CNN has shown promising results in image classification problems, both for general images [3] and domain-specific images such as medical imaging [25–27]. In the civil and infrastructure domain, Zhang et al. [1] and Grandsaert [5], for example, attempted to apply deep CNN in crack detection. As a supervised classifier, the success of CNN relies on large amount of training data, which are neither available nor easy to develop/label for natural scene crack classification problems.

66.2.4 Web Image Retrieval and Existing Datasets

Training data are critical to the performance of image classification algorithms. Outside of the civil infrastructure domain, researchers tended to retrieve such image data from Web resources [28–30]. For example, Li and Fei-Fei [31] used keyword queries to retrieve images and used the top-ranked ones for training a classifier. Schroff et al. [32] leveraged text information associated with the images to help in ranking. Yao et al. [33] used multiple query expansion to retrieve more relevant results.

In the civil infrastructure domain, researchers tend to collect such image data using data acquisition platforms. For example, there are datasets for crack detection [7, 8, 10, 11, 34, 35]. Some of them contain less than 300 images [7, 10, 11], which are not enough for deep learning. Also, all of them are taken from a close view of the surface, which is not sufficient in terms of natural scene analysis. Furthermore, the datasets are not labeled for the crack types.

66.3 Methodology

An approach to incrementally retrieve and automatically annotate web images for supporting crack classification is proposed. The proposed method aims to incrementally retrieve and label diverse crack images, which could serve as pseudo training data for supervised machine learning-based crack classification algorithms. A weak CNN classifier first learns from a limited set of Web images, and then acts as a machine annotator and further labels a larger size of data. The research methodology, thus, includes four primary steps (as per Fig. 66.2): (1) class image retrieval, (2) weak CNN classification, (3) image retrieval and annotation, and (4) evaluation.

66.3.1 Class Image Retrieval

A set of images was retrieved and cleaned. The images were retrieved from the Web, using the Google Image Search and a set of class keywords, such as "fatigue crack". The downloaded images were then automatically cleaned based on their associated text. For example, non-real images (e.g., those from educational sources such demonstration figures and lecture slides) were removed. The 100-top-ranked images (i.e., ranked by Google) were then used as training data for the proposed supervised CNN classifier/annotator (Sect. 66.3.2), where the keywords were used as labels.

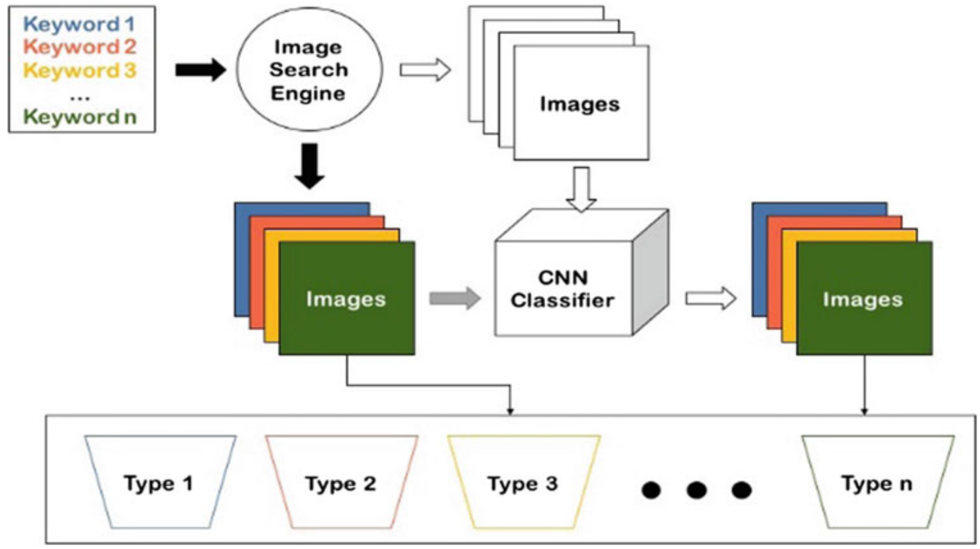

Fig. 66.2 Proposed data retrieval and annotation approach for creating pseudo training data

Table 66.1 Characteristics of the developed weak CNN classifier model

Layer no.	Example	Kernel size	Output size
1.	conv	3 × 3 (32)	128 × 128 × 32
2.	pool	2 × 2 (32)	64 × 64 × 32
3.	conv	3 × 3	64 × 64 × 32
4.	pool	2 × 2	32 × 32 × 32
5.	conv	3 × 3	32 × 32 × 64
6.	pool	2 × 2	16 × 16 × 64
7.			16,384
8.			128
9.			128
10.			2

66.3.2 Weak Convolution Neural Network Classification

A CNN classifier was developed to act as a machine annotator to automatically annotate a larger size of data (Sect. 66.3.3). The classifier was trained on the aforementioned dataset (Sect. 66.3.1). In developing the classifier, a set of random weights were initially used. The weights were then updated by minimizing the cost function with backward propagation. The proposed classifier is considered as a weak CNN, since it is only trained with few hundred images, with noise. As a preliminary experiment, binary classification was conducted: cracks were classified as fatigue cracks or non-fatigue cracks.

The authors assumed that crack patterns are low-level features, and a shallow CNN can better represent the features with few hundred images. There are three convolutional layers (conv), followed by one max-pooling layer (pool) for each convolutional layer (layers 1 to 6). A flatten layer is added later (layer 7). At the end, there are two fully-connected layers (fc) (layers 8 and 9), and one output layer for classification (layer 10), as per Table 66.1. In general, the convolutional layer aims to learn visual features. The pooling layers are used to reduce the spatial dimensions. Finally, after learning 2D features from the convolutional layer, the cubic is flattened to a vector, and connected with the fully-connected layers to do classification learning. The last layer is the soft-max layer to produce a probability distribution for each of the classes.

66.3.3 Image Retrieval and Annotation: Creating the Pseudo Training Data

A larger set of unlabeled images were further retrieved from the Web and classified using the trained CNN classifier (Sect. 66.3.2). The images were retrieved using the Google Image Search and general keywords, such as "cracking", for the queries. The classifier's results are a set of probabilities—for each instance-class pair, the probability that an instance belongs to a class. These probabilities indicate the confidence of the classifier in assigning the labels. A threshold was used to assign the final labels. After retrieval and automatic annotation, this image dataset could serve as the automatically labelled pseudo training data for future research.

66.3.4 Evaluation

The classifier performance was evaluated on natural scene crack images. To develop the ground truth, a set of images were manually labeled into two classes, positive (fatigue crack) and negative (non-fatigue crack). The classification results were evaluated based on recall and precision, with higher importance given to recall because fatigue cracks are critical and should not be missed. Recall and precision are defined in Eqs. (66.1) and (66.2), in which true positive (TP) refers to the number of retrieved images labeled correctly as positive, false positive (FP) refers to the number of retrieved images labeled incorrectly as positive, and false negative (FN) refers to the number of retrieved images labeled incorrectly as negative.

$$Recall = \frac{True\,Positive}{True\,Positive + False\,Negative} \tag{66.1}$$

$$Precision = \frac{True\,Positive}{True\,Positive + False\,Positive} \tag{66.2}$$

66.4 Experimental Results and Discussion

The experiments focused on retrieving and labeling fatigue cracks.

66.4.1 Classifier Training

To train the weak classifier (as per Sect. 66.3.2), the authors downloaded 100 images, including both positive and negative fatigue crack images. The following keywords were used to retrieve the images: “alligator crack” and “fatigue crack” for representing the positive training cases, and “longitudinal crack” and “transverse crack” to represent the negative training cases. After data cleaning, the weak CNN classifier was trained using 153 and 105 positive and negative images, respectively. Examples of the top-two retrieved images are shown in Figs. 66.3 and 66.4.

Fig. 66.3 Top two retrieved images using the “longitudinal crack” and “transverse crack” keywords (further annotated with “non-fatigue crack”)

Fig. 66.4 Top two retrieved images using the "alligator crack" and "fatigue crack" keywords (further annotated with "fatigue crack")

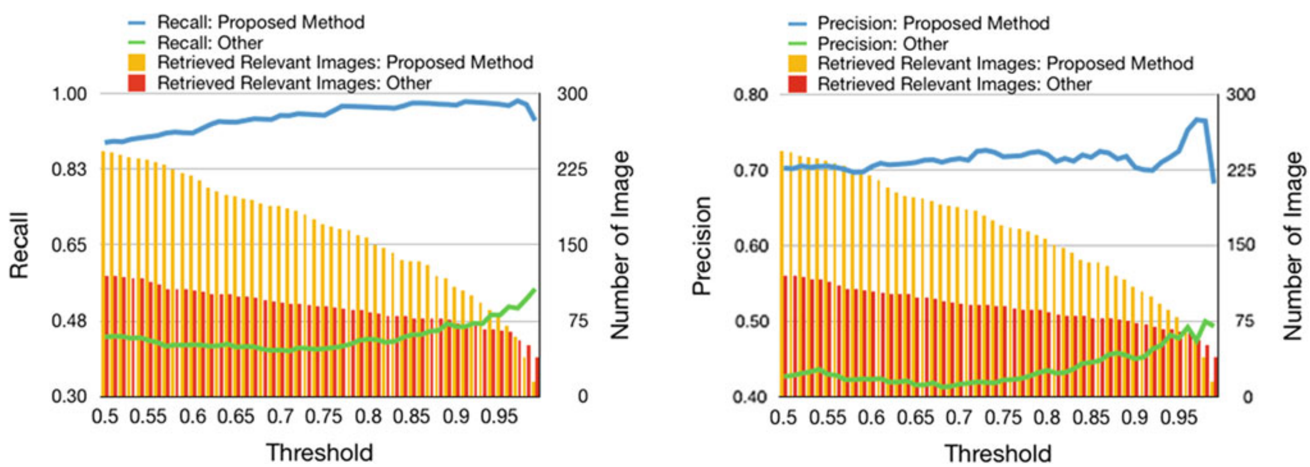

Fig. 66.5 Performance results for the classification

66.4.2 Classifier Evaluation

The proposed data retrieval and automated annotation approach was evaluated in two ways. First, the classifier performance was evaluated using the ground truth. The keyword "pavement crack" was used to retrieve more images from the Web. After data cleaning, 548 images were retrieved and labeled manually for developing the ground truth for testing (as per Sect. 66.3.4). Second, the impact of the dataset on the classification performance was evaluated. An existing dataset was manually labeled and used for retraining the classifier, instead of the authors' dataset. That dataset contains 132 and 151 positive and negative fatigue crack images, respectively. A set of threshold values were tested.

66.4.3 Performance Results

The proposed method was able to correctly label 188 out of 198 fatigue crack images, with a labeling recall and precision of 95 and 71%, respectively, as shown in Fig. 66.5. On the other hand, the classifier trained on the existing dataset was only able to achieve 41 and 42% recall and precision, respectively, as shown in Fig. 66.5. This indicates that the proposed method can retrieve and automatically annotate natural scene fatigue crack images with much higher recall and precision.

66.4.4 Error Analysis

An error analysis was conducted to further study how to improve the precision results, in future work. Three main sources of errors were identified: (1) some images have other types of cracks (e.g., longitudinal or transverse cracks) in addition to fatigue cracks; (2) the size of the training data may be insufficient; and (3) some images have undefined crack types. Figure 66.6 shows examples of misclassified images (false positives).

Fig. 66.6 Examples of misclassified images (false positives)

66.5 Conclusions and Future Work

In this paper, the authors proposed a data retrieval and annotation method to automatically retrieval and label crack images from the Web. The dataset aims to serve as pseudo training data for supervised machine learning-based crack classification algorithms. A weak CNN classifier first learns from a limited set of Web images, and then acts as a machine annotator and further labels a larger size of data. The proposed method achieved labeling recall and precision of 95 and 71%, respectively.

Several directions are proposed in future work. First, further efforts could be conducted to improve the performance results, especially the precision. The methodology could be improved in terms of data cleaning, feature learning, and model design aspects. Second, compared to datasets for general object classification problems, the developed dataset is relatively small in size. More data can be generated by extending the search queries. Third, and most importantly, automatic civil infrastructure inspection includes multiple types of defect detection and analysis. At this stage, this work only focused on fatigue cracks. In future work, the authors plan to develop a larger dataset, with more defect classes, to better support fully automated inspection of bridges.

References

1. Zhang, L., Yang, F., Daniel Zhang, Y., Zhu, Y.J.: Road crack detection using deep convolutional neural network. In: 2016 IEEE International Conference on Image Processing (ICIP) (2016). https://doi.org/10.1109/icip.2016.7533052
2. Adlinge, S.S., Gupta, A.K.: Pavement deterioration and its causes. Intl. J. Innov. Res. Dev. **2**(4), 437–450 (2013)
3. Krizhevsky, A., Sutskever, I., Hinton, G.E.: ImageNet classification with deep convolutional neural networks. Adv. Neural Inf. Process. Syst. (2012). https://doi.org/10.1145/3065386
4. Siebert, S., Teizer, J.: Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system. Autom. Constr. (2014). https://doi.org/10.1016/j.autcon.2014.01.004
5. Grandsaert, P.J.: Integrating pavement crack detection and analysis using autonomous unmanned aerial vehicle imagery. In: Air Force Institute of Technology Wright-Patterson AFB OH Graduate School of Engineering and Management (2015)
6. Zhang, C., Elaksher, A.: An unmanned aerial vehicle based imaging system for 3D measurement of unpaved road surface distresses. Comput Aided Civil Infrastruct. Eng. (2012). https://doi.org/10.1111/j.1467-8667.2011.00727.x
7. Chambon, S., Moliard, J.M.: Automatic road pavement assessment with image processing: review and comparison. Intl. J. of Geophys. (2011). https://doi.org/10.1155/2011/989354
8. Eisenbach, M., Stricker, R., Seichter, D., Amende, K., Debes, K., Sesselmann, M., Ebersbach, D., Stoecert, U., Gross, H.M.: How to get pavement distress detection ready for deep learning? A systematic approach. In: Neural Networks (IJCNN), 2017 International Joint Conference on IEEE (2017). https://doi.org/10.1109/ijcnn.2017.7966101
9. Pavement Interactive: http://www.pavementinteractive.org/
10. Oliveira, H., Correia, P.L.: CrackIT-An image processing toolbox for crack detection and characterization. In: Image Processing (ICIP), 2014 IEEE International Joint Conference on IEEE (2014). https://doi.org/10.1109/icip.2014.7025160
11. Zou, Q., Cao, Y., Li, Q., Mao, Q., Wang, S.: CrackTree: automatic crack detection from pavement images. Pattern Recognit. Lett. (2012). https://doi.org/10.1016/j.patrec.2011.11.004
12. Salman M., Mathavan S., Kamal K., Rahman M.: Pavement crack detection using the Gabor filter. In: Intelligent Transportation Systems-(ITSC), 2013 16th International IEEE Annual Conference on IEEE (2013). https://doi.org/10.1109/itsc.2013.6728529
13. Varadharajan, S., Jose, S., Sharma, K., Wander, L., Mertz, C.: Vision for road inspection. In: Applications of Computer Vision (WACV), 2014 IEEE Winter Conference on IEEE (2014). https://doi.org/10.1109/wacv.2014.6836111
14. Mertz, C.: Continuous road damage detection using regular service vehicles. In: Proceedings of the ITS world congress (2011)
15. Yamada, T., Ito, T., Ohya, A.: Detection of road surface damage using mobile robot equipped with 2d laser scanner. In: System Integration (SII), 2013 IEEE/SICE International Symposium on IEEE (2013). https://doi.org/10.1109/sii.2013.6776679

16. Yu, Y., Guan, H., Ji, Z.: Automated detection of urban road manhole covers using mobile laser scanning data. IEEE Trans. Intell. Transp. Syst. (2015). https://doi.org/10.1109/tits.2015.2413812
17. Byoung, J.L., Hosin, D.L.: A robust position invariant artificial neural network for digital pavement crack analysis. In: TRB 2003 Annual Meeting (2002)
18. Saar T., Talvik O.: Automatic asphalt pavement crack detection and classification using neural networks. In: Electronics Conf. (BEC), 2010 12th Biennial on IEEE (2010). https://doi.org/10.1109/bec.2010.5630750
19. Radopoulou, S.C., Brilakis, I.: Automated detection of multiple pavement defects. J. Comput. Civil Eng. (2016). https://doi.org/10.1061/(asce)cp.1943-5487.0000623
20. Hoang, N.D., Nguyen, Q.L.: A novel method for asphalt pavement crack classification based on image processing and machine learning. Eng. Comput. (2018). https://doi.org/10.1007/s00366-018-0611-9
21. Washington State Department of Transportation. Pavement Surface Condition Rating Manual. Olympia, WA (1992)
22. American Association of State Highway and Transportation Officials. AASHTO Guide for Design of Pavement Structures. Washington D.C (1993)
23. Miller, J.S., Bellinger, W.Y.: Distress identification manual for the long-term pavement performance program. United States Federal Highway Administration. Office of Infrastructure Research and Development (2014)
24. LeCun, Y., Bengio, Y., Hinton, G.: Deep learning. Nature. **521**(7553), 436 (2015)
25. Roth, H.R., Lu, L., Liu, J., Yao, J., Seff, A., Cherry, K., Kim, L., Summers, R.M.: Improving computer-aided detection using convolutional neural networks and random view aggregation. IEEE Trans. Med. Imaging (2016). https://doi.org/10.1109/tmi.2015.2482920
26. Ciresan, D., Giusti, A., Gambardella, L.M., Schmidhuber, J.: Deep neural networks segment neuronal membranes in electron microscopy images. In: Advances in Neural Information Processing Systems, pp. 2843–2851 (2012)
27. Cirean, D.C., Giusti, A., Gambardella, L.M., Schmidhuber, J.: Mitosis detection in breast cancer histology images with deep neural networks. In: International Conference on Medical Image Computing and Computer-assisted Intervention, Springer, Berlin, Heidelberg (2013). https://doi.org/10.1007/978-3-642-40763-5_51
28. Krizhevsky, A., Hinton, G.: Learning multiple layers of features from tiny images
29. Everingham, M., Van Gool, L., Williams, C.K., Winn, J., Zisserman, A.: The pascal visual object classes (voc) challenge. Intl. J. Comput Vision (2009). https://doi.org/10.1007/s11263-009-0275-4
30. Deng, J., Dong, W., Socher, R., Li, L.J., Li, K., Fei-Fei, L.: Imagenet: A large-scale hierarchical image database. In: Computer Vision and Pattern Recognition, 2009. CVPR 2009. IEEE Conference on IEEE (2009). https://doi.org/10.1109/cvprw.2009.5206848
31. Li, L.J., Fei-Fei, L.: Optimol: automatic online picture collection via incremental model learning. Intl. Comput. Vision (2010). https://doi.org/10.1109/cvpr.2007.383048
32. Schroff, F., Criminisi, A., Zisserman, A.: Harvesting image databases from the web. IEEE Trans. Pattern Anal. Mach. Intell. (2011). https://doi.org/10.1109/iccv.2007.4409099
33. Yao, Y., Zhang, J., Shen, F., Hua, X., Xu, J., Tang, Z.: Automatic image dataset construction with multiple textual metadata. In: Multimedia and Expo (ICME), 2016 IEEE International Conference on IEEE (2016). https://doi.org/10.1109/tits.2016.2552248
34. Shi, Y., Cui, L., Qi, Z., Meng, F., Chen, Z.: Automatic road crack detection using random structured forests. In: IEEE Transactions on Intelligent Transportation Systems (2016)
35. Amhaz, R., Chambon, S., Idier, J., Baltazart, V.: A new minimal path selection algorithm for automatic crack detection on pavement images. In: 2014 IEEE International Conference on Image Processing (ICIP) (2014). https://doi.org/10.1109/icip.2014.7025158

A Machine Learning Approach for Compliance Checking-Specific Semantic Role Labeling of Building Code Sentences

67

Ruichuan Zhang and Nora El-Gohary

Abstract

Existing automated building code checking systems/software highly rely on human interpretation of the code. Different methods have been proposed and implemented to make building codes automatically analyzable and interpretable by computers. These methods have achieved different levels of automation in rule formalization, but they all require some level of human involvement to capture the compliance checking-related semantic information in the natural language building code sentences. For example, the state-of-the art approaches require human annotation or require human effort to develop annotation and/or extraction rules. To reduce the human effort in automated code interpretation, this paper proposes a machine learning-based approach to automatically label the semantic roles in building code sentences for supporting code compliance checking. The proposed method consists of three primary elements: (1) capturing the syntactic and semantic features of the building code sentences using natural language processing techniques; (2) adapting out-of-domain training data to the task at hand based on data similarity; and (3) performing semantic role labeling using a conditional random field (CRF) model. The proposed approach was tested on a corpus of annotated text from the International Building Code, and achieved promising global precision.

Keywords

Code checking • Machine learning • Natural language processing • Semantic role labeling

67.1 Introduction

Existing automated building code checking systems/software (e.g., the Solibri Model Checker) highly rely on human interpretation of the code. An expert needs to first read and interpret the text and then formalize the requirements in the form of computer-processable rules. Such approaches, although achieve some levels of automation, are still labor-intensive and time-consuming. To address this problem, different methods have been proposed and implemented to make building codes automatically analyzable by computers. These methods have achieved different levels of automation in rule formalization, but they all require some level of human involvement to capture the semantic information in the natural language building code sentences—especially for the syntactically and semantically complex sentences. For example, the state-of-the art approaches are mostly either annotation-based or rule-based. Annotation-based approaches (e.g., [1]) require human annotation to identify and annotate the regulatory concepts that describe the building code requirements. Rule-based approaches (e.g. [2]) require human effort to develop annotation rules for automatically conducting the annotation and/or extraction rules for extracting the target information. For both approaches, eliminating the human involvement totally is challenging, because such accurate and

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complete annotation and information extraction involves a deep level of semantic information analysis that requires complete understanding of building code requirement sentences—which are rich and complex in semantics and syntactics.

In comparison to rule-based approaches, machine-learning-based approaches aim to replace the hand-crafted-rule-based methods [3]. They aim to automatically capture the underlying patterns of the text data, by learning from a large size of text data. Supervised machine learning has been used in the domains of text mining, natural language processing, and computational linguistics to better understand the text data and extract information from such data.

To avoid/reduce the human effort in automated rule formalization for supporting automated compliance checking, a machine learning-based approach that includes three primary components is proposed: (1) semantic role labeling: automatically identifying the compositional semantics of building code sentences and automatically label the semantic roles in the sentences; (2) information extraction: automatically extracting the target semantic information based on the semantic roles, without the need for extraction rules; and (3) rule formalization: transforming the extracted information into rules. This paper focuses on semantic role labeling. A machine learning-based semantic role labeling approach is proposed, which consists of three primary elements. First, natural language processing techniques are used to capture the syntactic and semantic features of the building code sentence. Second, out-of-domain training data are adapted to the task at hand based on data similarity. Third, a conditional random field (CRF)-based algorithm is proposed and used for semantic role labeling. This paper presents the proposed approach and discusses the preliminary experimental results.

67.2 Background

67.2.1 Semantic Role Labeling

Sematic role labeling is a shallow semantic text analysis task that aims to extract the proposition units, where each unit consists of a target verb and all the constituents in the sentences that fill a semantic role of the verb [4]. The semantic roles include (1) numbered argument (A): arguments that are required or occur frequently for a verb; (2) modifiers (AM): modifiers are adverbs, adverb phrases, and prepositional phrases that describe and/or modify the verb [e.g., location (LOC), modal verb (MOD), extent (EXT), manner (MNR), and direction (DIR)]; and (3) reference (R). The numbered arguments and their grammatical definitions are summarized in Table 67.1. Semantic role labeling often acts as the cornerstone for further, much deeper annotation, understanding, and information extraction of the text. For example, the labeled semantic roles can be used for deeper IFC-oriented information annotation and/or extraction: the verbs would be candidates for IFC relationships and the noun phrases in arguments would be candidates for IFC objects and/or properties. The labeled semantic roles can also be used in entity-relationship conceptual modeling approaches such as the resource description framework (RDF), which models information in the form of subject–predicate–object which is similar to verb-argument.

67.2.2 Supervised Learning-Based Sequence Labeling

Supervised learning is one type of machine learning problems, where a function that maps input data (usually with features) to an output (such as categories) based on given input-output pairs (labeled training data) is learnt [5]. Different supervised learning algorithms can be used to learn the function from the training data. Among all the algorithms, conditional random fields (CRF) is designed specifically to deal with sequence labeling problems (e.g., semantic role labeling) [6], where given a

Table 67.1 Numbered argument

Semantic role	Grammatical definition	Example sentence from building code[a,b]
Agent (A0)	The entity that performs the action	"**The area of a membrane structure** shall not exceed the limitations in Table 503"
Patient (A1)	The entity that undergoes the action	"The area of a membrane structure shall not exceed **the limitations in Table 503**"
Verb-specific argument (A2)	Other entities that occur frequently for the action	"Draft curtains shall be constructed of **sheet metal**"

[a]Semantic role is bolded
[b]International Building Code 2009

sequence of words, a sequence of tags/roles which represent syntactic compositions (e.g., part-of-speech tags) and/or semantic compositions (e.g., semantic roles, sentiment levels, domain-specific semantic tags, etc.) needs to be found. CRF is a discriminative classifier built on the joint probability of the sequence of labels given the observed sequence of words. CRF is trained by maximum likelihood estimation, and a trained CRF assigns a probability distribution over all possible sequences of labels given a sequence of words [6]. The optimal sequence is the sequence of labels that have the maximum probability.

67.2.3 Parsing

Constituency parsing aims to organize words in a sentence into nested constituents based on phrase structures. The results of constituency parsing are often represented in the form of a tree, where the nodes are phrase structure categories, and the leaves are part-of-speech (POS) tags and words. Dependency parsing aims to analyze the grammatical structure of a sentence by linking the head words to words which modify those heads. A link indicates the grammar dependency from the current word to the head word. The results of both natural language processing techniques are usually used as features in machine learning problems to further analyze text data.

67.3 Semantic Role Labeling in Automated Compliance Checking

In the proposed approach, semantic role labeling aims to segment the whole building code sentence into several proposition units, each consisting of several semantic roles.

These semantic roles could further help in automatically extracting the target semantic information in a code sentence (e.g., subject of requirement, compliance checking attribute, etc.), without the need for extraction rules. The proposition units and the semantic role labels of the following example sentence are shown in Fig. 67.1: "at least three sides of each such larger tier shall have continuous horizontal openings not less than 30 inches in clear height extending for at least 80 percent of the length of the sides". The example sentence is segmented as two proposition units, where Proposition Unit 2 acts as A1 (i.e., the patient) in Proposition Unit 1.

67.4 Proposed Machine Learning Approach for Semantic Role Labeling of Building Code Sentences

The proposed semantic role labeling approach consists of three primary elements: (1) natural language processing techniques are used to capture the syntactic and semantic features of the building code sentence, (2) out-of-domain training data are adapted to the task at hand based on data similarity, and (3) a CRF-based algorithm is used for semantic role labeling. The research methodology, thus, consists of five primary steps: data preparation and preprocessing, training data adaptation, feature preparation, CRF-based semantic role labeler training, and evaluation (see Fig. 67.2).

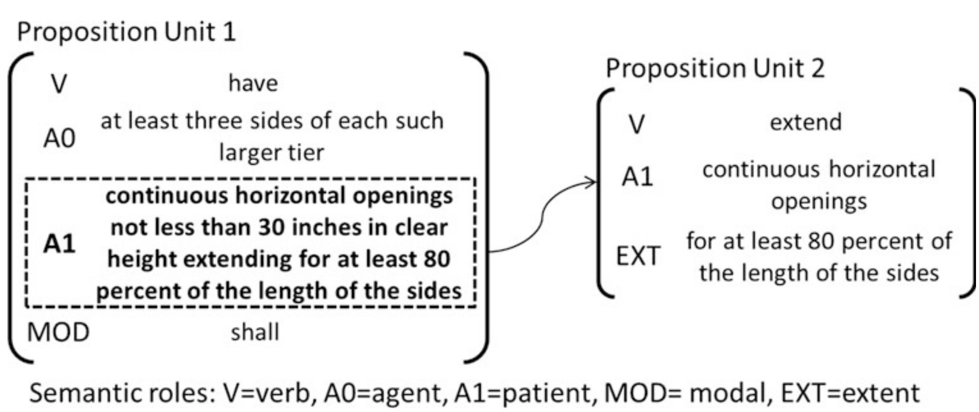

Fig. 67.1 The proposition units and the semantic role labels in an example sentence

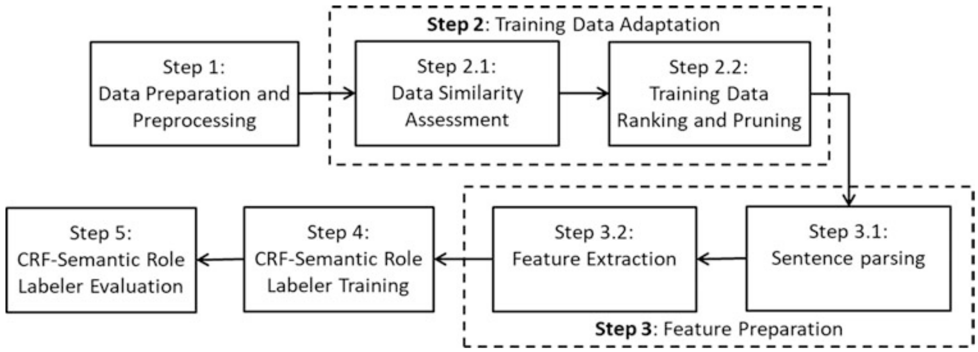

Fig. 67.2 Proposed machine learning approach for semantic role labeling of building code

67.4.1 Data Preparation and Preprocessing

For out-of-domain training data, the PropBank training dataset was used [7], which contains over 30,000 sentences from the 1989 Wall Street Journal that were annotated with semantic roles.

For training data adaptation and testing, around 300 sentences were randomly selected from the International Building Code (IBC) 2009 (IBC 2009). The sentences were randomly sampled from different sentence types, in terms of syntactic and semantic structures and sentence computability [8], to better evaluate the performance and scalability of the semantic role labeler. The sentences were then manually annotated. Figure 67.1 shows an example sentence, along with its semantic role labels.

Three steps of data preprocessing were then conducted to facilitate the subsequent feature generation and training data adaptation: tokenization, lowercasing, and stemming. Tokenization aims to split the whole sentence into units (e.g., words, punctuations). Stemming aims to reduce the derived words to their root forms.

67.4.2 Training Data Adaptation

The out-of-domain training dataset was adapted to the domain-specific machine learning task at hand based on data similarity. The adaptation methodology includes two steps: data similarity assessment and data ranking and pruning.

Data Similarity Assessment. Data similarity aims to assess the similarity between the out-of-domain data (i.e., the sentences in the PropBank dataset) and the domain-specific data (i.e., the sentences in the building code). The proposed similarity between two sentences is defined as the average of one minus the normalized levenshtein distance between the POS tag sequences of the two sentences, and the cosine similarity between the two sentences. The levenshtein distance aims to capture the syntactic-level dissimilarity between two sentences. The cosine similarity aims to capture the word-level similarity between two sentences.

Data Ranking and Pruning. The out-of-domain training data were pruned based on the semantic similarity. For each training sentence, the average and maximum of the similarities to all the testing sentences were calculated. All the training sentences were then ranked based on these averages and maximums. If a training sentence ranks at the bottom 25% for both average similarity and maximum similarity, the training sentence is pruned. This step removed more than 25% of all the training sentences, and a total of 20,000 sentences, which contain over 50,000 annotated propositional units were kept and used for preparing the features and training the CRF model.

67.4.3 Feature Preparation

Parsing. All sentences were parsed using the Stanford CoreNLP constituency and dependency parser [9]. The constituency parser tags the sentences using the Penn Treebank tag set. The tag set includes: (1) word-level tags, i.e., POS tags, such as nouns (NN), and numeric values (CD), (2) phrase-level tags such as noun phrase (NP), verb phrase (VP), prepositional phrase (PP), and (3) clause-level tags such as a simple clause not introduced by subordinating conjunction or a wh-word

(S) [10]. The sentences are then represented by phrase structure rules (e.g., "S → NP VP", which means the sentence is composed of a noun phrase followed by a verb phrase). The dependency parser tags the sentences using the Universal Dependency set. The set includes clausal argument relations such as passive nominal subject (nsubjpass), nominal modifier relations such as nominal modifier (nmod/nn), and other relations such as conjunct.

Feature Extraction. Three types of features were extracted from the original text data, and the results of both constituency and dependency parsing: plain text features, constituency-tree-derived features, and dependency-graph-derived features. Plain text features include the current, the preceding, and the following word, and also the predicate verb and the relevant distance from the predicate verb to the current word. Constituency-tree-derived features include: (1) POS tags of the current, the preceding, and the following word, and the predicate verb; (2) phrase-level tags of the current word and predicate verb, and the phrase-level tags corresponding to the lowest common parent node of these two words in the constituency parsing tree; (3) phrase structure rules of the current word and predicate verb, and the phrase structure rules corresponding to the lowest common parent node of the two words in the constituency parsing tree; and (4) the relevant height of the lowest common parent node. Dependency-graph-derived features include the head word of the current word, its POS tag, the dependency relation between the current word and the head word, and the relevant distance between the head word and the current word. Two features were further derived from each of the plain text features: the lower case of the word and the stemmed word. One other feature was further derived from each of the POS tag features: the first two letters of the original POS tag.

67.4.4 CRF Semantic Role Labeler Training

Given a sequence of words X in the sentence, a CRF model defines the probability of a corresponding sequence of roles Y as in Eq. 67.1, where the outer sum is applied over every feature function f_j, which is a function of the sentence s, the position i, the current and/or the preceding role l_i and l_{i-1}, and the inner sum is applied over every position i in the sentence; the length of the sentence is n and the total number of features is m; Z is the normalization term, and w are the parameters of the CRF model [6].

$$P(Y|X, w) = \frac{1}{Z}\sum_{j=1}^{m}\sum_{i=1}^{n} w_j f_j(s, i, l_i, l_{i-1}). \tag{67.1}$$

To find the optimal parameters w^* for the CRF model, given k training data pairs $\{(x_1, y_1),\ldots, (x_k, y_k)\}$, the conditional log likelihood of the training data with penalty is maximized, as shown in Eq. 67.2, where λ_1 and λ_2 are coefficients for L1 and L2 norm penalty applied to the parameters w.

$$w^* = \underset{w}{\operatorname{argmax}} \sum_{i=1}^{k} \log p(x_i|y_i, w) - \lambda_1|w| - \lambda_2\|w\|_2 \tag{67.2}$$

The whole set of training data was split into a training set and a validation set. The training set was used to train new CRF models, and the validation set was used to tune the hyper parameters λ_1 and λ_2.

67.4.5 Labeling Using CRF and Evaluation

Given a sequence of words and the trained CRF model, the labeling process aims to search the optimal sequence of roles that maximizes the sum of the conditional log likelihood. The searching is conducted using dynamic programming on the matrix of conditional probabilities. Thus, the optimal sequence of roles can be found in polynomial time instead of computing all the possible sums of conditional probabilities in exponential time.

Three metrics were used to evaluate the performance of the CRF semantic role labeler: precision (Eq. 67.3), recall (Eq. 67.4), and F1 measure (Eq. 67.5), where for a specific semantic role L, TP is the number of true positives (i.e., number of words correctly labeled as L), FP is the number of false positives (i.e., number of words incorrectly labeled as L), and FN is the number of false negatives (i.e., number of words not labeled as L but should have been) [11]. The evaluation metrics are computed globally, and for each type of semantic role.

$$\text{Precision} = \frac{TP}{TP + FP} \tag{67.3}$$

$$\text{Recall} = \frac{TP}{TP + FN} \tag{67.4}$$

$$F_1 = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \tag{67.5}$$

67.5 Preliminary Experimental Results and Discussion

67.5.1 Model Training

The entire training dataset was split into an 80:20 ratio, with 80% of the dataset as the training set and 20% of the dataset as the validation set. The training set was used to train the CRF model using the CRFsuite [12] built in Python. The validation set was used to tune the hyper parameters of the CRF model. Based on the validation results, 1 and 0.001 were chosen as the optimal L1 penalty and L2 penalty coefficients, respectively. To improve the computational efficiency of the training, an early-stop threshold on the number of iterations was set as 100. The precision, recall, and F1 measure of labeling the validation set are 0.72, 0.70, and 0.71, respectively.

67.5.2 Experimental Results

The trained CRF model was used to label the testing data. The global precision, recall, and F1 measure of labeling the testing data is 0.71, 0.63, and 0.65, respectively. The precision, recall, F1 measure, and the total count for each type of semantic role are shown in Table 67.2.

Table 67.2 Precision, recall, and F1 measure of each type of semantic role[a]

Semantic role	Precision	Recall	F1-measure	Count
A0	0.84	0.55	0.67	730
A1	0.70	0.78	0.74	3183
A2	0.64	0.71	0.67	1524
A3	0.23	0.73	0.34	37
ADV	0.21	0.23	0.22	227
DIR	0.20	0.62	0.30	13
EXT	0.00	0.00	0.00	34
LOC	0.69	0.19	0.30	884
MNR	0.84	0.26	0.39	560
MOD	0.95	0.93	0.94	187
NEG	0.98	0.98	0.98	49
PNC	0.25	0.28	0.26	131
TMP	0.59	0.53	0.56	188
V	0.99	0.99	0.99	485
R	1.00	0.67	0.80	36
Global/Total	0.71	0.63	0.65	8268

[a]*Semantic roles* A0 = agent, A1 = patient, A2 = verb-specific argument, A3 = other arguments, ADV = adverb, DIR = direction, EXT = extent, LOC = location, MNR = manner, MOD = modal, NEG = negation, PNC = purpose, TMP = temporal, V = verb, R = reference

Table 67.3 Confusion matrix of semantic role labeling results[a]

Semantic role	A0	A1	A2	ADV	LOC	MNR	TMP	NEG	MOD	V
A0	404	131	20	0	0	0	0	0	0	0
A1	23	2494	62	54	41	6	15	0	1	1
A2	0	261	1076	0	7	0	0	0	0	1
ADV	0	86	16	52	0	1	3	0	0	0
LOC	16	139	71	96	169	0	0	0	0	0
MNR	0	80	172	13	17	143	28	0	0	0
TMP	0	50	12	0	4	5	100	0	0	0
NEG	0	0	0	0	0	0	0	48	0	0
MOD	0	0	0	0	0	0	0	0	174	2
V	0	2	2	0	1	0	0	0	0	478

[a]*Semantic roles* A0 = agent, A1 = patient, A2 = verb-specific argument, A3 = other arguments, ADV = adverb, LOC = location, MNR = manner, TMP = temporal, NEG = negation, MOD = modal, V = verb

67.5.3 Error Analysis

The confusion matrix (Table 67.3) shows the distribution of mislabeled words in each type of semantic role. The model performs generally well when labeling numbered arguments [e.g., agent (A0), patient (A1), and verb-specific argument (A2)]. Given the fact that arguments over A2 are relatively rarely used in semantic role labeling, A0, A1, and A2 are the main focus of the analysis, and arguments with a number larger than two were neglected. The model performed relatively better in labeling A0 and A2, but sometimes confused A1 to A0 or A2. The model performed worse when labeling the modifiers [e.g., adverb (ADV), location (LOC), manner (MNR), temporal (TMP), etc.], except for the straightforward ones such as negation (NEG) and modal (MOD). The model confused ADV and LOC with A1, and confused MNR with A2, because (1) A1 and A2 can be prepositional phrases and most of the adverbs, locations, and manners are prepositional phrases; (2) the modifiers such as adverbs, locations, and manners tend to agglomerate and thus are labeled as a single semantic role; and (3) the constituency parser and dependency parser are not completely accurate in parsing the sentences, especially sentences with long and complex prepositional phrases and thus there are noises in the features derived from the constituency tree and dependency graph. Globally, the error also comes from (1) differences between the domains. For example, verbs that are rare in the training data but appear in the testing data create difficulty in labeling verb-specific arguments; and (2) longer and more complex sentences in the testing data.

67.6 Conclusion

In this paper, a machine-learning-based approach for semantic role labeling of building code requirement sentences was proposed. The proposed approach adapts out-of-domain training data to the task at hand based on a proposed data similarity measure, and performs semantic role labeling using a CRF model trained on the adapted data. Three different groups of features were proposed and used for learning: plain text features, constituency-tree-derived features, and dependency-graph-derived features. The trained CRF model achieved a global precision of 0.71, local precisions for negation and modal over 0.95, and local precisions for manner and numbered argument (e.g., A0) near 0.85. Future research effort is needed to further improve the accuracy of the proposed machine learning-based semantic role labeling approach, especially to improve the labeling performance on verb-specific arguments and modifiers such as adverb, location, and temporal.

This paper contributes to the body of knowledge in two primary ways. First, the proposed approach allows for the use of out-of-domain training data to tackle the scarcity of domain-specific training data, while adapting such out-of-domain data to a specific domain by performing data pruning. Second, the results show that the selected multi-source features are potentially effective for semantic role labeling of building code requirements. The main limitation of this approach, however, is that it is not able to directly extract compliance checking-related information, but rather segments a whole requirement into proposition units consisting of semantic roles that can be further used to extract those information.

In future work, the authors plan to pursue a number of directions to improve the performance of semantic role labeling: (1) leverage other categories of state-of-the-art machine learning algorithms; (2) extract more types of syntactic and semantic features, and test the combination of different types of features; and (3) combine the domain knowledge (e.g., domain ontology, expert-predefined rules, IFC concepts) with the proposed machine learning algorithm for semantic role labeling. Most importantly, in their future work, the authors plan to proceed with machine learning-based semantic information extraction based on the semantic roles.

References

1. Hjelseth, E., Nisbet, N.: Capturing normative constraints by use of the semantic mark-up RASE methodology. In: Proceedings of CIB W78-W102 Conference, pp. 1–10. (2011)
2. Zhang, J., El-Gohary, N.: Automated information transformation for automated regulatory compliance checking in construction. J. Comput. Civ. Eng. **29**(4), B4015001 (2015)
3. Jurafsky, D., Martin, J.: Speech and Language Processing, 3rd edn. Pearson, London (2014)
4. Carreras, X., Màrquez, L.: Introduction to the CoNLL-2005 shared task: Semantic role labeling. In: Proceedings of the ninth conference on computational natural language learning, pp. 152–164. (2005)
5. Russell, S., Norvig, P.: Artificial Intelligence: A Modern Approach, 3rd edn. Prentice Hall, USA (2010)
6. Cohn, T., Blunsom, P.: Semantic role labelling with tree conditional random fields. In: Proceedings of the Ninth Conference on Computational Natural Language Learning, pp. 169–172. Association for Computational Linguistics, USA (2005)
7. Palmer, M., Gildea, D., Kingsbury, P.: The proposition bank: a corpus annotated with semantic roles. Computational Linguistics Journal **31**, 1 (2005)
8. Zhang, R., El-Gohary, N.: A clustering approach for analyzing the computability of building code requirements. In: Construction Research Congress 2018, pp. 86–95. American Society of Civil Engineers, USA (2018)
9. Manning, C., Surdeanu, M., Bauer, J., Finkel, J., Bethard, S., McClosky, D.: The stanford corenlp natural language processing toolkit. In: Proceedings of 52nd annual meeting of the association for computational linguistics: system demonstrations, pp. 55–60. Association for Computational Linguistics, USA (2014)
10. Marcus, M., Kim, G., Marcinkiewicz, M., MacIntyre, R., Bies, A., Ferguson, M., Katz, K., Schasberger, B.: The Penn Treebank: annotating predicate argument structure. In: Proceedings of the workshop on Human Language Technology, PP. 114–119. (1994)
11. Zhai, C., Massung, S.: Text Data Management and Analysis: A Practical Introduction to Information Retrieval and Text Mining. Morgan & Claypool, New York (2016)
12. Naoaki Okazaki: CRFsuite: a fast implementation of Conditional Random Fields (CRFs), http://www.chokkan.org/software/crfsuite/. Last accessed 21 Apr 2018

68 Requirement Text Detection from Contract Packages to Support Project Definition Determination

Tuyen Le, Chau Le, H. David Jeong, Stephen B. Gilbert, and Evgeny Chukharev-Hudilainen

Abstract

Project requirements are wishes and expectations of the client toward the design, construction, and other project management processes. The project definition is typically specified in a contract package including a contract document and many other related documents such as drawings, specifications, and government codes. Project definition determination is critical to the success of a project. Due to the lack of efficient tools for requirement processing, the current practices regarding project scoping still heavily rely on a manual basis which is tedious, time-consuming, and error-prone. This study aims to fill that gap by developing an automated method for identifying requirement texts from contractual documents. The study employed Naïve Bayes to train a classification model that can be used to separate requirement statements from non-requirement statements. An experiment was conducted on a manually labeled dataset of 1191 statements. The results revealed that the developed requirement detection model achieves a promising accuracy of over 90%.

Keywords

Project definition • Requirement management • Requirement extraction • Machine learning • Natural language processing • Text classification • Naïve bayes

68.1 Introduction

A poor project definition will lead to cost overrun, behind schedule, and rework during design and construction. One of the most challenging problems of a construction project is to capture the project definition and accurately realize them during design and construction stages. Contractual requirements of a construction project are needs, wishes, and expectations of the client that define the design, construction, and other project management activities. Correctly understanding project requirements is critical to the success of project delivery [1]. Effective requirement management can enable a complete fulfillment of the owner expectations, and avoid costly redesign and rework [2]. Since requirements are described using natural language in a text format (e.g., contracts, specifications, government codes, drawings) [1], a considerable burden has been imposed on professionals across project stages (e.g., designers, contractors) to process and restructure them in a systematic and manageable manner. Requirement processing involves manual identification, analysis, and prioritization of implicit and explicit requirements [1, 3]. Sketches, matrices, and excel spreadsheets are among the most common storing methods used by designers to effectively manage required input information for design and construction verification [4]. The

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ad hoc natural business language of the client needs to be translated into an engineering language [3]. For instance, the requirement 'pleasant internal environment' can implicitly refer to the following design attributes: 'room space', 'air flow velocity', 'temperature' and 'sound insulation'. The conventional practice of requirement processing is extremely human-intensive, tedious, and error-prone [5, 6]. A computational technique that supports project scope determination would effectively enable early detection of poor definition such as missing or conflicting requirement information. Consequently, it would help allow fast and error-free project delivery.

To fulfill that demand, this study proposes an automated method for recognizing requirement texts from construction contract documents to support early scope determination. The study utilizes a supervised machine learning method to train a binary text classifier that can be used to distinguish requirement and non-requirement statements. This domain-specific model is developed using domain-specific data of construction contract texts. The following sections explain the study background, related studies, and details of the machine learning method.

68.2 Project Scope Definition Determination

Project scope definition is a collection of the owner's requirements that the designer and contractor need to fulfill. Figure 68.1 shows a typical life cycle of a construction project. As shown in the figure, the project definition originates from the user's needs and is fully described before construction begins. This information is initially included in letting documents such as requests for proposals (RFPs) in the early stage. When an agreement is achieved in the form of a contract, this becomes contractual clauses between the owner and the contractor. A contract package includes a contract and other related documents such as drawings and specifications. For the traditional design-bid-build delivery method, the project design is defined with a high degree of details, while the design-build method includes only overall design requirements. If a project is poorly defined in the contract package, requests for information (RFIs) and change orders may be needed during the construction stage. Failing to recognize missing or conflicting information will cause project delay, rework, and cost overrun.

Project definition includes all the requirements for design, construction methods, testing methods as well as submittals. Project definition rating index (PDRI) [7], which was developed by the Construction Industry Institute (CII), is a commonly used tool to assess the definition completeness of a project. It can be used to quickly analyze the definition package and successfully identify project risks prior to project execution. PDRI is a checklist of 70 definition elements that the project team must assess their completeness and preciseness for all project activities from planning to construction and up to project handover. Examples of major groups of elements are: project scope (e.g., objective statements, design criteria, site characteristics), value engineering (e.g., design and material alternative consideration, constructability analysis), deliverables (computer-aid design or building information requirements, deliverable definition), project control (e.g., project control requirements, accounting requirements). In the current practices, the process of reviewing project description is still relying on a manual process. The project team must read the project description and extract requirement statements. Other types of texts such as supporting and instruction will be ignored. Figure 68.2 below illustrates a contract section in which requirement texts are manually highlighted by the contractor. Those extracted statements may be stored in a structured

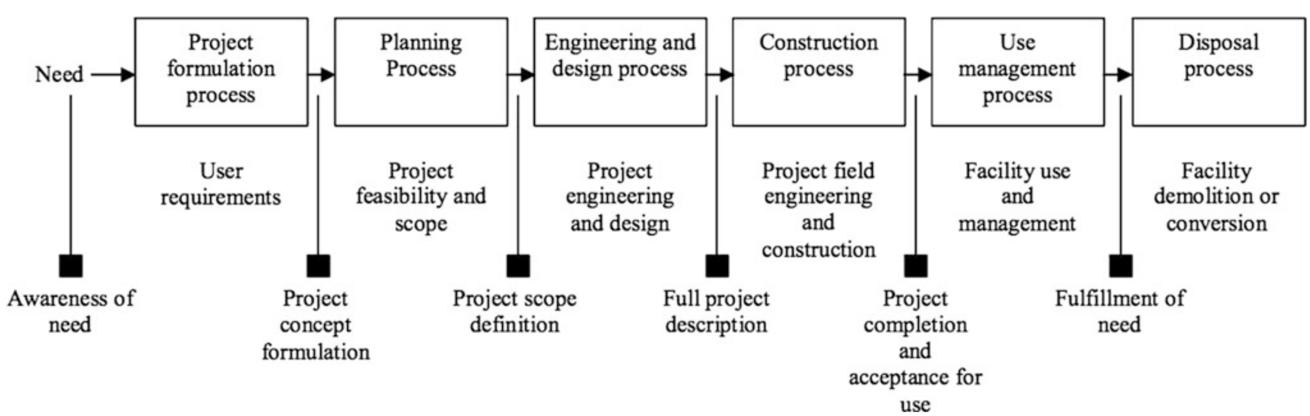
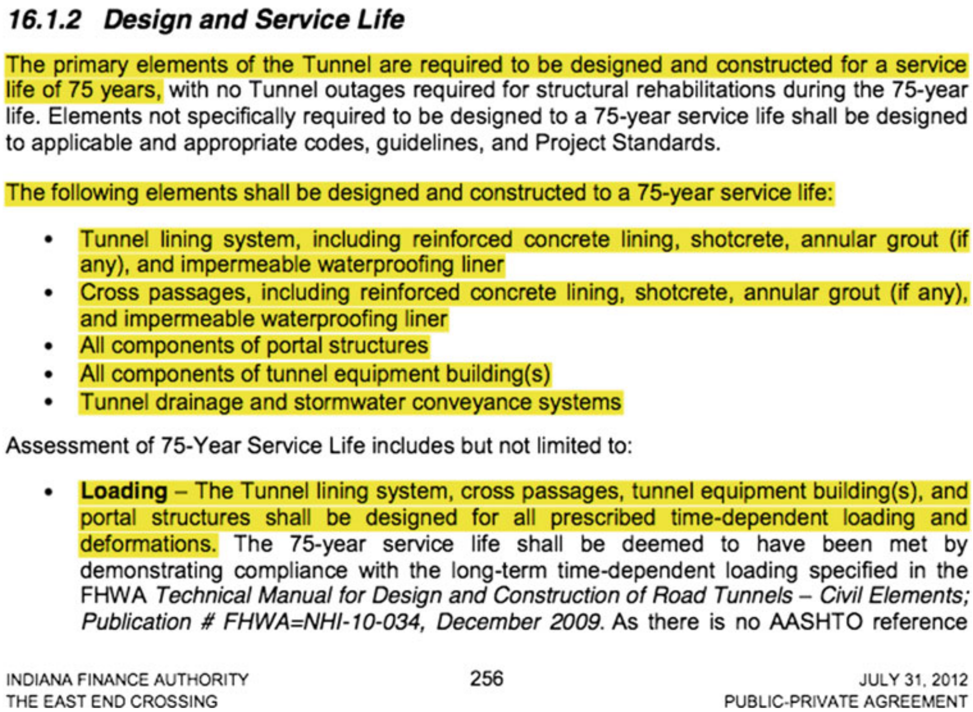


Fig. 68.1 Project life cycle [20]



16.1.2 Design and Service Life

The primary elements of the Tunnel are required to be designed and constructed for a service life of 75 years, with no Tunnel outages required for structural rehabilitations during the 75-year life. Elements not specifically required to be designed to a 75-year service life shall be designed to applicable and appropriate codes, guidelines, and Project Standards.

The following elements shall be designed and constructed to a 75-year service life:

- Tunnel lining system, including reinforced concrete lining, shotcrete, annular grout (if any), and impermeable waterproofing liner
- Cross passages, including reinforced concrete lining, shotcrete, annular grout (if any), and impermeable waterproofing liner
- All components of portal structures
- All components of tunnel equipment building(s)
- Tunnel drainage and stormwater conveyance systems

Assessment of 75-Year Service Life includes but not limited to:

- **Loading** – The Tunnel lining system, cross passages, tunnel equipment building(s), and portal structures shall be designed for all prescribed time-dependent loading and deformations. The 75-year service life shall be deemed to have been met by demonstrating compliance with the long-term time-dependent loading specified in the FHWA *Technical Manual for Design and Construction of Road Tunnels – Civil Elements; Publication # FHWA=NHI-10-034, December 2009.* As there is no AASHTO reference

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Fig. 68.2 Project scope description of project definition package

format such as MS Excel or MS Access for requirement management during the project delivery. By analyzing those requirements, the definition completeness can be evaluated and missing information can be identified early.

68.3 Related Studies and Gap of Knowledge

68.3.1 Natural Language Processing in AEC/F Industry

Natural Language Processing (NLP) is a collection of techniques that can analyze and extract information from natural language like text and speech. The major applications of NLP include translation, information extraction, and opinion/topic mining [8]. These applications are being accelerated by the availability of highly accurate text processing packages such Apache OpenNLP, NLP Standford, etc. which are able to support a variety of tasks such as tokenization [9, 10], Part-of-Speech (POS) tagging [11, 12], Named Entity Recognition (NER), etc. NLP methods can be classified into the following two main groups: [13] rule-based and [11] machine-learning (ML) based methods. Rule-based methods, which rely solely on hand-coded rules, are not able to fully cover all complicated sets of human grammatical rules [14]; and their performance are therefore relatively low. NLP research is shifting to statistical ML based methods [8]. ML models are able to accurately learn patterns from training examples to predict the output, hence they are independent of languages and linguistic grammars [13]. Many ML-based techniques to extract information from construction project texts show promising results [15–19].

68.3.2 Previous Studies and Research Gap

Previous studies on natural language requirement processing were focused on labeling a given set of clauses in government codes. For example, Salama and El-Gohary [15] developed a multi-label machine learning-based method for categorizing clauses in construction codes and standards into different topics such as environment, safety, health, etc. Zhou and El-Gohary [19] also compared the performance of various machine-learning approaches on classifying environmental regulatory clauses over a hierarchy of subjects. In another study, Zhou and El-Gohary [18] developed a method using domain ontology that showed a better performance compared to machine learning. The classification models resulted from those studies, however, are designed particularly for environment specifications and would not work well for project scope management which is concerned with another classification structure. From a personal interview with an experienced professional of a design-build firm, the authors found that contractors are more interested in grouping requirements into specific work tasks (e.g., foundation design, foundation construction, etc.) that can support them in effectively monitoring the requirement fulfillment along with the project progress. More importantly, no study found in the state-of-the-art that can enable automated extraction of requirement statements from a large amount of text in PDF documents and digital design CAD drawings. Existing requirement classification models in the construction domain assume the availability of requirement statements. Since a project package also includes non-requirement texts such as instruction sentences, separating requirements from other texts is needed. Given a large and complex project, manual reading and extracting requirement statements will be tedious and extremely labor-intensive. There is a need for an algorithm for distinguishing requirements from non-requirements texts.

68.4 Proposed NLP-Based Method for Scope Definition

This paper presents an initial effort of an on-going research project that is aimed at developing a system to support scope definition evaluation based upon project description texts such as letting documents or contracts. The overall architecture of the system is illustrated in Fig. 68.3. The system includes the following key modules: [13] requirement extraction, [11] requirement classification, [7] project scope definition assessment. NLP and machine learning will be utilized to develop this platform. The system can analyze a project description package and return such outcomes as project definition rating index, missing information, conflicting requirement statements. Further explanations for those components are presented below.

1. Requirement extraction. A project scope definition document is written in human language. The texts in those documents can be classified into: requirements, supporting texts and instruction texts. Of those, the project members need only requirement texts. The goal of this stage is to support automated extraction of requirement texts from project description documents.
2. Requirement classification. This stage aims to classify requirement texts into different categories in accordance with the commonly used PDRI checklist. This list defines various types of project definition elements that are important to the completeness of the project definition such as design criteria and location description. This module will assign requirements to corresponding definition elements.
3. Project definition assessment. This module is expected to be a series of various machine learning algorithms that can determine the definition completeness rating, identify risk areas, and detect missing/conflicting information. This information will help the project team to locate and address poor definition areas early in the project timeline.

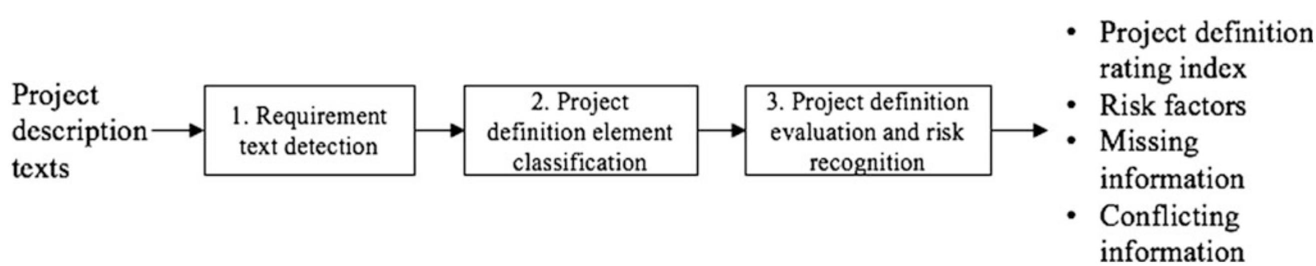

Fig. 68.3 Proposed architecture for NLP-based project scope determination

68.5 Requirement Text Detection

This paper is focused on the first module of the proposed architecture for automated project scope determination explained earlier. A project contract package includes various text documents (contracts, specifications, etc.) and design drawings that contain both requirements and non-requirement statements. One of the most critical task to establish such a project definition determination platform is distinguishing requirement sentences and non-requirement sentences. Non-requirement sentences could include instruction texts and supporting texts. Supporting texts provide background and context rather than specific requirements. Instruction texts provide guidance or suggestions which are not mandatory for the contractor to perform.

68.5.1 Methodology

This study proposed a novel method for extracting requirement sentences from a project description package. To support filtering requirements out of a project package, a binary text classification model was developed that can distinguish 'requirement' and 'non-requirement' texts. Requirement statements typically consist of indicating words such as 'shall'. A review of a preliminary project corpus revealed that several phrases occur frequently in requirements. Figure 68.4 below shows the top phrases commonly appears in requirement sentences, where uni-grams, bi-grams, and tri-grams respectively refer to phrases with one, two, and three words. This study utilized a supervised machine learning model to train the requirement extraction model based on the occurrence of keywords in the input texts.

Requirement detection is formalized as a binary classification model. In this model, the two classes are requirement and non-requirement. This study employed Naïve Bayes, which is a probabilistic supervised machine learning method, to develop the classifier. Naïve Bayes is based upon the bag of word method which represents each text as a collection of words. The bag of word can either contain every word in the text or only important words. Also, the bag of words can be constructed as a bag of n-grams. An n-gram is a string of multiple consecutive words such as bigrams (two words) and trigram (three words) in the text. In general, a selected element in the bag of word is called a feature. As shown in Fig. 68.5, the classification model is constructed using the probabilistic information of labels and features in a manually labeled training dataset.

The predicted label is the most likely label given those words of the sentence and is determined using the following equation.

$$c_{NB} = \underset{c \in C}{\operatorname{argmax}} P(c_j) \prod_{x \in X} P(x|c)(1)$$

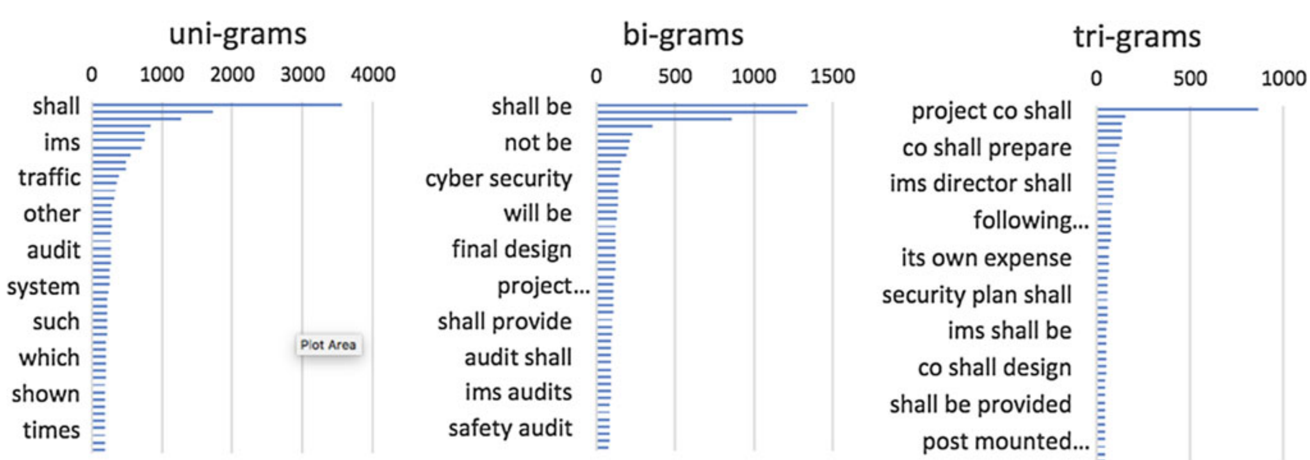

Fig. 68.4 Frequency of top n-grams found in project requirement texts

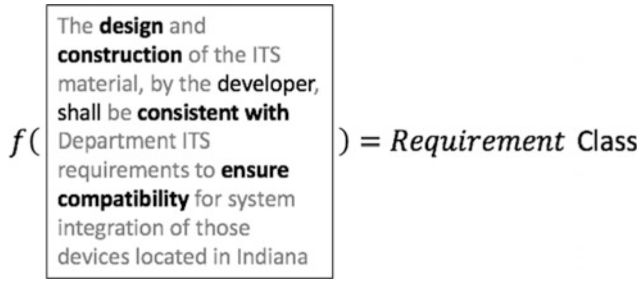

Fig. 68.5 Bag of word method (highlighted words are pre-selected features)

where c is a certain class of the set of classes which includes ‘requirement’ or ‘non-requirement’ in this study, x is a certain selected feature. $P(c)$ is the probability of a text is labeled as class c in the training dataset. $P(x|c)$ is the probability that the text which is labeled as c contains feature x.

68.5.2 Data Collection and Preparation

The goal of this study is to develop a domain-specific classifier for project scope requirement extraction. The training data used in this study were collected from the project description package of a previous project. The research team collaborated with a design-build business partner to develop advanced techniques for construction requirement processing. The industry firm has been creating a large dataset of manually labeled text during their past businesses. They committed to providing us with their historical data to support this research. In this paper, the requirement extraction model was developed on a preliminary data set of 1191 manually labeled statements including 589 requirements and 602 non-requirements using the Naïve Bayes method explained above. The text dataset was randomly split into a training set and a test set with a partition ratio of 7:3. The training set was used to develop the classification model. The test set was for evaluating the model performance. The section below explains the details of the developed model.

68.5.3 Results and Discussions

In order to identify the best prediction model, the classifier was trained using Naïve Bayes with different types of feature selection. Each type of feature yields a corresponding classification model. By comparing the accuracy between those models, an optimal one for project scope requirement extraction will be identified. These three models are [13] uni-grams, [11] uni-grams with stop words removed, and [7] n-grams. For the first model, a feature is a unique word in all the statements of the training dataset. The second model is similar to the first one, but discards all stop words such as ‘a’, ‘an’, ‘the’ which contributes little semantics to a natural language text. The last model considers a feature as an n-gram that is a phrase of n consecutive words. In this experiment, we tested it with n of 3.

Figure 68.6 compares the performance in accuracy between the three models. Accuracy, hereby, is defined as the percentage of correctly classified statements over the total tested statements. The results revealed that all three models achieved an accuracy of over 90% with no significant difference. Of those, the first model that considers individual words as features has an accuracy of 91.49%. This model slightly outperforms the other two models. In addition, the elimination of stop words in this study slightly decreases the accuracy to only 91.17%. This result contradicts with those suggestions found in the state of the art where researchers recommend to eliminate stop words. Finally, the tri-gram model is the one that underperforms its alternatives as the accuracy is just 90.17%.

The reliability of these results, however, still needs more validation analyses. For example, the performance of the system highly varies on the partition ratio between the training and test data. A sensitive analysis that changes the splitting ratio needs to be conducted to verify the difference in accuracy between different models. In addition, the current performance is still sufficient for practical application. A low performance might be due to the size of the dataset. Once a larger dataset is obtained, the performance is expected to be enhanced.

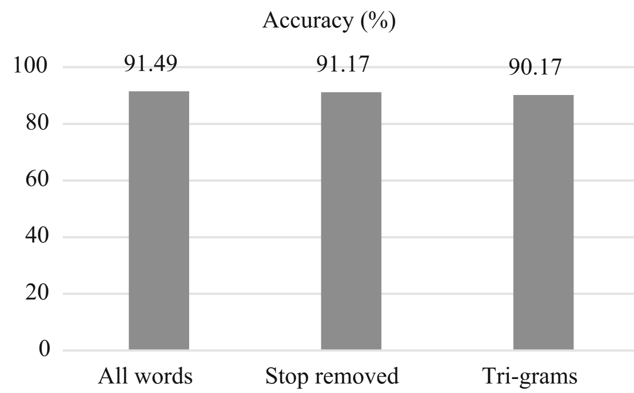

Fig. 68.6 Performance comparison between different feature selection

68.6 Conclusions

Project requirement determination by manually reviewing the project description package is a time consuming, tedious, and error-prone process. This study develops an automated method to requirement text recognition that can be used to support requirement processing. The study employs Naïve Bayes method to train a classification model for distinguishing requirements and non-requirement texts. The models were trained on a preliminary data set of 1191 statements from the contract package of a previous project. Three different models were developed, and their performance was compared. The results indicated that n-gram models underperformed uni-gram model and the removal of stop words has a negative impact on the accuracy. Uni-gram is the best model which achieves an accuracy of 91.49%.

This study has several limitations. First, the model was trained on a limited amount of training data. The research team has successfully secured an award from the college of engineering at Iowa State University that aims to support expanding the dataset. The data collected from this work will be used to enhance the requirement extraction model. Second, despite the fact that the Naïve Bayes method is a famous method for text classification, it is more suitable for small-size datasets. Future research is needed to test other types of machine learning algorithms such as support vector machine, k-mean clustering or random forest. An experiment on performance difference between algorithms will help to identify the best one for this domain-specific data.

This study provides a fundamental tool for automated project scope determination from contract documents. The requirement extraction model will enable the project team to quickly extract important requirements from texts. Since detecting requirements is a prerequisite task, the study will open a new gate for automated requirement processing and project definition evaluation. This helps the project team detect missing or conflicting information timely and consequently avoid project delay, rework, and cost overrun.

References

1. Jallow, A.K., Demian, P., Baldwin, A.N., Anumba, C.: An empirical study of the complexity of requirements management in construction projects. Eng. Constr. Archit. Manage. **21**(5), 505–531 (2014)
2. Jallow, A.K., Demian, P., Anumba, C.J., Baldwin, A.N.: An enterprise architecture framework for electronic requirements information management. Int. J. Inf. Manage. **37**(5), 455–472 (2017)
3. Kamara, J., Anumba, C., and Evbuomwan, N.: Requirements processing: a first step towards client satisfaction. Proceedings of CIB W55 & W65 Joint Triennial Symposium—Customer Satisfaction: A focus for research & practice, Cape Town, 5–10. (1999)
4. Ozkaya, I., Akin, Ö.: Tool support for computer-aided requirement traceability in architectural design: the case of designtrack. Autom. Constr. **16**(5), 674–684 (2007)
5. Kamara, J.M., Anumba, C.J., Evbuomwan, N.F.O.: Client requirements processing in construction: a new approach using qfd. J. Archit. Eng. **5**(1), 8–15 (1999)
6. Shah, U.S., Jinwala, D.C.: Resolving ambiguities in natural language software requirements: a comprehensive survey. SIGSOFT Softw. Eng. Notes **40**(5), 1–7 (2015)

7. Dumont, P.R., Edward Gibson Jr., G., Fish, J.R.: Scope management using project definition rating index. J. Manage. Eng. **13**(5), 54–60 (1997)
8. Cambria, Erik, White, Bruce: Jumping NLP curves: a review of natural language processing research [review article]. Comput. Intell. Mag. IEEE **9**(2), 48–57 (2014)
9. Zhao, H., Kit, C.: Integrating unsupervised and supervised word segmentation: the role of goodness measures. Information Sciences **181**(1), 163–183 (2011)
10. Webster, J.J., Kit, C.: Tokenization as the initial phase in NLP. Paper presented at the Proceedings of the 14th conference on Computational linguistics-Volume 4. (1992)
11. Cunningham, H., Maynard, D., Bontcheva, K., Tablan, V.: GATE: an architecture for development of robust HLT applications. Paper presented at the proceedings of the 40th annual meeting on association for computational linguistics (2002)
12. Toutanova, K., Klein, D., Manning, C.D., Singer, Y.: Feature-rich part-of-speech tagging with a cyclic dependency network. Paper presented at the Proceedings of the 2003 Conference of the North American Chapter of the Association for Computational Linguistics on Human Language Technology-Volume 1. (2003)
13. Costa-Jussa, M.R., Farrús, M., Mariño, J.B., Fonollosa, J.A.: Study and comparison of rule-based and statistical Catalan-Spanish machine translation systems. Comp. Inf. **31**(2), 245–270 (2012)
14. Marcus, M.: New trends in natural language processing: statistical natural language processing. Proc. Natl. Acad. Sci. **92**(22), 10052–10059 (1995)
15. Salama, D.M., El-Gohary, N.M.: Semantic text classification for supporting automated compliance checking in construction. J. Comput. Civil Eng. **30**(1), 04014106 (2016)
16. Zhang, J., El-Gohary, N.M.: Automated information transformation for automated regulatory compliance checking in construction. J. Comput. Civil Eng. **29**(4), B4015001 (2015)
17. Zhang, J., El-Gohary, N.M.: Semantic nlp-based information extraction from construction regulatory documents for automated compliance checking. J. Comput. Civil Eng. **30**(2), 04015014 (2016)
18. Zhou, P., El-Gohary, N.: Ontology-based multilabel text classification of construction regulatory documents. J. Comput. Civil Eng. **30**(4), 04015058 (2015)
19. Zhou, P., El-Gohary, N.: Domain-specific hierarchical text classification for supporting automated environmental compliance checking. J. Comput. Civil Eng. **30**(4), 04015057 (2016)
20. Halpin, D.W., Woodhead, R.W.: Construction Management. Wiley, New York (1998)

69 In Search of Open and Practical Language-Driven BIM-Based Automated Rule Checking Systems

Wawan Solihin, Johannes Dimyadi, and Yong-Cheol Lee

Abstract

Significant progress has been made towards BIM-based automated rule-checking systems. There are multiple approaches that show varying potentials as crucial components for open and practical rule checking systems. However, in the current state, we are not yet quite there as they are still several barriers that prevent the needed shift from proof-of-concept to the real-world implementation. This paper reviews various language-based rule checking systems that have been proposed and assesses their potentials and gaps that need to be overcome for them to become practical. It introduces metrics of eleven criteria to analyze various approaches to assess their readiness for the real-world implementations. The criteria cover a wide range of aspects including language expressiveness, ease of use to define a rule, openness, level of maturity, and performance. These criteria help to identify gaps that currently exist that need to be overcome to allow a leap from a proof-of-concept to the real-world implementation. From the assessment, it is obvious that no one single approach is currently capable of covering the entire spectrum of requirements for automated rule-checking systems. The assessment also shows that the possibilities of combining two or more approaches may accelerate the realization of an open and practical language-driven automated rule checking system.

Keywords

BIM • Automated rule checking • BIMRL • Language-driven rules

69.1 Introduction

The benefits of automated rule-checking systems have been recognized. However, the full benefits of such systems have not been fully realized. It is because of multiple challenges that range from the industry readiness with BIM, a wide-range acceptance of the standards, to the availability of the suitable tool to achieve the purpose. In recent years, many factors that inhibited the practicality of automated rule checking systems (RCS) have been overcome. The industry has been adopting BIM as part of their business practices, IFC standards have become mature enough, many BIM authoring tools are supporting the standards with increasing quality, and several countries have started mandating BIM requirements for the regulatory submission such as Singapore and the UK [1]. Despite all of these, the progress on the automated rule checking systems is still confined largely within the research domain [2]. More recently though, there have been renewed interests to revisit the real-world implementation of automated rule checking systems. This can be seen with such initiatives as the Korean government sponsored KBim project [3], the BuildingSMART Regulatory Room working group to identify

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potentially commercialisable rule checking systems [4], and the most recent RFPs from the Singapore government agencies: Building Construction Authority's (BCA) iGrant, Urban Redevelopment Authority's (URA) Intelligent Code Checking System, Public Utilities Board's (PUB) BIM Checking System. The current issue is that such system still requires high cost to develop. It is our interests to find an open and practical approach towards the system that allows much lower barrier to entry for such systems.

From the published research papers, there are several approaches that have been proposed to solve the challenges of the rule checking systems. At least two ways to classify different approaches have been proposed based on the complexity of implementation [5] and based on the areas of problems they address [6]. No one approach can cover the entire range of components required by a rule checking system. They vary in term of their complexity, performance and the required domain knowledge to define and run the rules. Since a rule checking system requires a way to define rules, it is logical that such a system will be language based. It provides flexibility to deal with wide range of rules and their requirements. This paper focuses on language-based approaches, even though some tools that limit language expressions with their user interface are also considered.

69.2 Review of Language-Based Rule Checking System (RCS)

There is a wide range of rules applicable to building models. Given the extent of rules involved, it is difficult for a single application to provide a general solution to the problem. The language-based approach, if defined well, potentially will provide a platform to allow basic building blocks that can be used to assemble much more complex and varying rules. The richness of the language determines the ease of defining rules but also sacrifice on the generality of the language for less complex and compact rule definitions. In the software world, this type of language is known as Domain Specific Language (DSL). The DSL is an efficient way to deal with specific domain requirements as a mean of making the language expression compact and efficient to address domain requirements. Rule languages for BIM fall generally into the DSL category because it is specific to building information and rules pertaining to buildings. There are two genres of DSL, i.e. an internal DSL and external DSL. The internal DSL "borrows" an existing language as the host language, extend it and adapt it to create a feeling of a particular language. Included in this category are: Lua script used in a commercial application called FORNAX™ to program rules using its C++ based APIs [7], SWRL (Semantic Web Rule Language) that uses series semantic web triplet concept to define a rule [8], SPIN (SPARQL Inferencing Notation) that combines concepts from object-oriented languages, query languages and rule-based systems to define rule and constraint languages that is based on the Semantic Web, and rule-based system such as DROOLS. XML based rule languages, such as mvdXML [9], RuleML, LegalRuleML [10], BPMN [11] also fall into the same category. They have advantages of being part of a larger community and standardized languages that provide a wider range of available tools and resources. However, since the languages may not be designed specifically for BIM, there will be a need to work around, extend or twist the language to fit BIM needs. This often leads to an awkward syntax and extra steps. The external DSL, on the other hand, is usually more concise or compact and feels more natural in defining the BIM-based rules since it is specifically designed and tuned for them. The disadvantage is that it requires its own custom parser and a new syntax that user needs to learn. Languages that fall into the external DSL include QL4BIM [12], BERA [13], KBim that uses meta-programming concept [14], and the authors' own BIM Rule Language (BIMRL) that combines SQL based query language, built-in support for spatial operators and function extension [15]. External DSL also includes visual language such as Dynamo on Revit, Grasshopper on Rhino, Marionette on Vector Works, and VCCL [16].

In addition to the general categories of internal and external DSL, there are other tools that are rather difficult to fit into the above, for example, NLP [17] that uses AI techniques to analyze building rules directly into executable rules, and RASE which uses manual markup into the rule texts and transform the rules into IFC constraint model [18].

With so many proposed approaches, it is difficult to have an overview of how much each approach and tool can satisfy BIM rule checking requirement. The initiative by the building SMART's Regulatory Room to gather such information and assess potential commercial applications of such tools or languages have not identified any tools that are sufficiently complete and ready for the real-world usage [4]. To address this gap, the authors look into various factors that are important in assessing the suitability or readiness of such tools for the potential real-world application. Based on these factors, the metrics with eleven criteria are proposed.

69.3 The Eleven-Criteria Metrics Assessment

The authors develop a set of criteria to help place those approaches and indicate their readiness towards the real-world implementations. The criteria are developed based on the need to have an open standard for rule language, which is capable to deal with complex rule requirements, concepts that fits for real-world implementation, ease of use. These arise from a combination of the real experience developing real-world rule checking system, works in the OpenBIM domain, and research works on RCS. Each of the language or approach will be assigned one of five scores: Low (◯), Moderate (◑), High (●), Not Applicable (▬), or Unknown (◈). While it is not always easy or possible to compare all the languages since there are no common examples for one-to-one comparisons, the authors try their best to use available references or examples to determine the appropriate classifications for each of the languages. One of the sources is from the building SMART's Regulatory Room's project on the automated rule checking, where several of the languages are applied to one building code based on a piece of regulation (article 34.1, Fig. 69.1) in the Korean Building Act providing a good source of comparisons even though not all are presented in a complete form for the rule [4]. It is not the aim of this classification to identify which language is better compares to the others but to show potentials and gaps that will be useful in order to help shift the current status towards a real-world implementation. Using this assessment, the authors hope to encourage further development of the language or to develop a combined research between two or more approaches for one or more practical implementations that the industry could benefit in the immediate future. The assessment is shown in Table 69.1.

The criteria include the following metrics:

1. The formal or standard schema for the rule definition

The existence of standard schema for rule definition is one of the important aspects of openness and standard way to represent a computable form of rules. While there are several rule languages that can be used to define rules in standard computable forms, only LegalRuleML, mvdXML, and RASE that qualified on this measure because they define a standard schema and specific to BIM.

2. Language expressiveness

Language expressiveness is important to assess how capable the language is to define wide-range of rules. Less expressive language will be difficult to use and may become too clumsy when used with complex requirements typically found in building codes. BIMRL that is specifically designed to deal with BIM related rules with minimum programming knowledge needed is highly expressive and compact. The example of BIMRL (partial snippet) for the Korean Building Act is given in Fig. 69.2.

Korean Building Act 34.1* *"Installation of Direct Stairs"

On each floor of a building, direct stairs leading to the shelter floor or the ground (including slope ways; hereinafter the same shall apply) other than the shelter floor (referring to a floor having a doorway leading directly to the ground and the shelter safety zone of a skyscraper under paragraphs (3) and (4); hereinafter the same shall apply) shall be installed in the way that the walking distance from each part of the living room to the stairs (referring to the stair nearest to the living room) is not more than 30 meters: Provided, That in cases of a building of which main structural part (excluding a performance hall, assembly hall, auditorium and exhibition hall which are installed on underground floors and which have a total floor area of not less than 300 square meters) is made of a fireproof structure or non-combustible materials, the walking distance of not more than 50 meters (in cases of multi-unit dwellings higher than 16 storeys, not more than 40 meters) is permitted, and in cases of a factory prescribed by Ordinance of the Ministry of Land, Infrastructure and Transport, which is equipped with automatic fire suppression systems such as sprinklers, in an automated production facility, the walking distance of not more than 75 meters (in cases of unmanned factories, 100 meters) is permitted.

Fig. 69.1 The Korean Building Act 34.1 "Installation of Direct Stairs" [4]

Table 69.1 The eleven-criteria metrics assessment

Language or tool (Legend: ○ Low; ◑ Moderate; ● High; — Not Applicable; ◇? Unknown)	1. Formal or standard schema for the rule definition	2. Language expressiveness	3. Ease of defining rules	4. Minimum logic or programming constructs	5. Minimum domain knowledge required	6. Support for complex rules	7. Integrated geometry engine	8. Performance indication	9. Openness	10. Interface to other languages and systems	11. Level of maturity
NLP	—	—	—	○	○	○	—	◇?	○	○	○
RASE and IFC Constraint Model	○	◑	◑	◑	○	○	—	◇?	●	○	○
LegalDocML and LegalRuleML	●	◑	◑	◑	○	○	—	—	●	○	◑
BPMN	—	◑	◑	○	○	○	—	—	●	—	●
Mvdxml + IfcDoc	●	◑	◑	●	○	○	—	◑	●	○	◑
BIM Assure	—	◑	●	●	●	○	—	●	○	○	◑
QL4BIM	—	◑	◑	◑	○	○	◑	◑	●	○	○
BERA + BOM	—	◑	◑	◑	◑	◑	○	◑	◑	○	○
KBim	—	◑	○	○	○	◑	○	◇?	○	○	○
BIMRL	—	●	●	●	●	◑	◑	●	●	◑	◑
DROOLS	—	◑	◑	◑	○	○	—	◑	◑	●	●
Rule Table	—	○	●	●	○	○	—	◇?	◑	○	●
Prolog	—	○	○	○	○	◑	—	◇?	◇?	○	◑
SWRL + IfcOWL	—	◑	○	○	○	○	—	◑	●	◑	●
SPARQL and SPIN + IfcOWL	—	◑	○	○	○	○	—	◑	●	◑	●
Revit Model Review	—	○	◑	●	○	○	—	◑	○	○	◑
Dynamo + Revit	—	○	●	◑	○	◑	◑	◑	◑	○	●
Grasshopper + Rhino	—	○	●	◑	○	◑	◑	◑	○	○	●
Marionette + VectorWorks	—	○	●	◑	○	◑	◑	◑	○	○	●
VCCL	—	○	◑	○	○	○	—	◇?	○	○	○
FORNAX Lua scripting	—	○	○	○	◑	●	●	●	○	○	●
[a] Solibri Model Checker (SMC)	—	—	—	—	◑	◑	●	●	—	—	●

[a] *SMC is included here due its popularity even though it is not strictly language-based rule checking system*

3. The level of ease to define rules

A language should be ideally easy and intuitive to define building rules. The different tool will have a different level of difficulty. While a certain level of complexity will be expected for complex rules, it helps if the language is consistent no matter whether it is a simple rule or a complex one. An example that allows easy definition of rules is given below for a commercial application BIM Assure that is UI driven. This makes it very easy for typical users to define any rules, albeit restricted to certain types of rules that work on explicit properties and relationships. In this category, most of UI-driven language score well, but not all are given full High mark due to their generic language styles that require a lot more programming type of definition to achieve the same impact.

```
CHECK
{ ifcspace s, ifcdoor d
   WHERE property(s,HabitableSpace)='TRUE'
and classificationof(d).classificationitemcode='2.6.2'
and classificationof(d).classificationname='BCIS'
and s.container=d.container
   COLLECT s.elementid spaceid, d.elementid doorid, s.name spacenumber;
} AS SET1;
{ IfcSpace SC
   Where CONTAINS(SC,USEGEOMETRY).ElementType='IFCFLOWTERMINAL'
and CONTAINS(SC,USEGEOMETRY).Name like 'Sprinkler%'
   COLLECT SC.ElementId SPACEID, SC.Name SPACENUMBER,
SC.LongName SPACELNAME, COUNT(unique CO.ElementID) SPRINKLERNO
   GROUP BY SC.ELementId, SC.Name, SC.LongName
} AS SET2;
EVALUATE computePathAndDistance(spaceid, doorid) output ?traveldistance
From SET1 LEFT OUTER JOIN SET2 USING (SPACEID, SPACENUMBER);
ACTION
   WHEN ?traveldistance>30000 and
NOT (?BuildingClassification='En_30_50_50'
and (?SprinklerProtectedAuto ='yes'
OR ?ProtBySprinklerSystem>0
OR SPRINKLERNO>100))
OR NOT ((?NonCombustibleCnt/?MainStructCnt)>0.8
OR ?FireProtectionClass='FireProof')
   { … }
```

Fig. 69.2 A rule snippet in BIMRL for the Korean Building Act 34.1 [4]

```
rule "KOREAN-0-1-0-OUTSCOPE" salience 75 when
   exists Applicability(id=="KOREAN-0-1",applicable==true)
   not Building(fireproof==true||made_of_fireproof_materials==true) from
bim.fetch("Building")
   not Building(fireproof==null || made_of_fireproof_materials==null) from
bim.fetch("Building")
   then results.na("KOREAN-0-1-0"); end

rule "KOREAN-0-1-0-FAIL" salience 0 when
   Applicability(id=="KOREAN-0-1",applicable==true)
   not Result(id=="KOREAN-0-1-0")
   exists Floor(walking_distance_from_living_room_to_stairs>50) from
bim.fetch("Floor")
   not Floor(walking_distance_from_living_room_to_stairs==null) from
bim.fetch("Floor")
   then results.fail("KOREAN-0-1-0"); end
```

Fig. 69.3 A rule for the Korean Building Act 34.1 written in DROOLS [4]

4. Little or low requirements for logic or programming constructs

Due to the wide range of complexity of BIM rules, it is inevitable that some level of programming or logic will be needed to encapsulate complex rule requirements. These criteria assess the level of dependency on programming constructs. Generally, the lower level of language allow flexibility to write complex rules but at the expense of general accessibility to non-programmers. Higher level language will be easier to be understood, but usually hard to deal with complex rules. An example of such rule written using DROOLS rule engine is given in Fig. 69.3. Combination of the two may be desirable to address this issue, but the language must have built-in capability to support this. The possibility of language extension such as through plugin mechanism may provide the much-needed support. Tools such as FORNAX™ Lua based script has been shown to be able to deal with complex building codes, but it requires specialized skill in Lua programming to do this.

```
<Rules>
  <AttributeRule RuleID="PredefinedType" AttributeName="PredefinedType" />
    <AttributeRule AttributeName="IsNestedBy">
      <EntityRules>
        <EntityRule EntityName="IfcRelNests">
          <AttributeRules>
            <AttributeRule AttributeName="RelatedObjects">
        <EntityRules>
          <EntityRule EntityName="IfcDistributionPort">
            <AttributeRules>
              <AttributeRule RuleID="Name" Description="The name of the port."
AttributeName="Name">
         <EntityRules>
           <EntityRule EntityName="IfcLabel" />
         </EntityRules>
           </AttributeRule>
             <AttributeRule RuleID="Flow" Description="The flow direction of
the port." AttributeName="FlowDirection">
         <EntityRules>
           <EntityRule EntityName="IfcFlowDirectionEnum" />
         </EntityRules>
           </AttributeRule>
            <AttributeRule   RuleID="Type"   AttributeName="SystemType   <Enti-
tyRules>
```

Fig. 69.4 An example of the mvdXML rule [9]

5. Little or low level of domain knowledge required

This assesses how much expertise and specific domain knowledge a user would need to be able to use the language or system to define rules. Since the rule is BIM specific, most of the languages require intimate knowledge of building domain and building codes. The Medium rating is given only to those that simplify IFC. Only BIM Assure that provides pre-mapped categories and UI guided rule definition. Figure 69.4 shows part of the mvdXML rule. Since it is tightly linked to IFC, the intimate knowledge of IFC is a must. All rules using mvdXML operate within IFC model and its entities.

6. Support for complex rules

Complex rules typically involve geometry and spatial operations. In this measure, most of the languages are given Low since they mostly do not support integrated geometry and spatially related rules. Only FORNAX™ with its comprehensive API with integrated support of geometry and spatial operations is given a High rating. The example of Lua scripting in FORNAX™ is given in Fig. 69.5. The visual programming tools are given only Medium because they do not have direct support for spatial operations and higher semantics knowledge required in complex building codes. Most of the other languages will require programming extension to support such requirements.

7. Integrated geometry/spatial engine

In many BIM-based rules, there are many rules that require geometry and spatial reasoning to perform rule checks. Therefore, it is critical to have access to such geometry engine. Ideally, this should be fully integrated that allows a single coherent language can be used to perform queries and check in one integrated manner. This topic has not been very well researched, probably because it involves rather complex requirements when dealing with geometry. Only QL4BIM and BIMRL are known to consider spatial queries to be integrated into the language. Product specific visual language such as Dynamo, Grasshopper, and Marionette are capable to work on geometry too, but not a complete set of spatial operations.

8. Performance indication

What is the performance indication of the system to execute various rules? The authors are unable to collect all the necessary performance indicator of some of the languages. They are left with a question mark. In this measure commercial languages such as FORNAX™ Lua and BIM Assure perform best as they are designed to perform. The only one that is also designed for efficient query and checking is BIMRL.

```
function checkfunction(storey) -- common codes for GFA function
   FXGFA.DebugMsg("__| BuildingStorey ".. storey:GetAttri("Name") .." |__")
   ParseObjectGroup(storey)
   local elevationStorey = storey:Elevation();
   local grpCoverElement = FXGroup.new()
   for key, value in pairs(tblCoverElement) do
      grpCoverElement = grpCoverElement + value
   end
   local grpElementType = FXGroup.new()
   for key,value in pairs(tblElementType) do
      grpElementType = grpElementType + value
   end
--[[GFA 7.30.5 Gondola platform at roof top]]
   local  FinalPrj  =  FXGFA.GondolaPlatformAtRoofTop(storey,  elevationStorey,
grpCoverElement, grpElementType);
   if isIncluded == true then
      FXGFA.IntegrateGFA(storey, FinalPrj, elevationStorey, msg)
   else
      FXGFA.IntegrateNonGFA(storey, FinalPrj, elevationStorey, msg)
   end
end
```

Fig. 69.5 FORNAX™ Lua scripting example for gross floor area computations

9. Openness

The issue of openness of the language or tool is an important factor that allows utilization of available tools, ready knowledge available, and some assurance for longevity because the specifications are open.

10. Interface to other languages and systems

Ability to interface to other languages and systems will be crucial to enable much more complex or complete solution for the building rules from the definition, to the runtime of the rule execution. This also helps to complement the tool with other tools that may be addressing the more specific problem instead of a single or monolithic approach to the BIM rules. Open sourced rule engine such as DROOLS allows interfaces to other Java-based tools.

11. Level of maturity

The level of maturity is measured by how long the language has been introduced, how widely it is used, how actively it is maintained, and how many implementations that have been done with it. which include how recent the language or system is developed or maintained, whether it has been adopted into a real system, and the scope.

69.4 Conclusions

The ideal language should be rated high in all the criteria. Based on the assessment, none of the languages fulfill that. There are several promising languages or systems have emerged such as BIMRL, DROOLS rule engine, and on the commercial side FORNAX™ Lua scripting, which has the most mature implementation and supports complex rules. They still need to have the ability to support standard rule specifications. This may be achieved by supporting specification language such as LegalRuleML. The visual programming languages also show a lot of potentials, even though currently are mainly supported within proprietary native systems. Adoption of the visual programming language into already strong implementations may offer very promising user-friendly RCS.

The widest gap seems to be in the area of geometry and spatial support, and integration with other systems. Most languages treat the rule specifications, rule execution, and the data to be distinct and in a neatly separated compartment and hence hardly any that integrate the geometry and spatial into the language. This assumption is largely limiting since in many building codes the rule specifications often interdependent with the logic of checking and the data. BIMRL and QL4BIM offer such support, but to be able to support truly complex rules, they may need to be augmented with procedural languages such as C++, C#, Lua, or Java. BIMRL is designed to work with plugin concept and integration of the plugin into the language as an extension in a similar manner to a stored procedure in the relational database world.

The authors hope that this study helps to identify the priority and a more focused approach for BIM-based rule development and by not reinventing the wheels. By extending the already promising language and combining with other language(s), the result will be closer to the ideal rule language for BIM and therefore making the BIM automated RCS closer to its practical availability and its full potential to help the AECO industry. To bring BIMRL closer to the ideal language, we intend to enhance it by incorporating a visual programming language, a formal rule specification such as LegalRuleML, and possibly with a more powerful engine such as FORNAX™ Lua.

References

1. BCA: All set for 2015: The BIM Roadmap. Build Smart Magazine, no. 9, p. 4 (2011)
2. Dimyadi, J., Amor, R.: Automated building code compliance checking—where is it at? CIB WBC **2013**, 172–185 (2013)
3. Kim, I.: Automated building code checking related activities in Korea (2015). Online at http://iug.buildingsmart.org/resources/London/Regulatory%20Room/korea_automated-building-code-checking-related-activities-in-korea_khu
4. bSI Regulatory Room WG: Report on open standards for regulations, requirements and recommendations content (2017)
5. Solihin, W., Eastman, C.: Classification of rules for automated BIM rule checking development. Autom. Constr. **53**, 69–82 (2015)
6. Dimyadi, J., Solihin, W.: Editorial: CIB W78 special track on compliance checking. J. Inf. Technol. Constr. **21**, 315–316 (2016)
7. NovaCityNets: FORNAX (2016). http://www.novacitynets.com/fornax/index.htm
8. W3C: SWRL: a semantic web rule language—combining OWL and RuleML. W3C (2004). Online at http://www.w3.org/Submission/SWRL/
9. Chipman, L.T., Wiese, T.: mvdXML, Build. Model Support Gr (2013). no http://www.buildingsmart-org/downloads/accompanying-documents/formats/mvdxml-documentation/mvdxml-schema-documentation-v1-1-draft
10. LegalRuleML_TC: LegalRuleML. OASIS (2012), https://lists.oasis-open.org/archives/legalruleml/201208/msg00040/LegalRuleML-palmirani2012_-RuleML2012v3.pdf
11. Dimyadi, J., Solihin, W., Eastman, C., Amor, R.: Integrating the BIM rule language into compliant design audit processes. In CBI W78 2016 (33rd CIB International Conference on IT in Construction) (2016)
12. Daum, S., Borrmann, A.: Checking spatio-semantic consistency of building information models by means of a query language. In Proceedings of the International Conference on Construction Applications of Virtual Reality (2013)
13. Lee, J.K.: Building environment rule and analysis (BERA) language and its application for evaluating building circulation and spatial program. Georgia Institute of Technology (2011)
14. Park, S., Lee, Y.-C., Lee, J.-K.: Definition of a domain-specific language for Korean building act sentences as an explicit computable form. J. Inf. Technol. Constr. **21**(26), 422–433 (2016)
15. Solihin, W.: A simplified BIM data representation using a relational database schema for an efficient rule checking system and its associated rule checking language. Georgia Institute of Technology (2015)
16. Preidel, C., Daum, S., Borrmann, A.: Data retrieval from building information models based on visual programming. Vis. Eng. **5**, 18 (2017)
17. Zhang, J., El-Gohary, N.M.: Integrating semantic NLP and logic reasoning into a unified system for fully-automated code checking. Autom. Constr. (2016)
18. Hjelseth, E., Nisbet, N.: Capturing normative constraints by use of the semantic mark-up (RASE) methodology. In CIB W78 2011 28th International Conference-Applications of IT in the AEC Industry (2011)

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70 Image-Based Localization for Facilitating Construction Field Reporting on Mobile Devices

Youyi Feng and Mani Golparvar-Fard

Abstract

Current studies reveal the exceptional advantages of high-efficiency onsite information management for facilitating the design/building progress of construction projects. In particular, the prevailing methods of construction field reporting still primarily rely on manual on-site documentation of project information. Fortunately, state of the art computerized technologies provides solutions with great potential for boosting the efficiency of gathering and managing on-site information for field reporting. Providing on-demand access to such information in real-time requires an autonomous method for localizing and tracking (i.e. calculating the position and orientation) of a construction filed reporter on job site. This, in fact, will reduce both working time and efforts for providing on-demand access to project information. Mobile devices such as smartphones/tablets can be utilized to enable the on-site personnel to manage the project information in a portable fashion while adopting cloud technology for instant online access. In this paper, we proposed a method for on-site localization that can estimate and track the position and orientation of a hand-held device in a near real-time manner. The developed method is infrastructure-independent and marker-less. The proposed method mainly consists of mapping, localization and alignment modules. Initially, a video stream is acquired using the built-in camera of the mobile device scanning the target building. A 3D point cloud is then reconstructed from the acquired video data. Afterward, the localization algorithm outputs the location/orientation of the queried images using feature-based matching with the base 3D point cloud map generated earlier. Finally, global localization of frames is estimated by using the alignment parameters of the 3D point cloud with a Geo-referenced BIM model to transform the localized frames to the global reference. The proposed solution enables the field reporter to access, retrieve, save and edit the project information more efficiently on the construction site.

Keywords

Field reporting • Localization • SLAM • Point cloud • BIM

70.1 Introduction

Recent research efforts have been focused on improving information management on construction sites to provide on-demand access to project information and facilitate field reporting, whereas the prevailing methods of construction field reporting still primarily rely on written documents where the on-site field reporters need to manually record and update project information. During this process, field reporters have to carry large stacks of specifications and drawings with them which is usually inconvenient. Advances in computer vision techniques, as well as the hardware of mobile devices, actualized the idea of boosting the efficiency of gathering and managing project information on construction sites for facilitating the process of field reporting.

The fact that construction field reports are location-based makes it important to devise automated systems for localizing and tracking position/orientation of construction facilities/personnel on a job-site. Such system will reduce both working

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time and resources required for providing on-demand access to project information. With the rapid development of the computational power of portable handheld devices as well as computer vision-based techniques, mobile devices such as smartphones, tablets have created an unprecedented opportunity to enhance both the performance and efficiency of the current practice of construction field reporting especially while utilizing cloud-computing technology.

70.2 Background

Recent research efforts for improving accuracy and efficiency of construction fielding reporting have primarily focused on developing mobile Augmented Reality (AR) techniques to provide on-demand access to project information. However, to generate such a prompt and accurate field report, precisely tracking the position and orientation of onsite facilities as well as the field reporter himself on a construction job site is a crucial procedure [1, 2].

Prior research work reveals that the primarily applied localization approaches can be divided into four different categories based on the techniques used for estimating the pose: (i) sensor-based localization, where the user's position is tracked by using wireless local network (WLAN), GPS, and/or other sensors such as gyroscope, magnetometer sensors; (ii) fiduciary marker-based localization, where the user's location/orientation is determined by using predefined/preinstalled optical fiduciary markers; (iii) model-based localization, in this method, prior information (pre-built 3D point cloud of the physical world) is used to identify the user's relative location and orientation. (iv) Visual Simultaneous Localization and Mapping (Visual SLAM), algorithms for tracking and mapping visual features from images/videos to compute the user's location information.

Although the approaches stated above have the potential to provide fast location information to field personnel, they still have their drawbacks. Firstly, sensor-based methods, which uses RF-based (Radio Frequency) location tracking techniques, e.g. GPS and WLAN. They actually heavily rely on pre-installed infrastructures, such as wireless access points and GPS satellite receivers, yet under the complex and congested construction environment, GPS sensors sometimes are not reliable due to weak or lost satellite signals (especially when the construction sites are located in a dense urban area). Secondly, place fiduciary makers and applying quick response (QR) codes can interpret location information of mobile devices. This type of marker-based method does not depend on any network/infrastructure pre-installation or any mobile sensors. It is free of mobile data noise/accumulated-error-draft and works well in both indoor and outdoor environments, yet the field workers have to attach visual markers on each interested construction object. Tagging hundreds or even thousands of objects with 2D visual markers is quite a time-consuming procedure, which renders this application often impractical on complex construction sites. The Model-based method suffers from accumulated drift errors, requires pre-reconstruction of the 3D point cloud model of the physical world, and does not typically scale well [3].

70.3 Related Work

The fast innovation and development of computer vision techniques over the past decade have led to new research on the application of image-based localization methods for marker-less mobile systems. Some researchers have focused on visual SLAM (Simultaneous Localization and Mapping) for mobile systems by using parallel threads of tracking and mapping.

SLAM was originally proposed by Durrant-Whyte and Leonard [4] based on the earlier work of Smith et al. [5]. It solves the problem of generating and updating 3D maps of an indoor/outdoor environment while simultaneously tracking the location of the users within the environment. SLAM is a localization approach that tracks the spatial position and orientation of the agent with respect to its surroundings rather than one particular algorithm [6]. While doing location tracking, it constructs 3D maps (point cloud) through triangulating the detected features from the images of the environment.

Most modern simultaneous localization and mapping systems are based on tracking a set of visual features detected in image frames acquired from video cameras. Then, those tracked feature points can be utilized to triangulate the spatial position and at the same time, the estimated point locations can also be used to compute the camera orientations (spatial pose) within that observed environment. Even with a single camera sensor, by combining the measurements and tracking different feature points over multiple keyframes, it still has the capability to recover camera pose and position with high accuracy.

In this paper, we implemented a vision-based localization solution that can localize and track the position and orientation of handheld users on construction job sites in a near real-time manner on mobile devices. The approach does not call for any pre-installed fiduciary markers. It mainly includes 3D point cloud map generation, image-based localization, and alignment of point cloud with BIM model procedures. All these computing procedures are implemented and running on a remote server. Initially, a video will be acquired using the built-in camera of a mobile device by scanning around the job site by an on-site worker. Next, 3D point cloud map of the job site is to be generated from the acquired video stream by executing the mapping process. At the same time, localization process will also be executed by tracking the query image frame received from the end user. Afterward, the server will send the location/orientation results against the 3D map back to the end user. Finally, users can also align the 3D point cloud maps with their BIM models remotely on the user client for retrieving global location information as well as facilitating the identification, processing, and communication of discrepancies between actual and expected construction performances for project managers.

70.4 Problem Statement and Objective

Efficiently and accurately localizing and tracking position/orientation of onsite personnel will reduce both working time and efforts for providing on-demand access to project information. SLAM algorithm has significant potential to achieve onsite localization and tracking goals with high performance and fewer prerequisites (compared with GPS, fiduciary marker-based, model-based methods). Due to the availability of inexpensive, high-resolution and "point-and-shoot" cameras on mobile devices, it provides a rich source of information pertaining to construction facilities (images, videos, and aerial photos etc.) and makes it possible to apply SLAM on construction sites. This paper aims to identify the feasibility as well as test the performance and efficiency of applying the SLAM-based method to the task of tracking and localizing handheld users for construction field reporting on mobile devices.

70.5 Implementation and System Description

70.5.1 ORBSLAM-Based Localization System

In this research, an image-based localization prototype based on ORBSLAM algorithm [7–9] was developed with a client-server structure. It includes a mobile client designed on Android platform, an HTML-based (web viewer-based) client (this client has platform independence, it can be utilized on any device (e.g. IOS, Android, Windows phone and desktop etc.) that has a web browser) and a remote Linux server.

The principle of the localization system is illustrated in the flowchart as shown in Fig. 70.1. Firstly, end users can take photos/videos or select existing images/videos on the client and upload them to the server. Next, the server processes received image frames and generate a local 3D point cloud map by executing the mapping procedure. Afterward, the user can send query images (either real-time captured or stored on the mobile device) to the server. Then, the server localizes the query images against the 3D map. Moreover, users can align the 3D point cloud with BIM model by simply selecting at least 4 couples of corresponding points from the point cloud and BIM models on the client. Once alignment completes, the server sends the transformed global location information (aligned with BIM model) back to the client users.

70.5.2 Improved Mapping and Localization System

In order to apply the approach to facilitate the process of field reporting, the field reporters (end users) should not only be able to map the site on a specified time manner (daily, weekly, it actually depends on the construction progress), but also be able to localize themselves at any time, any location when doing field reporting. However, the SLAM method does the localization simultaneously with mapping by using successive image frames, yet it is not capable of doing post-localization. Therefore, the original SLAM algorithm does not fulfill the requirement of conducting field reporting on construction sites.

To overcome this drawback, we proposed an improved ORBSLAM-based mapping and localization system that has a client-server structure. This structure is designed to enable the field reporters (end users) to get quick (near real-time) response from the server whenever they send a query frame from the client.

The improved localization system includes a mobile client designed on Android platform, an HTML-based client and a remote Linux server, when the client connected with Wi-Fi or local server network, the users can do onsite video recording by using built-in camera of their mobile devices. Mapping process can be done once the video collection completes. The generated 3D point cloud maps then can be stored on the remote server. Once the users take new query images and send them to the server, the localization system will immediately get them localized and send the location information back to the users. Figure 70.2 shows the user client on Android platform of the improved localization system.

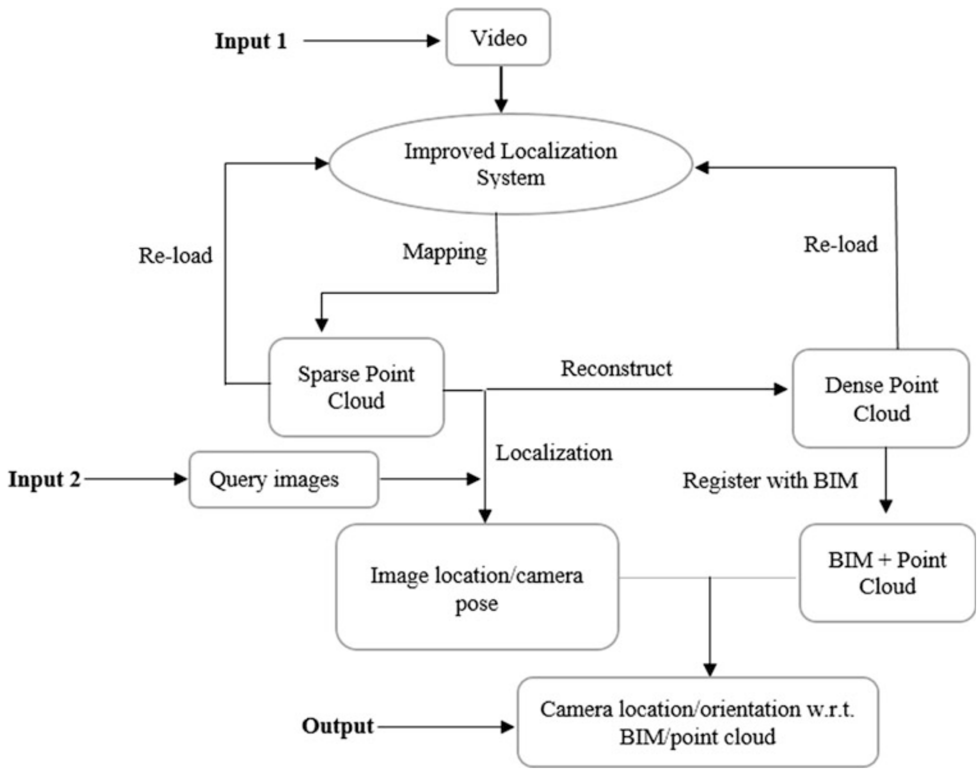

Fig. 70.1 Flowchart of mapping and localization prototype

70.6 Case Study

70.6.1 Data Collection

The data used in this study was collected in the Newmark Civil Engineering Lab (NCEL) at the University of Illinois at Urbana-Champaign. A 1 min 52 s video and ground truths were collected. The images in Fig. 70.3 show the scenes of NCEL.

70.6.2 Ground Truth

Ground truth data in this experiment was collected by the Google Project Tango tablet. It has motion tracking and area learning functions that enable users to track the device's position and orientation within a detailed 3D environment. The reason why we use Tango to generate the ground truth data is that the absolute ground truth for the NCEL dataset is unattainable. Furthermore, based on the performance evaluation of Project Tango conducted by Roberto et al. in 2016, for indoor scenarios, the Tango's precision of motion tracking is within 2 cm at a 95% confidence level [10]. According to their results, we can utilize the motion tracking data produced by the Tango as a reference to help evaluate the accuracy performance of our proposed localization solution.

In Fig. 70.4, the blue lines are the recorded 3D trajectories of the device. And the 3D point cloud data was generated by exporting points from the 3D mesh model reconstructed by the Project Tango.

70.6.3 Data Testing

To process the collected data, the recorded video was first input into the algorithm and processed on the server. After specified the settings, the algorithm processed the video data at a 10fps rate. As shown in Fig. 70.5, the green grids in the left picture are visual features that were real-time detected and tracked in each image frame. On the right side, the blue triangles

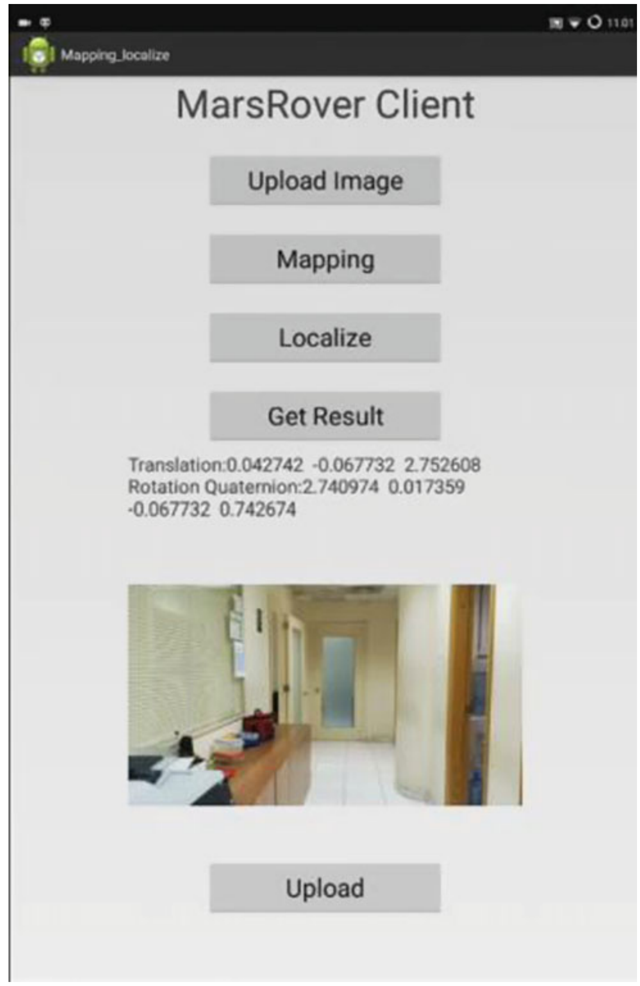

Fig. 70.2 Android client of the improved localization system

are the calculated poses of the device. Also, the generated 3D sparse point cloud is shown in the right window (red points of the point cloud were triangulated by using visual features within the current image frame, while the black points were generated without using the features in the current image frame).

Since the localization results are calculated against the 3D point cloud generated during mapping process and it is based on local coordinate system (not in real-world scale). Therefore, an improved localization system was developed, in the system, we implemented the interface for aligning 3D point cloud maps with BIM or 3D mesh models by manually selecting 4 couples of corresponding points on the web-based client. After the alignment of 3D point cloud maps and the BIM or 3D mesh models, the location information was transformed to the model-referred coordinate system and would be sent back to the end users.

70.6.4 Experimental Results and Accuracy Evaluation

After the SLAM process, a set of 30 image frames was down-sampled from the NCEL dataset to evaluate the accuracy of the localization system. Spatial location of the camera device can be represented by its 3D trajectory, in which 3D position and spatial orientation are represented by (Xi, Yi, Zi) coordinates and (q1, q2, q3, q4) quaternions respectively. In order to evaluate the accuracy of the localization results in the experiment, we need to compare the 3D position and orientation separately with the ground truths.

For evaluating 3D position accuracy, location errors are considered as the spatial distances of the corresponding points between the experimental results and ground truths. Three-dimensional distances can be calculated by $D_i = \sqrt{(Xi - Gxi)^2 + (Yi - Gyi)^2 + (Zi - Gzi)^2}$, where Xi, Yi, and Zi are the 3D spatial coordinates of the experimental results, while Gxi, Gyi, and Gzi are 3D spatial coordinates from the ground truth data.

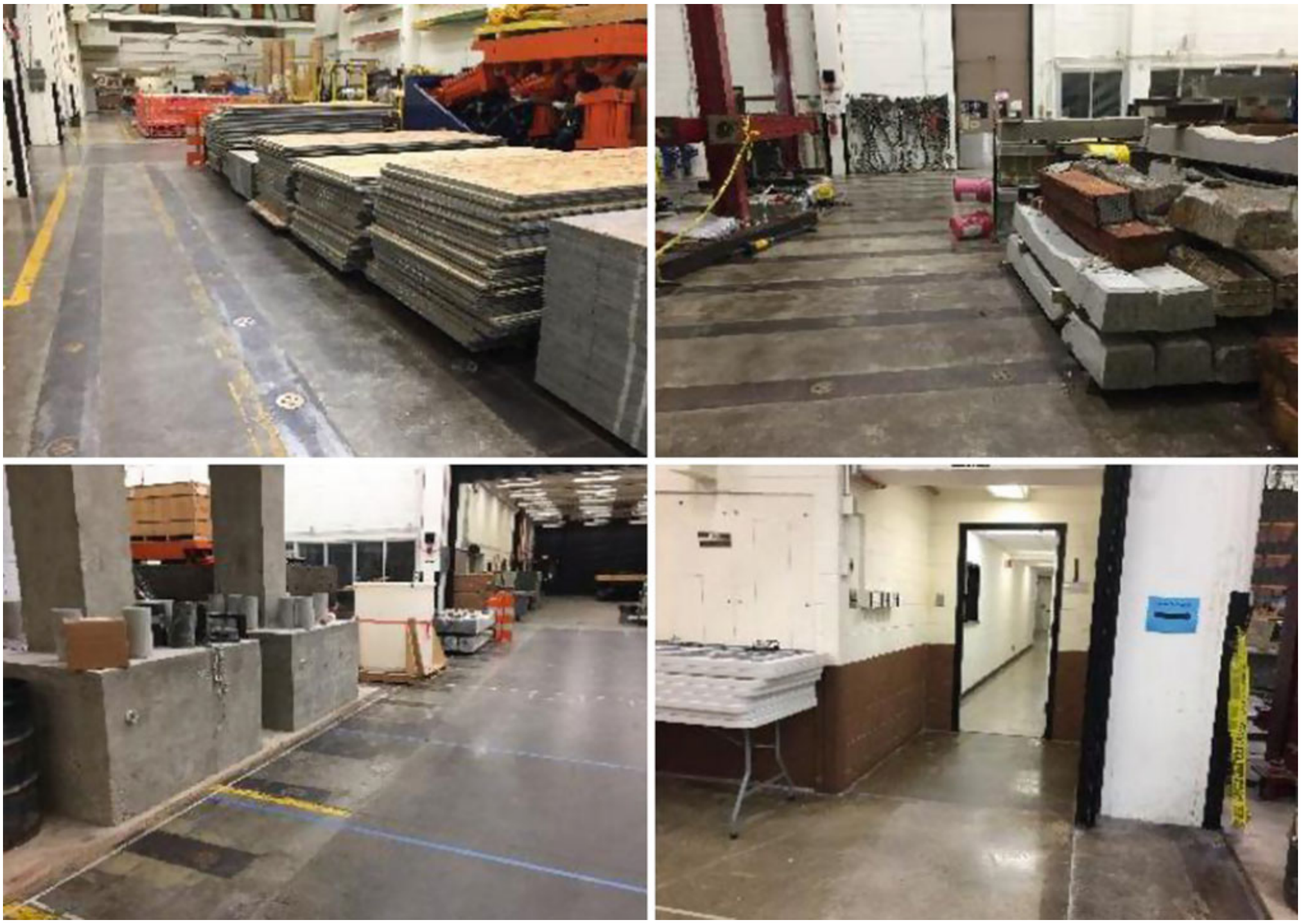

Fig. 70.3 Newmark civil engineering lab (NCEL) site

We calculated the Root Mean Square Error (RMSE) and standard deviation (STD) of the spatial distances for the experimental results by using the equations below.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} Di^2}{n}}$$

$$\mathrm{STD_s} = \sqrt{\frac{\sum_{i=1}^{n} (Di - \bar{D})^2}{n-1}}$$

(Here, n is the number of tested image frames, it is 30 in the experiment. STDs is the sample standard deviation).

To evaluate the accuracy of spatial orientation, we need to compare the quaternion matrices between the experimental results and the ground truths. The angle between two quaternions can be used to measure the differences in spatial orientation. When the angle ɵ between two quaternions is zero (in which case, there is cos(ɵ) = 1), which means the two quaternions are oriented in the same direction. Therefore, the Mean Absolute Percentage Error (MAPE) of the angle of corresponding quaternions between the experimental results and ground truths can be calculated by the equation below.

$$\mathrm{MAPE} = \frac{100\%}{n} \sum_{i=1}^{n} \left| \cos\left(\frac{\mathrm{Qti} \cdot Qgi}{|Q\mathrm{ti}| \cdot |Qgi|} \right) - 1 \right|$$

(Qti is the quaternion matrix from experimental results, and Qgi is the quaternion matrix from ground truths).

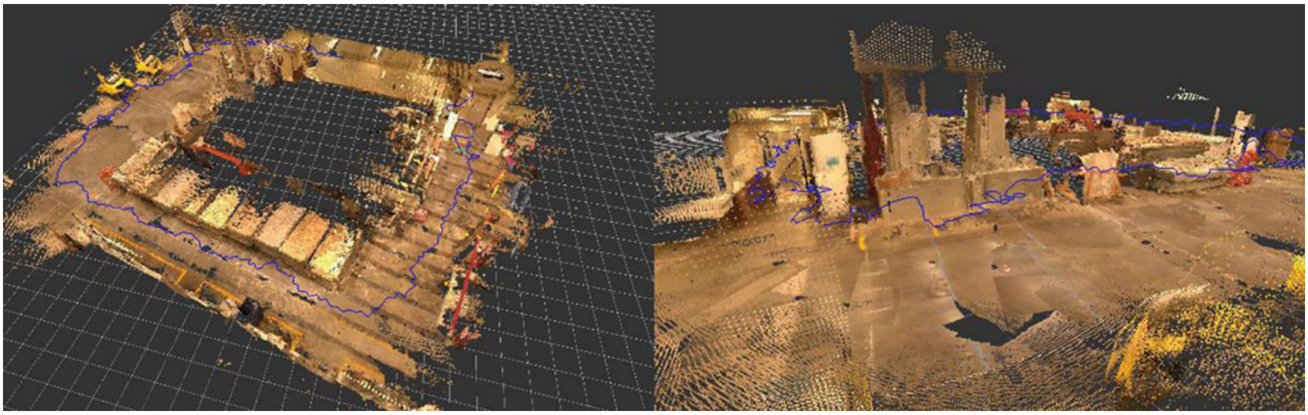

Fig. 70.4 Ground truth data of NCEL dataset

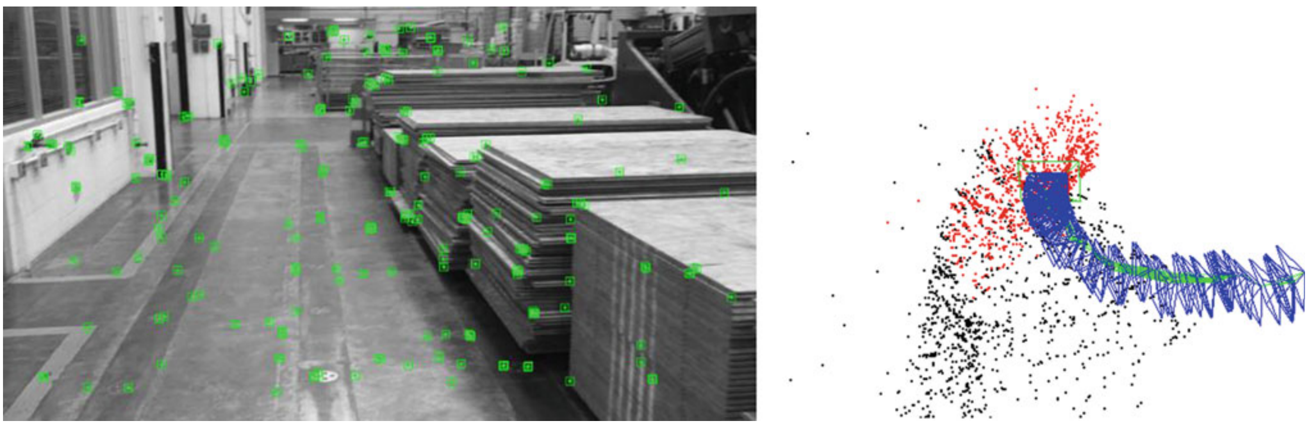

Fig. 70.5 Data testing of the localization system

In the experiment, the root mean square error of 3D position was calculated to be 0.03274 m, while the standard deviation is 0.00882 m for the testing dataset. For spatial orientation, the mean absolute percentage error is 0.001348, which is 0.1348% for the tested orientation results.

From the above calculation, we can see that the accuracy performance of the 3D position results is around 3.27 cm for the localization. According to the evaluation on Project Tango conducted by Roberto et al., we can claim that the proposed localization system can achieve a 3.27 ± 2 cm precision performance for indoor real-world scenarios. The spatial orientation results have a 0.1348% error, in which we used cos(ɵ) as the observations of spatial orientation to compare experimental data with ground truths. Through the accuracy evaluation in our laboratory, it reveals that the proposed localization solution in this study holds a great potential for construction onsite workers to help them get quick and highly accurate location information.

70.6.5 System Efficiency

The system localization running time was also recorded and shown in Fig. 70.6. The average processing time is around 1.071 s, which is in a near real-time manner.

70.7 Conclusion and Future Work

A mapping and localization solution with a client-server structure was proposed in this paper. It includes a mobile client designed as a smartphone application, a web-based client, and a remote computing server. A case study was conducted to evaluate the accuracy and efficiency performance of the proposed solution. According to the evaluation results, the solution

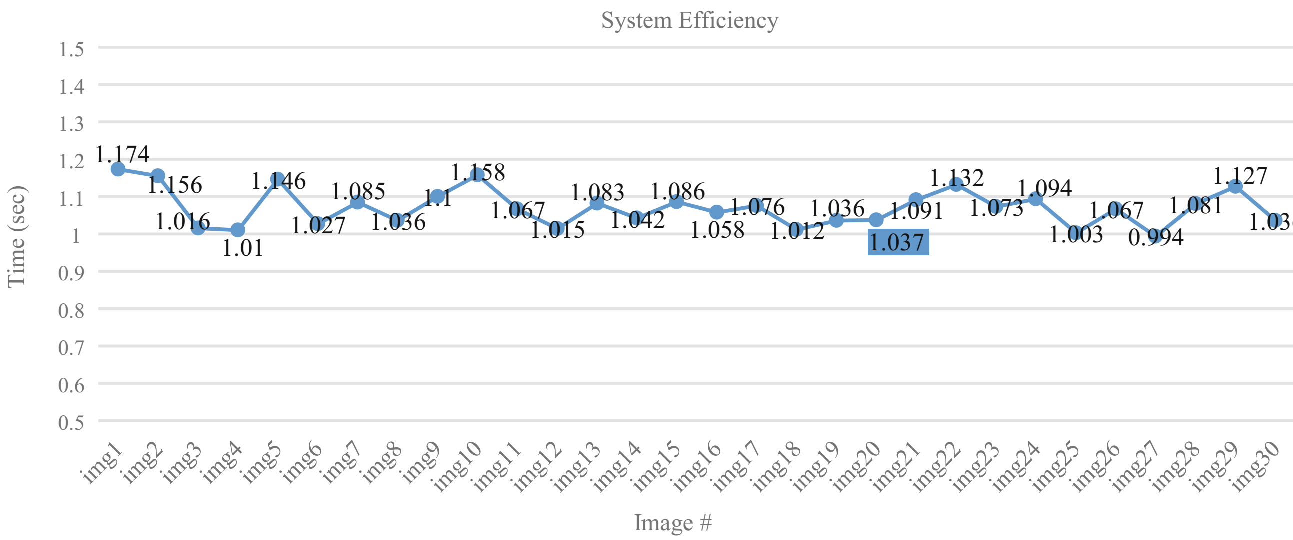

Fig. 70.6 System running time

proposed is potential to be applied to help construction field workers to obtain location information in near real-time. It will help to boost the efficiency of location-based tasks on construction sites, such as field reporting and progress monitoring.

The proposed solution still has some limitations that call for further research. Despite the fact that the system achieved near real-time localization, the mapping process is executed on the server side which means that the server has to wait till the users complete video recording and uploading processes that actually decreases the efficiency of the system. Also, approaches for updating 3D maps that are needed for tracking changes in dynamic construction environment were not discussed in this work. Furthermore, since the system is in a client-server structure, both the server and the user client need to connect to a wireless network (Wi-Fi, LTE, etc.). In future work, the authors will further evaluate the performance of the system and obtain feasible approaches to reduce the accumulated drift error produced during the localization procedures.

References

1. Golparvar-Fard, M., Peña-Mora, F., Savarese, S.: Application of D4AR—A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication. ITcon **14**, 129–153 (2009)
2. Golparvar-Fard, M., Peña-Mora, F., Savarese, S.: Integrated sequential as-built and as-planned representation with D4AR tools in support of decision-making tasks in the AEC/FM industry. J. Constr. Eng. Manage. **137**, 1099–1116 (2011)
3. Bae, H., Golparvar-Fard, M., White, J.: Image-based localization and content authoring in structure-from-motion point cloud models for real-time field reporting applications. J. Comput. Civ. Eng. **29**(4), B4014008 (2014)
4. Leonard, J.J., Durrant-Whyte, H.F.: Mobile robot localization by tracking geometric beacons. IEEE Trans. Robot. Autom. **7**(3), 376–382 (1991)
5. Smith, R., Self, M., Cheeseman, P.: Estimating uncertain spatial relationships in robotics. Autonomous Robot Vehicles, pp. 167–193. Springer, New York (1990)
6. Thrun, S., Leonard, J.J.: Simultaneous localization and mapping. In: Springer Handbook of Robotics, pp. 871–889 (2008)
7. Mur-Artal, R., Tardós, J.D.: Fast relocalization and loop closing in keyframe-based SLAM. In: IEEE International Conference on Robotics and Automation (ICRA), May 2014, pp. 846–853 (2014)
8. Mur-Artal, R., Montiel, J.M.M., Tardos, J.D.: ORB-SLAM: a versatile and accurate monocular SLAM system. IEEE Trans. Rob. **31**(5), 1147–1163 (2015)
9. Mur-Artal, R., Tardós, J.D.: Orb-slam2: An open-source slam system for monocular, stereo, and RGB-D cameras. IEEE Trans. Rob. **33**(5), 1255–1262 (2017)
10. Roberto, R.A., Lima, J.P., Araujo, T., Teichrieb, V.: Evaluation of motion tracking and depth sensing accuracy of the tango tablet. In: 2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct), pp. 231–234 (2016)

71 Towards an Automated Asphalt Paving Construction Inspection Operation

Clyde Newcomer, Joshua Withrow, Roy E. Sturgill Jr., and Gabriel B. Dadi

Abstract

Collecting load tickets is an example of an antiquated practice that puts inspectors in harm's way either adjacent to traffic, in close proximity to moving or backing equipment, or at times requires climbing onto trucks to reach tickets. Technology exists to collect this information electronically allowing for safer, efficient inspection methods. Departments of Transportation are charged with inspecting an increasing work load with a diminishing number of inspection staff. Recently, doing more with less has led to the prioritization of inspection activities and resulted in less collection of data and visual inspection on projects. Technology advancements are available to improve data collection and provide for more efficient inspection. Using GPS and GIS technology tied into electronic scale report-out systems, a fleet tracking system traces haul routes, reports travel time and tonnage, and even assists contractors with equipment matching and balancing. Data from this system coupled with other technologies remote monitoring of temperature, intelligent compaction, and network enabled cameras provide an opportunity to enhance inspection and increase construction inspection productivity all the while enriching detail of project records. Challenges to the system include connectivity, interoperability, and usability. The contribution of this paper is to provide a framework in which to combine these commercially available technologies into a multi-faceted, enhanced inspection approach.

Keywords

Asphalt paving • Remote inspection technology • E-ticketing • Intelligent compaction

71.1 Introduction

Evolutions in the business models that State Transportation Agencies (STA) use for the development of highway construction projects are driving changes in their construction staffing needs. These changes are driven by several factors including: (1) fluctuations in funding levels (e.g. lean periods of state funding followed by the influx of federal stimulus funding); (2) dynamic sources of funding (i.e. changes in how projects are funded) across STA project portfolios (e.g. local vs. state vs. national, public-private partnerships, or any combination of funding agencies); (3) alternative contracting methods (e.g. design-build, QA/QC practices, warranty contracts); (4) changes in traditional job responsibilities (e.g. integration of construction and maintenance departments); (5) increased use of consultant services to augment in-house personnel (e.g. design outsourcing, construction inspection outsourcing); (6) changes in project requirements (e.g. increased environmental mitigation requirements for planning and construction); and (7) advances in design and construction technology (e.g. GPS machine control, 3D design). These evolutions occur at a time when STAs are experiencing significant staff turnover. Experienced personnel are leaving STAs through retirement and being replaced by less experienced personnel

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who are encountering more rapid increases in responsibility earlier in their careers than their predecessors. In some STAs, retiring personnel are not being replaced at all. These changes are impacting all divisions of STA personnel, particularly those tasked with the construction of highway infrastructure.

71.2 Background

These personnel transitions are also occurring at a time when STA human resources are decreasing as the volume of lane-miles managed is increasing. NCHRP Synthesis 450 [1] found that among 40 STAs between 2000 and 2010, state managed lane miles increased by an average of 4.10%, while the number of full-time equivalent staff decreased by 9.7%. When full-time equivalents were normalized across the managed road system, the responding STAs full-time equivalents per million dollar of disbursement on capital outlay decreased by an average of 37.3%. Compounding these challenges are recent demographics of STA construction staff, which indicated that the most frequent age range of construction staff was 40–50 years old and that the average years of experience was 10–15 years [1]. This indicates that STA construction staff will continue to experience a loss in knowledge and skill due to retirements. This is leading STAs to utilize Construction and Engineering Inspection (CEI) consultants to assist in project delivery. NCHRP Synthesis 450 reported that 96% of STA respondents indicated that their agencies were using CEI consultants to assist in executing construction projects [1].

Although there is an increased use of CEIs across STAs, their reception has been mixed. Given those challenges and the limited STA inspection staff, there is an opportunity to leverage technology. Construction inspectors conduct a variety of QC/QA services, but one of the most significant efforts in Kentucky is asphalt paving inspections. Asphalt paving inspections are also ideally suited for technology deployment due to the quantitative nature of many of their responsibilities. The primary objective of this research effort is to propose a theoretical framework for the automation of asphalt paving inspection operations by leveraging existing technologies. The findings will be used in future work to test the effectiveness of the proposed framework compared to traditional practices on actual asphalt paving projects. Table 71.1 outlines a list of typical inspection duties and potential technologies to assist in those operations.

71.3 Framework

71.3.1 Potential Technologies

After mapping the responsibilities for inspectors on asphalt paving projects, technologies were identified in the third column of Table 71.1. Three identified technologies allow for the automation of many of the quantifiable, typical asphalt inspection tasks. Those technologies are electronic ticketing (e-ticketing), paver mount thermal profiling, and intelligent compaction and are discussed in detail in the following sections.

71.3.2 E-ticketing

Electronic ticketing, or E-ticketing, is used during the construction phase of projects. In short, this provides agencies with the ability to go paperless. A combination of GPS units in critical equipment (haul trucks, batch plant, and paver) with a GIS

Table 71.1 Asphalt Paving inspector duties and potential technologies

Inspection operation	Inspector responsibility	Technology employed
Ticket receipt and acceptance	Collect tickets	E-ticketing: Integrated GPS, GIS, and plant weighing operations
Tracking theoretical tonnage	Determine theoretical tonnage by station	E-ticketing: Integrated GPS, GIS, and plant weighing operations
Temperature monitoring in the Truck Bed and Paver Hopper	Take temperature readings as normal	Paver mounted temperature profiler
Temperature monitoring behind the Paver and Screed	Take temperature readings as normal	Paver mounted temperature profiler
Monitoring roller operation (as per test strip)	Check as normal	Intelligent compaction
Communicating with contractor QC for nuclear density measurements	Check as normal	Intelligent compaction

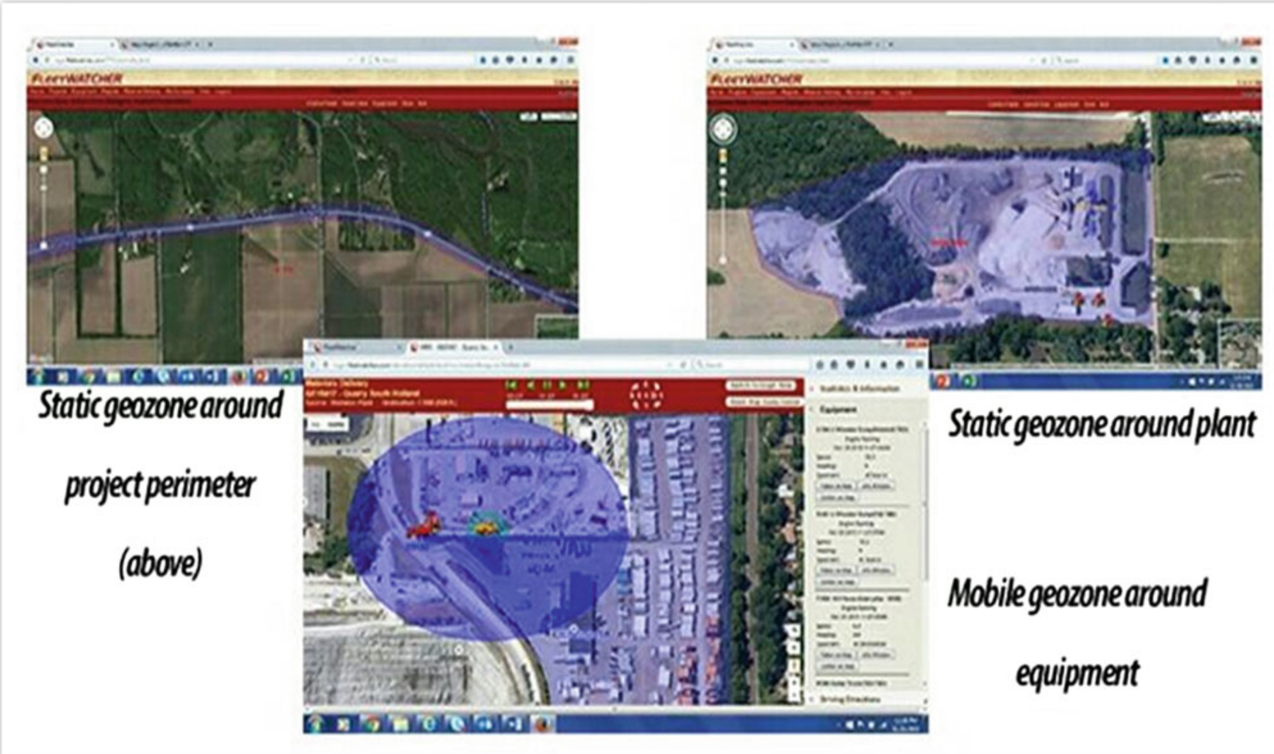

Fig. 71.1 E-ticketing Geozones [2]

interface allows inspectors to track load information and hauling information for project monitoring and documentation. The technology requires the establishment of geozones around the perimeter of the plant site, a tighter sub-geozone established around the scale to zero in on load-out times, and a mobile geozone of approximately 20-foot radius at the paver (E-ticketing shows promise of speeding process and improving accuracy at asphalt full job sites) (see Fig. 71.1) [2]. GPS trackers will be placed in each truck to notify the team, inspectors, contractors, and personnel when the asphalt trucks arrive and when they leave the jobsite. While this effort proposes its use on asphalt paving, the technology is flexible to meet other similar material delivery and storage operations. Additionally, the software also works with the batch plant, to relay additional data to the personnel in the field. In the past, each asphalt truck carried a load ticket. Now, this study will be replacing the load ticket with an e-ticket.

Each e-ticket will have the ticket receipt and acceptance, delivery and dump times, ability to track theoretical tonnage, and track the vehicles and see where they are on the road [3]. Additionally, a geozone around the entire project detects when the truck enters and leaves the project zone, but also a smaller geozone around the actual paver allows inspectors to know when the truck is engaged with the paver. This is very important because trucks waiting on other trucks to finish dumping is inefficient and can potentially negatively impact quality. Since it is vital to not have back log or wait time, this system allows for efficiency and the capability to track the truck queue on the project. The technology itself is just an application that can be installed on other smart-devices. With this technology, the inspector will be able to multitask using mobile devices. After accessing the electronic delivery ticket for the material, the e-ticket can be linked to the daily work report for measurement and payment [4].

71.3.3 Paver Mounted Thermal Profiler

Temperature of the asphalt mix at placement is a key quality indicator for the long-term performance of the pavement. Colder placement temperature makes for less effective compaction efforts and thus a lower density final pavement. Thus, many STAs require spot checks for surface temperatures of the paved surface, however, this does not provide for a full representation of the temperature across the mat. Recent developments have allowed for this data capture through a paver mounted thermal profiler. This technology is an infrared scanner that is placed on the back of a paver. Once installed, the technology uses infrared sensors to create a live thermal profile of the asphalt mat. While using this infrared technology, inspectors will be able to view temperatures across the mat at any station they desire. Infrared scans will identify any cold

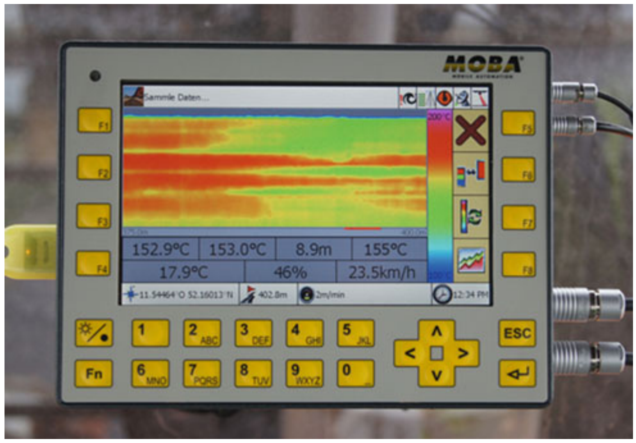

Fig. 71.2 Paver-mounted thermal imaging profile [6]

spots or streaks in the mat which directly relate to lower density sections [5]. Furthermore, density segregation will significantly impact the pavements' lifetime performance and that is why this technology is significant in stopping that process. They have a monitor placed on the paver that can show real-time results of the scans, each scan records thermal data of the mat (see Fig. 71.2) [5]. One such system is called PAVE-IR which allows for process optimization and documentation in road construction [6].

Personnel also have the option to place additional sensors on equipment, such as on the compactor, back of the dump trucks, on the screed, in the hopper, and so forth. With this thermal visualization, the construction now has insights into the quality of the material being laid. MOBA Mobile Automation delivers a breakdown of the system's components in which they accurately depict what each component can sustain and deliver to the entire innovative technology. If there are differences in the material being laid, immediate measures can be taken to correct the road. This technology is also compatible with every paver. There exist three main competences of the infrared scanner, "high-precision data acquisition with innovative cloud solution linked to open interfaces for current asphalt logistics and process systems, as well as a highly scalable reporting system" [6]. This combination of the innovative tool accurately depicts measurement to evaluation.

There have been several other STAs to successfully utilize infrared temperature monitoring on a pilot project including Iowa and Texas. The PAVE-IR system by MOBA is one such system that costs roughly $34,000 for each pavement operation or $18,000 to rent the equipment for a two-month project. The price for a rental of the equipment covers a $3000 installation charge, plus an additional $7500 charge per month of rental. Devices such as a Microsoft tablet will allow an inspector to see the pavement data given. Java, Adobe, and MOBA Pave Project are pre-installed on the device. This will allow for data transmission close to real time. Eventually with the help of this equipment among others being implemented in this project, technicians will be able to monitor and inspect resurfacing projects without having to be on site, allowing them to become more efficient and able to inspect multiple projects simultaneously [6].

71.3.4 Intelligent Compaction

Intelligent Compaction is a process that involves the usage of modern vibratory rollers equipped with an in situ measuring system that allows for constant feedback to the roller operator [7]. Additionally, GPS technology is used for project mapping, combined with software that automates the documentation from the project rollers [7]. Compaction rollers equipped with Intelligent Compaction technology also maintain a continuous record of color-coded plots that include the number of roller passes, computer generated material stiffness measurements, and the location of the roller on the project limits [7]. The GPS system is vital for accurately locating the roller along the project area [8]. The system may be a combination of using a single or multiple real-time kinetic system with an on-site base station or virtual reference station, depending on the terrain of the project site [8]. With the antenna placed on the top of the roller cab, the effective range of a GPS station on a project may be approximately 2 miles long when the line of sight is unobstructed [8]. By monitoring the position of the roller along the project area, the measurements that are recorded correspond to a certain location. By providing the relation between the location on the project and the measurement recorded, a picture can be created of the overall compaction consistency on the project [9].

An accelerometer is a key component of the Intelligent Compaction system that is mounted near the vibratory drum of the roller [8]. Double drum rollers, as are commonly used for asphalt compaction, may have two accelerometers, with one mounted near each drum [8]. The function of the accelerometer is to measure the vertical acceleration of the roller frame as it progresses along the project area [8]. The vertical acceleration that is recorded by the accelerometer is then used to indicate stiffness values of the material.

Temperature sensors may also be used on an Intelligent Compaction roller system to monitor the temperature of the surface of the asphalt material. Mixes are best compacted within certain ranges to avoid any "tender zones" that may occur on a project area [8]. These areas normally occur within the range of 219–230 °K, and permanent damage may be caused to the asphalt material if it is not correctly monitored while compaction operations occur with materials within this temperature range [9]. By monitoring the surface temperature of the mixture constantly, the roller operator can see temperature variations in real time, showing the operator when to begin rolling and when to stop [9]. A surface temperature record can also be created for the project and allow for better records to be kept throughout the project and enhance project administration [8].

Visual display is key for the Intelligent Compaction system to display real time compaction information, in both numerical and graphical form so that appropriate adjustments can be made [8]. Displayed information can range from parameters such as roller amplitude, frequency, GPS location, and speed [8]. The effects of the roller are displayed in various colors so that the operator can visually track the progress over along the project, monitor the increase in layer stiffness, and ensure a more uniform compaction coverage [8].

Finally, data can be stored and processed from the Intelligent Compaction roller. Each proprietary software can convert the vertical acceleration from the accelerometer to downward displacement and combine with the other collected information to create a continuous profile of the level of compaction along the project [8]. Data from the roller can be stored and downloaded at any time for further analysis and documentation [8].

Some systems may be equipped with automatic feedback controls (AFC), which can regulate system components such as roller vibration, amplitude, and frequency [7]. The AFC system can allow the roller operator to receive quick feedback regarding how the project environment and materials are responding to compaction efforts [7]. This quick feedback can lead to more correct decisions being made, and ultimately a greater ability to increase project quality control in real time [7].

While Intelligent Compaction does not differ in the way in which asphalt compaction occurs, as it is still dependent upon the combination of the weight of the roller machine and the vibratory system, it does offer benefits to producing a better final product. Intelligent Compaction allows the roller operator to answer questions such as where the last roller pass stopped at, whether the return pass covered the proper area, and did the previous pass have the proper overlap [9]. The Intelligent Compaction system also allows for the roller operator to monitor the asphalt mat temperature to ascertain when the best time to begin rolling is, without confirmation from some other project personnel who may not be constantly available to answer questions [9]. For projects that also require night paving work in order to be completed on schedule, Intelligent Compaction has multiple benefits in projecting the progression of compaction work for the roller operator to identify and evaluate in real time, which would be much more difficult under the poor lighting conditions normally found during night operations [9]. By incorporating measurement capabilities within the compaction roller, it is possible to ensure that project specifications and requirements are being met in real time. By meeting specifications during the initial compaction process, overall quality can improve, along with maximized productivity, reduced rework, and minimized costs [10].

71.4 Results of Previous Studies

71.4.1 Technology 1—E-ticketing

E-ticketing has multiple benefits, with time and cost savings from the use of electronic documentation being the priority. The list of benefits is significant:

> Reduction or elimination of paper, operations in a secure environment, ease of document access and searchable text, real-time document access, controlled and improved document distribution and workflow, standardization of reports and forms, reduced storage and less loss of paperwork, enhanced disaster recovery, doing varies tasks anywhere with no mobile restrictions, improved cash flow, reduction in claims, field staff on the jobsite for a higher percentage of time, easier access to manuals, plans and project information, faster document approval, ability to sign electronic documents remotely, faster and more accurate payments to contractors, transparency- documents available for viewing by all project partners, integration with other core systems, such as accounting and asset management systems [4].

As of 2017, there are many offices that have implemented e-ticketing technology into their resources. Considerable milestones are taking advancement as Iowa reaches paperless technology, PennDOT goes mobile, as well as Michigan leading the way with their state mandated e-construction initiative [4]. Michigan has recorded massive savings along with the effective use of their inspector's time.

Iowa DOT inspectors claimed that, "we have the ability to send out automatic emails and texts when orders are placed, deliveries are loaded, and orders are completed. Customers can sign in and track their trucks to the job" and also communicating the frequent time management this electronic tool saves, "if you've ever worked with concrete, you know it hardens over time. There is a window at which the concrete must be poured for it to be acceptable to use on one of our projects. Now the inspector can more closely monitor the timing of deliveries for quality control" [3]. Iowa plans to work with their industry partners closely to communicate when their material ships, processes, and enters the project.

71.4.2 Technology 2—Paver Mounted Thermal Profiler

Utilizing an infrared scanner behind the paver could greatly increase pavement performance and life, by allowing the contractor to fix poor sections immediately, rather than after failure. This method could also increase safety of the paving operation by reducing the need of the inspector to walk alongside the operation and the need to record the temperature of the pavement inside the truck. With the mapping of temperature contours, materials can be evaluated by measurement of their surface temperature and its variations. To benefit the life of the road, this technology can prevent cold spots, such as, fatigue cracks, raveling, and potholes [5]. Increasing the life of the road directly correlates with the decrease in maintenance costs. IR analysis can come in multiple forms; including paver stops, passes, and temperature profile readings [5].

Data processing and reports will maintain the raw temperature profile of the analysis zone, paving area, and sensor width. There are "three steps to eliminate invalid temperature measurements: (1) Eliminate measurement locations within 2 ft of the mat's edge, eliminate temperature readings less than 170 Fahrenheit and greater than 400 Fahrenheit, and eliminate data with paver stops greater than 60 s" [5]. Studies found by the SHRP2 RO6C that "properly installed and maintained tarps significantly reduced the temperature differentials by about 40%" which could show advantage in our study [5]. The feedback that was posted in the webinar by the SHRP2 RO6C Technology to Enhance Quality Control on Asphalt Pavements quoted some noteworthy reviews from customers, stating, "the scanner helps in adding trucks for increased uniformity, adjusting practices, and shows the benefits of short hauling; the scanner data is a vivid tool for showing how readability is influenced by the uniformity of temperatures" and "the IR scanner technology saves one grind of a project, the equipment paid for itself; Maine DOT" [5]. However, it must be considered for quality thermal readings that the proper equipment is used and purchased. Trucks with good beds, material transfer vehicles (MTV) with remixing capability, paved automation, and so forth will make the Paver Mounted Thermal Profiler perform adequately.

71.4.3 Technology 3—Intelligent Compaction

The major benefits of IC can be categorized as improved density, increased productivity, reduction of repair costs, continuous record, identification of non-compactable areas, and improved depth of compaction. Improved Density, "agencies and the public receive a better return on their monetary investment in pavements when their funds can lengthen service lives and reduce maintenance costs;" Increased Productivity, "because IC systems are designed to operate at optimum compactive effort, compaction is more efficient. The result: equivalent or better levels of density in less time and with fewer roller passes than are typically required;" Reduction of Highway Repair Costs, "this enhanced method of achieving uniformly adequate density aims to reduce the occurrence of spot failures and improve the efficiency of compaction operations, thereby lowering costs for paving contractors, State DOTs, and the traveling public;" Continuous Record of Material Stiffness Values, "possible benefits include instant identification of weak areas that need to be reworked or recompacted, the avoidance of harmful overcompaction, and potential use in design or performance specifications through integration with pavement modulus values;" Identification of Non-Compactable Areas, "there are several options: removal and replacement of weak underlying materials, stabilization and recompaction of underlying materials, or modification of the compaction requirements for the specific material. Users now possess the ability to more accurately determine their project's weak spots and assess their subsequent choices for successful compaction;" and Improved Depth of Compaction, "can increase the maximum amplitude used during initial roller passes. Evaluation of thick aggregate base materials in the U.S. has produced evidence to confirm the usefulness of this feature" [7]. To further understand overcompaction, it is defined by the "crushing of aggregate or low air void content, leading to rutting or flushing" [11].

71.5 Model Framework

In this study, these intelligent technologies, when merged together, provide an opportunity to collect rich, accurate quality inspection data. These technologies aim to increase productivity, safety, quality, and overall, the life-expectancy of the road. Each of these technologies are unique, but will benefit the Kentucky Transportation Cabinet (KYTC) greatly. KYTC will receive better quality roads, be able to keep track of the project, and know the details of progress, what materials are needed, timeline of completion to communicate to the public, and the cost. E-ticketing will help contractors remain in contact with their workers to check on their headway. This also allows contractors knowledge of load time to hold workers accountable [3]. Contractors will be able to determine why trucks are late (whether it be traffic situations, off-task breaks, etc.), and how many trucks they need on the project. By knowing this information ahead of time, contractors will be able to find discrepancy, hold accountability, and spend money more wisely. “Unlike traditional random sampling, continuous testing uses multiple inputs to ‘look for’ failure zones and has a high probability of detecting defects before they lead to premature failures” [11]. An example of the technologies utilized in practice developed in the “beginning (of) 2016, Alaska DOT used the IC and PAVE-IR paver-mounted thermal scanner technologies as contractor pay factors as part of project acceptance … They plan to offer bonuses for increasing the asphalt compaction averages—and require remediation for compaction below the standards” [11].

Another advantage of these technologies is to reduce the number of penalties due to poor performance. For example, if KYTC tests the road during the trucks initially paving it, and they fail the density test, the contractor is fined. While using intelligent compaction and the paver mounted thermal profiler, personnel can adjust problems by using real-time screening from their sensors to correct the road. Therefore, a better quality road during the project equals less potential fines. The goals of these two technologies working together is early detection of mistakes and possible weakness in the development of the road. If the contractors invest the money initially, the technology will pay off in the long run. Contractors will have less future maintenance of the road and the State will no longer have to continuously rehire for preservation. In favor, contractors will have a better product and potentially gain jobs outside of state due to their quality project development. KYTC has few resources to keep up with this growing statistic, hopefully with the help of technological advancements they will be able to reduce costs and enhance longevity.

Safety will be a large benefactor with these technologies. Inspectors will no longer have to walk up to the truck to get a loading ticket, where incoming traffic in their lane can be a concern or the truck itself, so they are safer using the e-ticketing process. Secondly, they will not have to measure the temperature of the mat because the infrared scanner will detect it for them and display and record it on a smart-device. It can be quite dangerous for inspectors to travel between paver equipment and roller machines, especially if the operator cannot see them. Thirdly, this can prevent inspectors from a fall or a trip onto the mat where they may get burned from the high temperatures of the asphalt. Due to intelligent compaction and paver mounted thermal profiler technology the inspectors do not need to get close to measure for cold spots or density issues, but rather read the data from a screen. In conclusion, these technologies can save a lot of time by preventing testing stops due to uncertainty and collect data continuously throughout the whole project to see the progress while keeping inspectors safe.

A proposed asphalt inspector dashboard displayed in real-time on a mobile computing device will allow for remote inspection of asphalt paving projects. Thus providing KYTC will the ability to provide high quality inspection activities with the limited human resources available. Each technology collects GPS data that can be tied to project station points, thus, batches from the electronic ticket can be tied to thermal profiles and later compaction values. Thus if quality issues arise later, KYTC can quickly see if it could perhaps be traced back to tracking/delivery, paving, or compacting. With that information, the appropriate maintenance activities can be determined.

71.6 Limitations

There are several limitations anticipated. There is a possibility of inconsistent data exchange, which would not relay the data correctly. A disconnection between information abstracted from the paver to the tablet or other smart device, database information retrieval lost, or hardware connection problems (such as the GPS) losing service could throw off the collection of data. There will likely be issues at the human-technology interface. With training and repetition, contractors and KYTC personnel should make improvements in acquiring the data and making informed decisions with it. In addition, these technologies are commercially available, and thus, creating an inspector’s dashboard by merging data from multiple platforms may cause proprietary issues.

71.7 Future Work

An urban, re-surfacing project in the state of Kentucky will be deploying the proposed technologies during the 2018 paving season. The researchers will be concurrently evaluating performance, documenting best practices, and finally, making recommendations and comparisons to traditional asphalt inspection practices on this project. Depending on future project lettings, the research will also be conducted on smaller, rural projects and a larger highway re-surfacing project in 2018.

71.8 Conclusions

As technology develops throughout the world, transportation is constantly having to keep up with the demands of growth and efficiency while maintaining a cost-effective, safe, and lasting project. The three technologies discussed have been proven to be beneficial through prior research and application. E-ticketing can eliminate paper, enable real-time document use, create viewing availability for all project partners, and maintain a safer work environment. The paver mounted thermal profiler allows contractors to fix defective sections immediately, evaluate materials by measurement of their surface temperature and its variations, and benefit the life of the road by detecting cold spots and saving on maintenance costs. Lastly, Intelligent Compaction strengthens and stabilizes uniformity of pavement materials, and in turn, achieves a durable roadway. Implementing these technologies concurrently would significantly impact roadway construction, efficiency, cost, safety, and time management. The Kentucky Transportation Cabinet would benefit from these technological advances in the long run by producing stronger, quality roads and developing a faster system that saves in resources while communicating data systematically with all stakeholders. As resources for STAs are reduced, leveraging technologies such as those proposed has the opportunity to maintain a high level of quality and service while managing with fewer personnel.

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References

1. Taylor, T., Maloney, W.: Forecasting highway construction staffing requirements. NCHRP Synthesis 450, Washington, D.C (2013)
2. Iowa DOT: eTicketing show promise of speeding process and improving accuracy at asphalt job sites. Transportation Matters for Iowa|Iowa DOT. 17 Dec 2015. Accessed 16 Mar 2018. http://www.transportationmatters.iowadot.gov/2015/12/eticketing-show-promise-of-speeding-process-and-improving-accuracy-at-asphalt-job-sites.html
3. Iowa DOT: Improving accountability in the construction process with ETicketing for concrete loads. Transportation Matters for Iowa| Iowa DOT. 21 Nov 2016. Accessed 16 Mar 2018. http://www.transportationmatters.iowadot.gov/2016/11/for-iowa-department-of-transportation-inspectors-tablet-computers-are-quickly-becoming-the-most-essential-tool-on-a-construc.html
4. Weisner, K., Bryan, C., Alicia, S.: The age of E-construction. Public Roads, 1 July 2017. 16 Aug 2017. Accessed 16 Mar 2018. https://www.fhwa.dot.gov/publications/publicroads/17julaug/02.cfm
5. FHWA, AASHTO: SHRP2 RO6C technology to enhance quality control on asphalt pavements: paver mounted thermal profiler. SHRP2 Solutions: Strategic Highway Research Program, 31 Jan 2018
6. MOBA: PMTP Paver Mounted THERMAL PROFILING Asphalt Road Construction Concrete Pavers MOBA PAVE IR. MOBA Mobile Automation AG. Accessed 16 Mar 2018. http://moba-automation.com/machine-applications/asphalt-pavers/pave-ir/
7. Chang, George, and Others: Accelerated implementation of intelligent compaction technology for embankment subgrade soils, aggregate base, and Asphalt Pavement Materials. FHWA **12**(002). July 2011. Accessed 16 Mar 2018. FHWA
8. Nieves, A.: Summary of intelligent compaction for HMA/WMA paving. FHWA-HIF **13**(053), 1–9 (2014)
9. Stoeckel, K.: Intelligent compaction. Asphalt Pavement Association of Oregon (2013). http://www.apao.org/presentations/past-asphalt-conferences/intelligent-compaction-technology-discussion.pdf. 13 Feb 2018
10. White, D., Pavana, V., Heath, G.: Iowa's intelligent compaction research and implementation. Iowa Department of Transportation Research News, November 2010. Accessed 16 Mar 2018. https://core.ac.uk/download/pdf/11353324.pdf
11. Sommerfeldt, R.: Using continuous full coverage asphalt testing to ensure pavement quality. 10 Jan 2018. Accessed 16 Mar 2018. https://www.rocktoroad.com/roads-paving/technology/using-continuous-full-coverage-asphalt-testing-ensures-pavement-quality-5693

72

Computer Vision and Deep Learning for Real-Time Pavement Distress Detection

Kristina Doycheva, Christian Koch, and Markus König

Abstract

Despite of the increased level of automation in vehicles, the detection of pavement distress, such as cracks and potholes, is mostly performed manually. We propose a methodology for automated pavement distress detection based on computer vision. Thereby, images obtained by cameras installed in common passenger vehicles are analyzed in real time, resulting in cost savings and a reduced amount of stored data. For this purpose, the wavelet transform was implemented on Graphics Processing Units (GPU). In addition, median filtering and top-hat transform were also implemented on GPU to enable real-time noise removal and correction of non-uniform background illumination. To distinguish between surface types, we incorporated textural features into our methodology and deep learning was utilized to determine the distress type (cracks, potholes or patches). Results obtained by different vehicles were aggregated to improve the reliability of the methodology. Case studies were conducted for validation and tests achieved promising results.

Keywords

Pavement distress detection • Graphics processing units • Textural features • Deep learning

72.1 Introduction

The number of cars on the road is expected to double by 2040 [1]. This expectation is based on the fact that the number of passenger vehicles registered in 2017 increased compared to 2016 [2]. For example, the total number of passenger vehicles registered in Germany on January 1, 2017 was 45,803,560 (1.6% more compared to 2016). As passenger cars fulfill the desire for mobility and flexibility, they accounted for 83.4% of inland passenger transport in the European Union in 2014 [3].

In order that the reliability of cars as a means of passenger transport remains high, infrastructure in good condition is essential. However, in recent years, the condition of municipal roads has deteriorated. As a result, pavement distress, such as cracks, potholes and patches is visible on the road surface. This distress affects the driving quality and leads to traffic congestions. Furthermore, vehicle damage due to accidents caused by distress such as potholes is often incurred.

To extend the life of the road pavement, maintenance activities need to be planned carefully and executed timely. Thereby, maintenance activities should be frequent and cost-effective [4]. Surface treatments, such as pothole repair and crack sealing, are amongst the most important pavement maintenance activities. To allow surface treatment, the precise location of distress should be known. To this end, the condition of the road surface should be frequently evaluated. The presence of defects, such as cracks, potholes and patches, should be detected and the extent and severity of the distress should be estimated to allow planning repair actions appropriately.

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72.2 Related Work

Nowadays, the detection of distress is mostly performed manually by teams of inspectors who observe the condition of the roads while driving. However, this method is costly if we consider the extent of the existing road network. Moreover, it is also subjective, because it is based on the evaluation by a single expert. A further critical drawback of the manual evaluation is the need to provide a safe surveying environment by controlling the traffic during an inspection.

Due to these and other drawbacks, an automated pavement distress detection approach is necessary.

Several publications propose such approaches. Some of them are based on sensors such as accelerometers, but the majority utilizes computer vision to detect distress in pavement images. The vision-based approaches are usually based on the assumption that pixels, which belong to the distress area, have different intensities compared to the pixels in the background (i.e., the intact pavement) [5].

While only a few methods are capable of detecting different types of distress [6, 7], most approaches are specifically developed for a particular type of distress. Commonly, statistical properties of the images are used to derive features for distress detection. Machine learning algorithms employ these features to build classifiers that can distinguish between images of intact pavement and images containing distress. Approaches for crack detection, which are based on machine learning, have been presented [8–10]. Another approach was proposed by Zou et al. [11], who analyze the difference in the intensities of regions in an image and derives a crack probability map based on tensor voting. Approaches for potholes have also been proposed [12, 13]. A small number of methods for patch detection have been developed. Cafiso et al. [14] have proposed a method for analysis of images with respect to patches based on clustering. Radopoulou et al. [15] have applied morphological operations to segment patch regions. All publications cited above report promising achievements and classification results. Nevertheless, they suffer from some issues and limitations. For example, a huge amount of data must usually be stored persistently and processed offline. In addition, collecting data for sensor-based methods, such as methods based on accelerometers, affects passengers comfort while driving, because it is required to drive straight over the distress.

Collecting data for computer-vision based methods, in contrast, can be per-formed while avoiding driving over the distress. However, methods based on computer vision strongly depend on the weather condition and daytime the images have been obtained at, because they could lead to non-uniform illumination. Moreover, most methods cannot be applied in general, because they do not distinguish between different pavement types and are optimized for a specific pavement surface.

72.3 Research Questions and Objectives

This work aims to compensate these deficiencies by answering the following research questions:

- How can pavement distress be both reliably and cost-effiectively detected without affecting traffic?
- In case of automated distress detection, how can the amount of stored data be reduced?
- How can distress be detected on various types of pavement surfaces under diverse lighting conditions?
- Is it possible to distinguish between different distress types and, if so, how can that be achieved?
- How can distress locations be determined precisely using inexpensive hardware?

To answer these research questions, the objective of this work is to propose a cost and storage efficient automated approach for pavement distress detection. This approach should minimize classification subjectivity and allow driving with usual speed with minimal driving restrictions. Moreover, distress should be detected under various lighting conditions and on different types of roads, whereby the type of distress should also be determined. In addition, the distress location and the severity or extent of the distress should be estimated and results obtained from different vehicles should be aggregated in order to guarantee reliability.

72.4 Methodology

In order to answer these research questions and to achieve the objective presented above, in this paper the following concept is proposed (Fig. 72.1).

Since nowadays there is a trend that new vehicles are equipped with rear view cameras [16], common vehicles such as taxis and buses equipped with such cameras and Global Positioning System (GPS) receivers can be used instead of inspection vehicles. The cameras obtain images of the road surface while the vehicles are driving at their usual speed on their usual route. Although the quality of the images may be worse than the quality of images taken by special inspection vehicles, images taken by various vehicles at the same location are used in order to increase the reliability of the detection.

The distress detection is distributed and based on two stages, namely rough detection and ne detection. In the rough detection stage, vehicles constantly obtain images of the pavement surface of parts of the road network. These images are analyzed in real time with respect to pavement distress. If distress is detected on an image, the classification label of the distress type and the GPS coordinates of the vehicle at the time the image was taken are saved persistently and forwarded to a central server. The potential distress locations identified by different vehicles are clustered and requests containing their GPS coordinates are sent to the ne detection vehicles in the second stage.

The fine detection vehicles activate their cameras only when they approach potential distress locations. Algorithms that are more complicated than the ones utilized in the rough detection stage are then applied on the images in order to determine automatically the severity and extent of the distress. Thereby, different algorithms are used by different vehicles, such as taxis and buses, whereby each vehicle receives a request form the server containing a list of potential distress locations and the id of the algorithm that has to be used by that vehicle. At the end, the results are combined, so that the final evaluation is based on numerous results and should, thus, be accurate. Moreover, the results of the ne detection stage are used to improve the rough

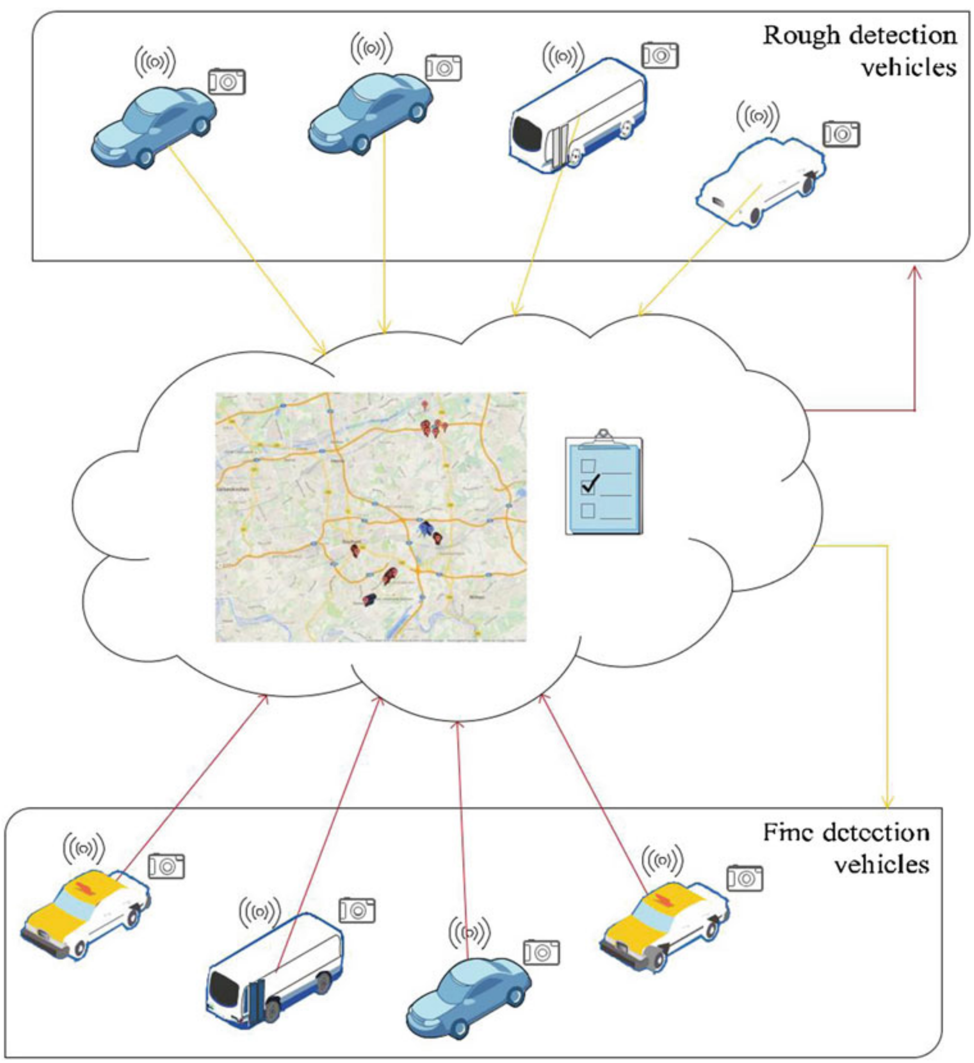

Fig. 72.1 Distress detection concept based on common vehicles

detection. For example, if a crack image was misclassified in the rough detection stage, the correct classification label of the distress at the specific location by the ne detection vehicle is used to update the classification model.

This paper focuses mainly on the rough detection stage, which has been fully implemented. An approach for clustering locations determined by different vehicles has also been developed and implemented. Several state-of-the-art algorithms for fine detection have been adopted and implemented, but they have not been extensively tested yet.

72.5 Implementation

72.5.1 Rough Detection

An overview of the rough detection approach is presented in Fig. 72.2. The rough detection method is based on the wavelet transform and it was implemented on a GPU in order to allow real-time distress detection, as described in [17]. The wavelet transform has been used by Zhou et al. for pavement distress image classification [7]. Nevertheless, if it is executed on a CPU and implemented using sequential code, the wavelet transform and the calculation of features for classification based on it require too much time and make it inpossible to perform image analysis in real time. Prior to applying the wavelet transform on the images, the latter are pre-processed to remove noise and shadows. For this purpose, median filters and top-hat transforms were also implemented on the GPUs.

Although the wavelet analiysis leads to good classification results, it is not capable of detecting distress on various types of road surfaces, because the values of the classification features strongly depend on the surface texture. To incorporate pavement surface texture characteristics, textural features were integrated. The calculation of the textural feature values was carried out on GPUs using the Open Computing Language (OpenCL), as presented in [18]. In particular, four features proposed by Haralick [19] and computed based on the gray-level co-occurence matrix (GLCM) of an image are calculated and used to enhance the distress detection.

Based on the wavelet transform and the textural features, distress can be detected reliably in images of various types of road surfaces. However, to accurately evaluate the state of the pavement surface, it is necessary to also determine the type of the distress, i.e., to distinguish between cracks, potholes and patches. To this aim, state-of-the-art concepts from deep learning were incorporated. Specifically, a classification model was generated using AlexNet, a deep convolutional neural network developed by a team at the University of Toronto [20]. In addition to determining the category an image most probably belongs to, the network associates a probability value to the prediction. In our methodology, this probability is taken into account by being compared to a value above which the result is assumed to be reliable. This threshold value is derived for each class based on experimental results, as described in the following section.

Finally, if sufficient training data is available for the specific conditions and the wavelet-based method can be applied, the results of the methods described above are combined. As a consequence, the confidence that the final rough detection result is correct increases greatly.

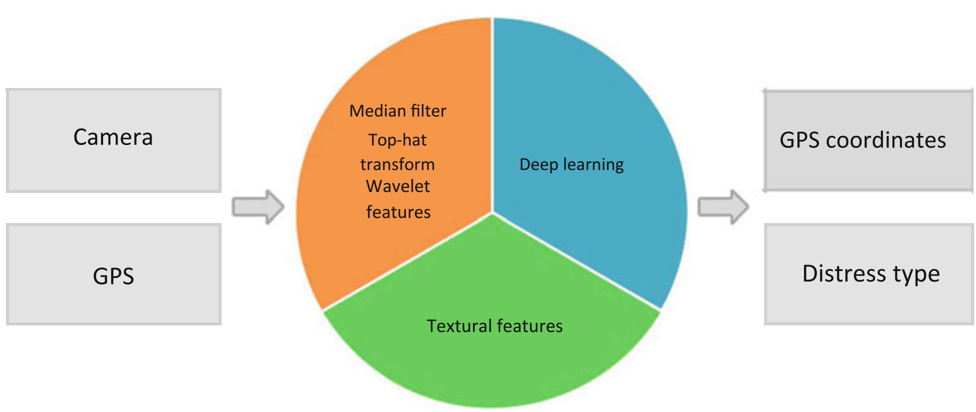

Fig. 72.2 Rough distress detection approach

72.5.2 Fine Detection

The fine detection is based on a suite of algorithms specifically developed for different types of distress. Since the algorithms perform differently well depending on the lighting condition, extent of the distress and the available training data, the ne detection is based on ensemble learning. The idea behind ensemble learning is that by combining multiple classification models, a model which out-performs the individual models is obtained [21]. The models can be combined by using methods such as majority voting, weighted averaging, stacking, etc. Different analysis algorithms will be investigated and implemented in the future. In addition, various ways to build an ensemble model based on these algorithms will be examined and evaluated.

Moreover, with the recent advances in deep learning [22], convolutional net-works are capable of not only classifying an image into one of many possible categories, but also detecting (localizing) a single object within an image and determining its size as well. Future work includes examining the possibility of using deep learning to estimate the severity and extent of the distress.

72.5.3 Georeferencing and Location Clustering

To allow the subsequent maintenance of roads, it is required that the locations of all detected distresses are known. To this end, GPS receivers capable of determining the geographical coordinates (latitude and longitude) of a vehicle are installed. Using these coordinates, the images of a potential distress can be georeferenced. To increase the reliability of the detection, repeated measurements or analyses can be performed by various vehicles using different algorithms. The results of these analyses are then combined to estimate the location of the distress more precisely. Thus, errors due to GPS inaccuracy are avoided. Moreover, outliers, i.e., single non-repeated and thus probably incorrect results, are eliminated.

In this work, the GPS coordinates are processed using a clustering method. The DBSCAN algorithm [23] was applied to identify the clusters, assign the distress coordinates to these clusters and eliminate outliers. Afterwards, the precise distress location is determined using statistical evaluation. The average values of the latitude and longitude coordinates are calculated from all points belonging to the same cluster. Finally, statistical evaluations and the number of detected distress instances per road section are used to determine which sections of the road are in poorest condition.

72.6 Case Studies

72.6.1 Validation

To validate the approach presented in this thesis, several case studies were con-ducted. A high-frequency camera was installed on a rear-door back-carrier of a car as shown in Fig. 72.3. In addition, a GPS receiver was mounted on the top of the car. Using the camera, more than 50,000 images of the road surface in Bochum and Witten, Germany were obtained. However, some of these images contained more than one type of distress. In total, 37,982 images contained either cracks (6419 images), patches (5437 images), potholes (150 images) or no distress (12,682 images). These images were used to test the rough detection methodology. The images were randomly split, so that 90% were used for training and the remaining 10% were used for validation. A classification accuracy of 88% was achieved. However, the training dataset contained a small number of pothole images and as a result the pothole images were mostly classified incorrectly. The accuracy can be improved by using a more appropriate dataset.

Furthermore, threshold values above which the classification is assumed as reliable were calculated. For this purpose, the average probability values for the correctly and incorrectly classified images for each class were computed. For example, in case of cracks the average confidence for incorrectly predicted classes was equal to 70%, while the probability associated to correct predictions was significantly higher (85%). Due to this reason, it could be assumed that images classified as containing cracks with a probability higher than 77% presumably do contain cracks.

The location clustering was tested using a small case study. A vehicle obtained images of a road section in Bochum, Germany, twice and then analyzed them with two different algorithms. In total, 642 distress locations were detected. Out of these, 382 locations were detected by the first algorithm and the remain-ing 260 locations were identified by the second algorithm. After applying the DBSCAN algorithm, 122 clusters were generated. The clusters were built under the condition that a cluster must contain at least two points, whereby the maximum distance between two points is 5 m. The results indicate that distress was incorrectly detected by the first algorithm at locations where distress was not actually present.

Fig. 72.3 Vehicle used for the case studies

These points were determined by the DBSCAN algorithm as outliers. In the next step, the distress location was estimated by means of statistical evaluation.

72.6.2 Performance Evaluation

Performance tests were carried out to evaluate the speed-up achieved by utilizing GPUs for the implementation. Images with di erent sizes, namely 256 $\times$ 256, 512 $\times$ 512, 1,024 $\times$ 1,024, and 2,048 $\times$ 2,048 pixels, were used. A 2.10 GHz Intel Core i7-4600 CPU was used to execute a sequential version of the code and the parallel version was executed on an Nvidia Tesla C2070 GPU. The highest speed-up was achieved for images with 2,048 $\times$ 2,048 pixels. In case of the median filter, top-hat transform and wavelet transform, the overall speed-up was 9,009, while the GPU execution of the calculation of the gray-level co-ocurrence matrix and the textural features was 81 times (for the GLCM), respectively 1381 times (for the features), faster than the sequential execution.

72.7 Summary and Outlook

In this thesis, a methodology towards pavement distress detection has been presented. The methodology is based on computer vision. In particular, the wavelet transform and textural features of images obtained by a camera installed in a vehicle were used to detect potential distress such as cracks, potholes and patches. The analysis was implemented on GPU to allow real-time distress detection while the vehicles are driving. In addition, a GPU implementation of the median filter was adopted and top-hat transform was implemented on GPU to pre-process the images by removing noise and correcting non-uniform background illumination.

To determine the distress type, deep learning was utilized. As a result, it is possible to classify images into one of the four categories intact pavement, crack, pothole, and patch. The images were georeferenced using a GPS receiver installed on the top of the vehicle and a precise GPS location was estimated by clustering potential distress locations detected by different vehicles.

The methodology is based on the idea that common passenger vehicles are used instead of special surveying vehicles. Although the quality of the data obtained by passenger vehicles may not be as high as the quality of the data obtained by special vehicles, reliable detection of the distress is possible, because more than one vehicle executes the same analysis algorithm for the same road. In addition, results produced by different methods are combined.

The case studies have proven that by exploiting GPUs, pavement distress detection can be performed in real time. The integration of the textural features allowed detecting distress on various types of road services. It has been demonstrated that deep learning accurately classifies images according to the distress type, which is important in order to plan further maintenance actions properly.

Recent developments also allow further refinements of the methodology. For instance, deep learning is not only capable of classifying an image into different categories, but of localizing objects within an image. The latter could be used in the future to determine the extent of the distress. Also, the information provided by automated pavement distress detection can be used not only by municipalities in order to schedule further maintenance actions, but also by ordinary citizen by warning them when they approach severe distress that has not been fixed, for example. Future research may also include integrating pavement distress data into Building Information Models (BIM) for roads, which can be used to support management processes.

References

1. Smith, M.N.: The number of cars worldwide is set to double by 2040, April 2016. https://www.weforum.org/agenda/2016/04/the-number-of-cars-worldwide-is-set-to-double-by-2040
2. Bekker, H.: Germany: Total number of registered cars, March 2017. https://www.best-selling-cars.com/germany/2017-germany-total-number-registered-cars/
3. Eurostat: Passenger transport statistics, April 2018. http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics
4. Pavement Interactive. Pavement maintenance—prevention or repair?, May 2013. http://www.pavementinteractive.org/2013/05/27/pavement-maintenance-prevention-or-repair/
5. Koch, C., Georgieva, K., Kasireddy, V., Akinci, B., Fieguth, P.: A review on computer vision based defect detection and condition assessment of concrete and asphalt civil infrastructure. Adv. Eng. Inf. **29**, 196–210 (2015)
6. Lokeshwor, H., Das, L.K., Goel, S.: Robust method for automated segmentation of frames with/without distress from road surface video clips. J. Transp. Eng. **140**(1), 31–41 (2014)
7. Zhou, J., Huang, P.S., Chiang, F.-P.: Wavelet-based pavement distress detection and evaluation. Opt. Eng. **45**(2), 027007 (2006)
8. Li, L., Sun, L., Ning, G., Tan, S.: Automatic pavement crack recognition based on BP neural network. Promet Traffic Transp. **26**, 11–22 (2014)
9. Moussa, G., Hussain, K.: A new technique for automatic detection and parameters estimation of pavement crack. In: 4th International Multi-Conference on Engineering Technology Innovation (IMETI 2011), 2011
10. Varadharajan, S., Jose, S., Sharma, K., Wander, L., Mertz, C.: Vision for road inspection. In: Proceedings of WACV 2014: IEEE Winter Conference on Applications of Computer Vision, 2014
11. Zou, Q., Cao, Y., Li, Q., Mao, Q., Wang, S.: Cracktree: automatic crack detection from pavement images. Pattern Recog. Lett. **33**, 227–238 (2012)
12. Koch, C., Brilakis, I.K.: Pothole detection in asphalt pavement images. Adv. Eng. Inf. **25**, 507–515 (2011)
13. Li, Q., Yao, M., Yao, X., Xu, B.: A real-time 3d scanning system for pavement distortion inspection. Meas. Sci. Technol. **21**(8), 015702 (2010)
14. Cafiso, S., Di Graziano, A., Battiato, S.: Evaluation of pavement surface distress using digital image collection and analysis. In: Seventh International Congress on Advances in Civil Engineering, 2006
15. Radopoulou, S.C., Brilakis, I.: Improving patch distress detection using vision tracking on video data. In Proceedings of the 21st International Workshop on Intelligent Computing in Engineering, 2014
16. National Highway Traffic Safety Administration (NHTSA). Federal motor vehicle safety standards: rear visibility, 2014
17. Doycheva, K., Koch, C., König, M.: GPU-enabled pavement distress image classification in real time. J. Comput. Civ. Eng. **31**(3) (2017)
18. Doycheva, K., Koch, C., König, M.: Implementing textural features on gpus for improved real-time pavement distress detection. J. Real-time Image Proc. (2016)
19. Haralick, R.M., Shanmugam, K., Dinstein, I.: Textural features for image classification. IEEE Trans. Syst. Man Cybern. **3**(6), 610–621 (1973)
20. Krizhevsky, A., Sutskever, I., Hinton, G.E.: Imagenet classi_cation with deep convolutional neural networks. In NIPS 2012: Neural Information Processing Systems, Lake Tahoe, Nevada (2012)
21. Rokach, L.: Ensemble-based classifiers. Artif. Intell. Rev. **33**(1–2), 1–39 (2010)
22. LeCun, Y., Bengio, Y., Hinton, G.: Deep learning. Nature **521**, 436–444 (2015)
23. Ester, M., Kriegel, H.-P., Sander, J., Xu, X.I.: A density-based algorithm for discovering clusters in large spatial databases with noise. In: Simoudis, E., Han, J., Fayyad, U.M. (eds.) Proceedings of the Second International Conference on Knowledge Discovery and Data Mining (KDD-96) (1996)

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A Flight Simulator for Unmanned Aerial Vehicle Flights Over Construction Job Sites

73

Hashem Izadi Moud, Mohamad A. Razkenari, Ian Flood, and Charles Kibert

Abstract

In 2015, the construction had the highest rate of fatalities among all industries in the United States. Unsafe operation of construction equipment is one of the main causes of fatal incidents. Operation, management and interactions between construction equipment and construction crews should be thoroughly regulated to minimize the risk of fatal incidents on job sites. While use of most traditional construction equipment is regulated, the construction industry has struggled with regulating new, innovative and smart equipment such as Unmanned Aerial Vehicles (UAVs) that have recently been introduced to construction job sites. In this paper, collision avoidance and spatial safety theories in construction are discussed. The bases of these theories are extended to UAV operation in order to establish the first known theory on safe use and operation of UAVs in construction. Also, basic principles of UAV flights are discussed. By applying the basic principles of UAV flights and construction spatial safety theories, a UAV flight simulator in construction environments has been developed in Unity game engine. The flight simulator is designed for UAV pilots, construction managers and safety managers, and enables users to fly a UAV within a simulated environment extracted from a BIM model. This UAV flight simulator is tested in a case study of a building currently under construction. This simulator can be used to assess UAV pilots' capabilities, test the risks of UAV flights in any construction environment, and UAV safe flight path planning.

Keywords

Flight simulator • Unmanned aerial vehicle • UAV • Flight simulation

73.1 Introduction

Unmanned Aerial Vehicles (UAVs) have been applied to a diverse range of construction related applications for more than a decade. UAVs have been used in structural health monitoring and inspection [1–8], 3D modeling and surveying job sites [9] progress monitoring [10, 11], infrastructures management [12–17], sustainable energy production site management [18], material tracking [19] and construction safety related applications [20]. Although there have been numerous efforts by governmental agencies, such as the Federal Aviation Administrations (FAA) and academia to explore, educate, address and govern UAV flight safety procedures [21], there have not been any rigorous studies specifically within the field of

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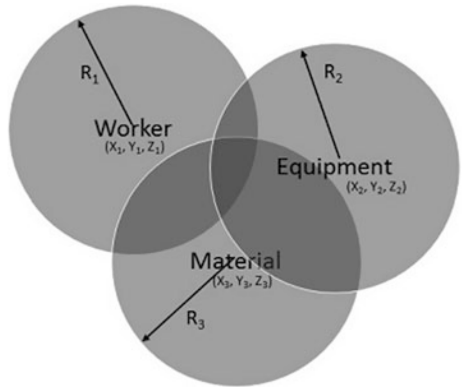

Fig. 73.1 Schematic view of a threatened proximity. Adapted from [25]

construction to investigate UAV flight challenges. The construction industry can generally consider to be hazardous, experiencing relatively high rates of both fatalities and casualties. In 2015, a total of 4836 fatal work incidents were reported in the US. Of these, nearly 20% (937) were attributed to construction, more than any other industry [22]. Using UAVs on construction job sites without full consideration of their safety threats, risks and hazards can put the well-being of construction personnel in jeopardy. Mechanical failure and human errors in operation are the two common risks associated with using UAVs that can lead to crashes, accidents, and mission failures [23]. In order to understand and help avoid UAV-related accidents, safe proximity between UAVs and other equipment, machinery, personnel, buildings and roads on site need to be studied. Also, there is a need to put plans in action that notify the UAV pilot, construction personnel, and safety officer on site from risky procedures such as close proximities between UAV flight paths and construction workers. An important strategy that can significantly help improve UAV flight safety is pilot training in simulated environments. This study investigates risks associated with UAV flights in close proximity to construction equipment and machinery, materials, construction personnel and structures. The objectives of this research are to: (1) present a recently built interactive UAV flight simulator that can be used for tasks such as UAV pilot training, UAV flight path planning and UAV flight assessment, based on the construction spatial safety theory, and (2) test the UAV flight simulator in a real construction job site environment in order to verify the usability of the UAV flight simulator.

73.2 Proximity and Collision Avoidance in Construction Safety

Spatial safety refers to safety related to the space comprising any construction site. The focus on construction safety has not been on spatial safety. Traditional construction safety plans are grounded on static data of job sites, 2D drawings and Occupational Health and Safety Administration (OSHA) regulations and recommendations. Temporal and spatial data have rarely been incorporated in OSHA regulations and recommendations or construction site safety plans. Live spatial and temporal data have not been a focus in construction safety planning. Although OSHA regulations and recommendations form an important part of establishing construction site safety, they do not satisfy the need for a live space and time aware construction safety planning scheme. There have been numerous efforts in academia to fill this gap and introduce dynamic safety site planning schemes that incorporate live and dynamic spatial and temporal data into safety plans [24–26]. This section mainly focuses on spatial theories that are dealing with proximity and how to avoid collision risks associated with UAVs. A few different theoretical frameworks have been proposed and tested in order to increase spatial and temporal awareness among construction equipment and personnel. A dominant collision avoidance theoretical framework in construction is proposed by Teizer et al. [25], which is based on a circular zoning view of construction equipment and personnel (see Fig. 73.1).

Teizer et al. [25] developed a proximity warning mechanism that alerts construction personnel operating in close proximity to construction machinery. This proximity warning mechanism is based on a theoretical framework that views construction materials, equipment and workers as objects surrounded by safe circles. Each object is surrounded by a safe circle. The warning mechanism triggers when at least two of these safe spheres overlap. The bases of the Teizer et al. [25] proximity warning system are: (1) each construction object is entitled to a safe sphere, (2) each object is in the center of its safe sphere and (3) it is safe for all objects to freely move until they enter another object's safe sphere. The proximity warning mechanism triggers and sends a warning when an object's safe sphere is threatened by another object's safe sphere. Figure 73.1 shows a schematic view of the threatened safety spheres in a construction site. The mathematical bases of the framework are presented as follow: (1) objects are safe as long as: $[(X_i,\ Y_i,\ Z_i) - (X_{i+1},\ Y_{i+1},\ Z_{i+1})] \geq (R_i + R_i)$, and (2) objects are not safe when: $[(X_i,\ Y_i,\ Z_i) - (X_{i+1},\ Y_{i+1},\ Z_{i+1})] < (R_i + R_i)$.

73.2.1 Spatial Safety of UAV in Construction Environment

Currently the use of UAVs on construction job sites does not follow any specific guidelines, safety codes, safety recommendations or regulations. The only existent guideline for UAV flights are the general rules and recommendations published by FAA for flying UAVs. Although UAVs have many potential applications for the construction industry, using UAVs without proper caution, including professional training of UAV pilots, could significantly increase the safety hazards on construction job sites. Flying UAVs in close proximity of personnel, equipment and structures increases the risks of injuries and mission failure. This section incorporates the Teizer et al. [25] spherical safe proximity strategy into UAV flights safety. Based on the Teizer et al. [25] proximity theory, equipment, workers and structures have a safe sphere surrounding them. The safe proximity between these objects is only maintained as long as these safe spheres do not cross over. Figure 73.2 shows a general proximity example between two UAVs on a construction job site based on Teizer et al. [25] spherical proximity theory. An example of standoff distance between two UAVs, a construction equipment (crane), a construction personnel and a building are presented.

The location of each element followed by safe sphere radius is as follows: UAV-1: {(X1, Y1, Z1), d-1}; {UAV-2: (X2, Y2, Z2), d-2}; Crane: {(X3, Y3, Z3), R-3}; Crew: {(X4, Y4, Z4), R-4}; Building: {(X5, Y5, Z5), R-5}.

An ideal *UAV proximity system* should issue a warning each time a UAV standoff distance collides with other construction objects safe surroundings, which is shown in the formula below: (1) For UAV-1: (X1, Y1, Z1) – {(Xi, Yi, Zi): i Ɛ (2, 3, 4, 5)} $\leq$ {d-1 + ((Ri: i Ɛ (3, 4, 5)) OR d-2)}, & (2) For UAV-2: (X2, Y2, Z2) – {(Xi, Yi, Zi): i Ɛ (1, 3, 4, 5)} $\leq$ {d-2 + ((Ri: i Ɛ (3, 4, 5)) OR d-1)}.

Based on these basic construction proximity principles, a UAV flight simulator is designed for pilots that warns users when the UAV proximity rules are compromised.

73.3 Principles of Unmanned Aerial Vehicle Flight Simulator

While the construction industry puts UAVs to good use, the investigation of their potential safety and risk should not be neglected. The UAV operation in close proximity to the construction activities and pieces of equipment may increase the collision hazards for site crews and workers. There is a need for applying safety control and monitoring systems for UAV

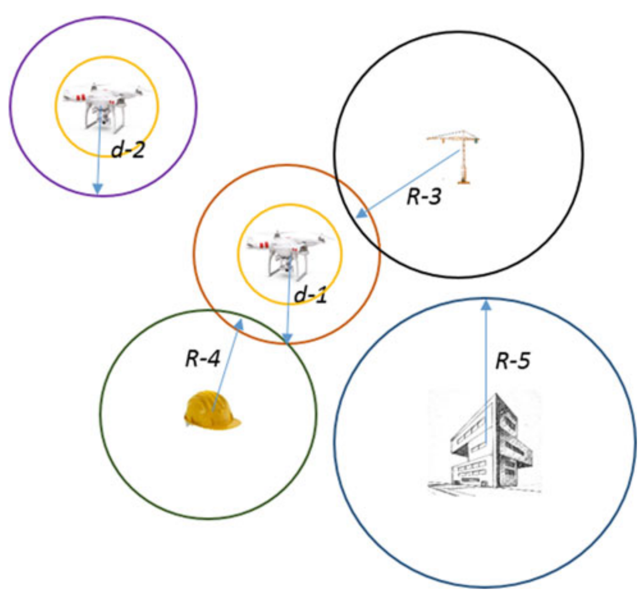

Fig. 73.2 An example of a close proximity situations between some objects in a construction environment

operation on the construction site. The primary consideration to augment the safety in UAV services is to supervise the training of operators with regards to the safety and proximity consideration. This section clarifies the considerations and assumption for developing a simulation platform for particular UAV applications. Next, after a quick review of the existing UAV simulators, the approach adopted in this study for developing the UAV simulation platform is discussed.

73.3.1 Considerations for UAV Simulation

The physical characteristics of UAVs are among the most significant inputs for the simulation process. UAVs are described and classified considering a wide range of characteristics, such as size, weight, flight range, endurance, capabilities, and engine type [27]. They have a rigid body with multiple actuators that produce forces and torques. UAVs come with specific operational parameters such as mass, inertia, coefficients for linear and angular drag, coefficients of friction and restitution which are necessary for computing rigid body dynamics. A quadcopter UAV, which is currently the most common type of UAV used in construction, has four propellers with adjustable rotation speed located at the vertices. By having C_T and C_{pow} as the thrust and the power coefficients, r as air density, D as propeller's diameter and $\omega_{\max}$ as the max angular velocity in revolutions per minute, the forces and torques generated by propellers at vertices are [28]:

$$F_i = C_T \rho \omega_{\max}^2 D^4 u_i \quad and \quad \tau_i = \frac{1}{2\pi} C_{\text{pow}} \rho \omega_{\max}^2 D^5 u_i \tag{73.1}$$

UAVs are used for a wide range of civil and military applications in very challenging outdoor or indoor environments. They may be exposed to multiple physical phenomena including gravity, air pressure, and strong magnetic fields. Taking into account all these phenomena in a simulation process will result in very accurate yet computationally expensive models. Therefore, the existing models are developed for desired accuracy in the selected case or scenario analysis.

73.3.2 Software Simulation Tools

There are a wide range of commercial or open source UAV simulators available each with its own specific configuration and features. The available simulators have a limited scope in terms of the operating environment. Craighead et al. [29] reviewed 14 of these simulators and their significant features. Gazebo [30], which is a major robot simulation tool, is one of the most popular simulation platforms for research work. It has a modular design that allows use of different physics engines, sensor models, and creates 3D worlds. Multiple examples of open source simulators have been developed using the Gazebo platform coupled with Application Programming Interfaces (APIs) to develop simulation applications [31–33]. Although Gazebo [30] has many robust features, it is challenging to create large-scale complex virtual environments that are closer to the real world. Game engines such as Unreal [34] and Unity [35], allow various advancements in rendering and creation of any environment but are slightly limited regarding vehicle creation. A good example is Microsoft AirSim [28], an open-source, cross-platform simulator for UAVs, built on Unreal Engine, with physically and visually realistic simulations. In addition, there are many commercial UAV simulators and training applications available with customized specifications. The commercial simulators are developed for specific applications such as structured flight challenges [36, 37], safety training [37, 38], and different working environments and flight scenarios [36, 38].

73.3.3 Drone Movement

The methodology adopted for the simulator considers a quadcopter with four propellers. The propellers generate thrust forces, F_1, F_2, F_3, F_4, by altering the rotation speeds, to achieve the desired movement or maintain the position of the UAV (Fig. 73.3). In the hovering condition, the forces of propellers must be equal and must add up to the weight of the UAV for the generated moments to cancel out. For vertical movement, the forces will increase or decrease equally and will cause no additional moment or angular speed. The gravity may change, slightly, in different environments and in a complex manner [28]. However, for most ground-based or low altitude UAV applications, the variations are negligible, and many models consider a constant number to model gravity [28]. In addition to gravity, the UAV may be subject to air density, air pressure, or other air movement based on the physical characteristics of the operating environment.

The controlled change in thrust forces will cause moment inequality and lead to angular movement of the UAV. If we consider X_L, Y_L, and Z_L, as the UAV local reference system and X_G, Y_G, Z_G as the Global reference system, and X_G as the

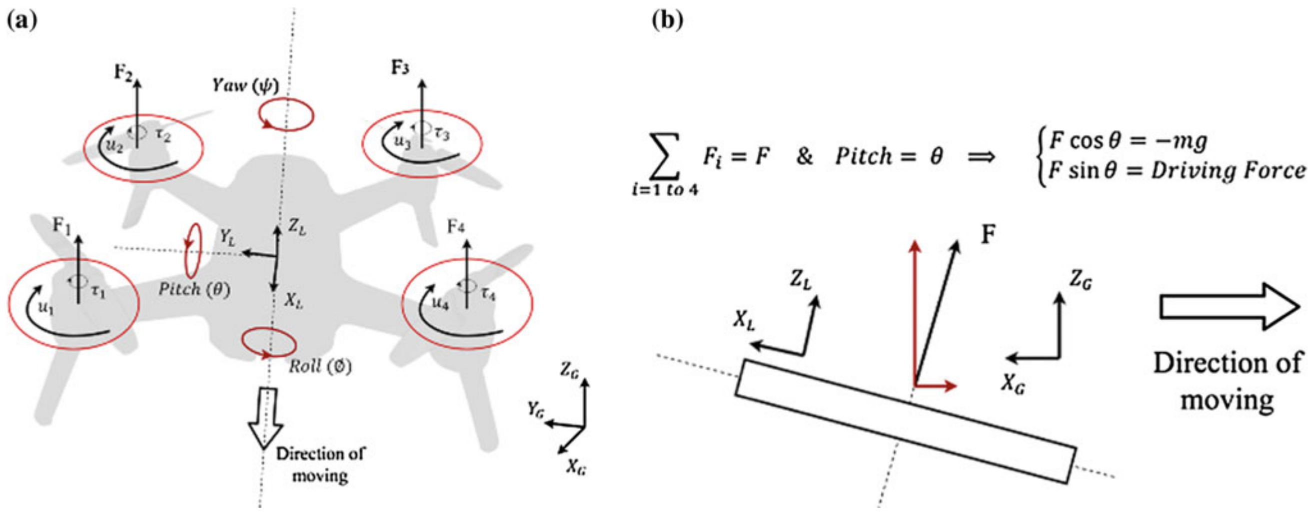

Fig. 73.3 An illustration of forces, movements, reference systems, and rotations in a UAV (left). The simple representation of driving force in X_G direction in the pitch rotation (right). Adapted from [28]

moving direction of the UAV, the angular movement in X_L, Y_L, and Z_L axis are respectively recognized by roll (∅), pitch (θ), and yaw (ψ) (Fig. 73.3). If the control signal is intended to move the UAV in the X_G direction, it will increase the total forces at the propellers until it cancels out the gravitational force in the Y_G direction and, as illustrated in (Fig. 73.3), an additional force in the X_G direction will lead to the lateral movement. Therefore, the UAV driving force is associated with the tilting angle and moving direction.

73.4 Unmanned Aerial Vehicle Flight Simulator

Using UAVs on construction job sites usually includes a pre-flight survey, setup (preparation), flight mission (take-off to landing), and post-flight data analysis. In this study, a visual interactive platform is developed in the Unity game engine to present the state of UAV safety during its operation. The proposed platform includes the process of creating a 3D environment of construction job sites where UAV flights can be simulated. All the existing simulators on the market have a pre-developed environment that is not customizable for a given project features. The platform also has a collision avoidance system with consideration of specific construction site safety features and Teizer's proximity theory [25]. The collision avoidance system is unique to this platform and is customized for construction project activities. The platform is the first proposed tool for training operators in the construction environment and with safety considerations. To create the 3D model of a building in the Unity platform, a BIM 3D model was exported in *.fbx* format and introduced to the game engine. The game development in the engine is powered with the C# scripting language. While the Unity platform allows definition of each subject separately, for this case study, the whole building was set as one object. By integrating 4D site-specific temporal and spatial safety information [39] with the Unity model, the simulator will allow users to monitor the safety level of each UAV operation or scenario considering the existing safety plan. There are two cameras in the model including the operator eye-level view which is used as the main camera for the game view and the UAV camera which is placed on the right side of the game view (Fig. 73.4). The simulation is based on a generic drone that is commonly used on construction job sites with an average speed of 50 km per hour (km/hr.) operating in an outdoor environment. The simulator has a modular architecture which allows the addition of new features, such as specific weather conditions, air density (for hot days or high altitude), air movement (wind, convection up the side of buildings), etc. However, these features are not considered within this case study. The next modeling step was to develop the control strategy for UAV movements. As mentioned earlier, a UAV is expected to have movement in three directions including forward or backward (X_G), right or left (Y_G), and up or down (Z_G). The forwards/backwards and right/left movements will include tilting angles, respectively pitch (θ) and roll (∅). The UAV tilting is associated with its weight and moving speed; however, the experiments show that the tilting angles are approximately between −30° and +30° [35] and the same values are used in the model.

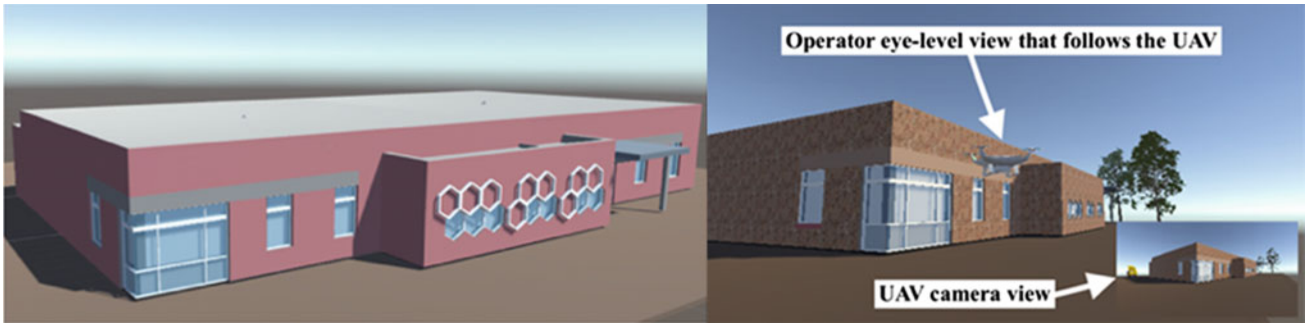

Fig. 73.4 The 3D building model in the Unity platform before rendering edits (left) and simulated UAV in the operator view and with additional UAV camera view (right)

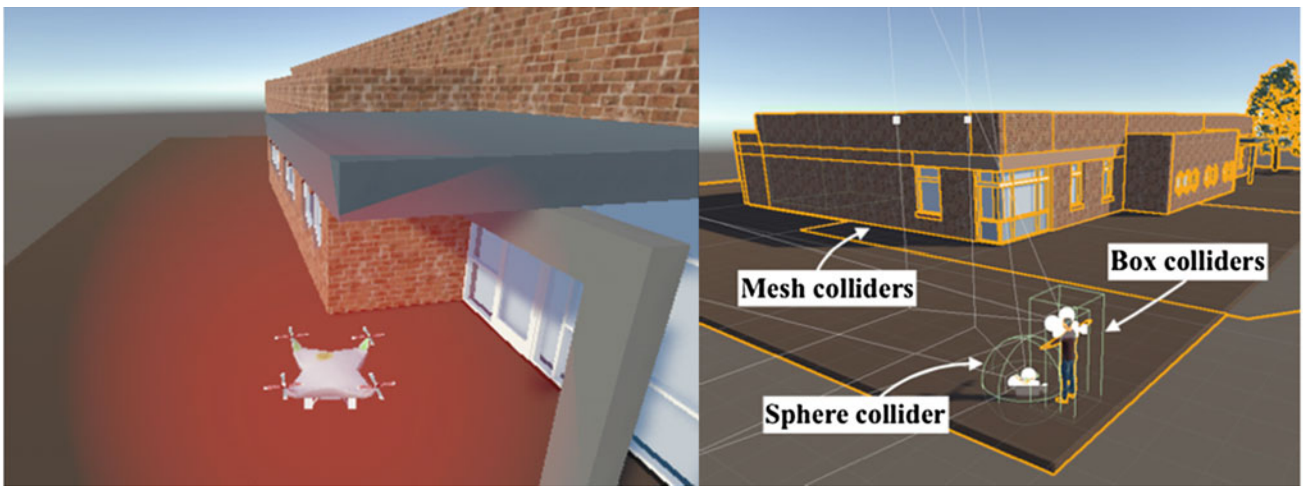

Fig. 73.5 The color-coded proximity warning system that works according to Teizer et al. [25] proximity theory (left); and sphere, mesh, and box colliders in the system (right)

In the simulator, the user can send inputs using a keyboard to control its movement. The UAV will move in the requested direction with the proper tilting angle for each movement. The user may select moving in more than one component of the directional vector at the same time (for example, up and forward). In this step, it was made sure that the simulated UAV prototype can maneuver through the simulated construction job site environment (Fig. 73.4). The next feature added to the simulator was the ability to capture real-time spatial information of the UAV during an operation. The coordination of UAV with respect to the set reference point in UNITY model for each update frame (9 frames per second) were recorded and exported as a text file. These coordinates can be used for further analysis or updating the safety plan on other platforms.

Finally, the users can set a customized proximity distance for any given UAV, construction component, item of equipment, or worker and the simulator provides a color-coded warning system to the UAV controller using the red signal if any of the proximity requirements are violated (Fig. 73.5). The warning system is developed by using pre-defined collision detection methods within the Unity platform. The warning system is working in the scope of Teizer's proximity theory for construction safety [25] and can easily be extended to the color-coded safety zones with specific configurations or other spatial related applications.

73.5 Discussion and Conclusion

This paper presents the first ever known UAV flight simulator, developed in Unity, that is dedicated to construction environments. This UAV flight simulator is based on basic principles of safe proximity theories used in construction safety research for developing collision avoidance systems. The presented UAV flight simulator uses a color-coded scheme to warn the users of near-collision incidents. It is easy to use for construction managers, safety managers, owners and UAV pilots. Some of the applications of this system are: (1) train UAV pilots to fly in complex construction job site environment, (2) assess complexity of construction job sites prior to plan UAV flights on site, and (3) safe UAV flight path planning. This simulator is tested using a BIM model of an actual construction site, which is currently under development. The BIM model of this project is exported to Unity and the platform is tested within this environment, navigating a UAV around the building. While more than a dozen UAV flight simulators are available on the market, this platform is distinguished by being dedicated to construction job sites. It works with the BIM model, is easy-to-use, and specifically tailored for needs of the construction environment. For the future, the authors plan on adding more features to this platform so that it can be applied to more complex construction environments.

References

1. Pratt, K.S., Murphy, R.R., Burke, J.L., Craighead, J., Griffin, C., Stover, S.: Use of tethered small unmanned aerial system at Berkman Plaza II collapse. In: 2008 IEEE International Workshop on Safety, Security and Rescue Robotics, pp. 134–139. IEEE, October 2008
2. Wefelscheid, C., Hänsch, R., Hellwich, O.: Three-dimensional building reconstruction using images obtained by unmanned aerial vehicles. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. **38**, 1 (2011)
3. Kruijff, G.J.M., Pirri, F., Gianni, M., Papadakis, P., Pizzoli, M., Sinha, A., Tretyakov, V., Linder, T., Pianese, E., Corrao, S., Priori, F.: Rescue robots at earthquake-hit Mirandola, Italy: A field report. In: Safety, Security, and Rescue Robotics (SSRR), 2012 IEEE International Symposium on IEEE, pp. 1–8. IEEE, November 2012
4. Eschmann, C., Kuo, C.M., Kuo, C.H., Boller, C.: Unmanned aircraft systems for remote building inspection and monitoring. In: 6th European workshop on structural health monitoring (2012)
5. Roca, D., Lagüela, S., Díaz-Vilariño, L., Armesto, J., Arias, P.: Low-cost aerial unit for outdoor inspection of building façades. Autom. Constr. **36**, 128–135 (2013)
6. Michael, N., Shen, S., Mohta, K., Mulgaonkar, Y., Kumar, V., Nagatani, K., Okada, Y., Kiribayashi, S., Otake, K., Yoshida, K., Ohno, K.: Collaborative mapping of an earthquake-damaged building via ground and aerial robots. J. Field Robot. **29**(5), 832–841 (2012)
7. Kerle, N., Fernandez Galarreta, J., Gerke, M.: Urban structural damage assessment with oblique UAV imagery, object-based image analysis and semantic reasoning. In: Proceedings, 35th Asian conference on remote sensing (2014)
8. Morgenthal, G., Hallermann, N.: Quality assessment of unmanned aerial vehicle (UAV) based visual inspection of structures. Adv. Struct. Eng. **17**(3), 289–302 (2014)
9. Siebert, S., Teizer, J.: Mobile 3D mapping for surveying earthwork projects using an unmanned aerial vehicle (UAV) system. Autom. Constr. **41**, 1–14 (2014)
10. Han, K., Lin, J., Golparvar-Fard, M.: A formalism for utilization of autonomous vision-based systems and integrated project models for construction progress monitoring. In: Proceedings of 2015 Conference on Autonomous and Robotic Construction of Infrastructure, pp. 118–131 (2015)
11. Lin, J., Han, K., Golparvar-Fard, M.: A framework for model-driven acquisition and analytics of visual data using UAVs for automated construction progress monitoring, pp. 156–164. Computing in Civil Engineering, Austin, Texas (2015)
12. Metni, N., Hamel, T.: A UAV for bridge inspection: visual servoing control law with orientation limits. Autom. constr. **17**(1), 3–10 (2007)
13. Rathinam, S., Kim, Z.W., Sengupta, R.: Vision-based monitoring of locally linear structures using an unmanned aerial vehicle 1. J. Infrastruct. Syst. **14**(1), 52–63 (2008)
14. Zhang, C., Elaksher, A.: An unmanned aerial vehicle-based imaging system for 3D measurement of unpaved road surface distresses1. Comput. Aided Civil Infrastruct. Eng. **27**(2), 118–129 (2012)
15. Eschmann, C., Kuo, C.M., Kuo, C.H., Boller, C.: High-resolution multisensor infrastructure inspection with unmanned aircraft systems, ISPRS-international archives of the photogrammetry. Remote Sens. Spat. Inf. Sci. **1**(2), 125–129 (2013)
16. Sankarasrinivasan, S., Balasubramanian, E., Karthik, K., Chandrasekar, U., Gupta, R.: Health monitoring of civil structures with integrated UAV and image processing system. Procedia Comput. Sci. **54**, 508–515 (2015)
17. Ellenberg, A., Kontsos, A., Moon, F., Bartoli, I.: Bridge related damage quantification using unmanned aerial vehicle imagery. Struct. Control Health Monit. (2016)
18. Matsuoka, R., Nagusa, I., Yasuhara, H., Mori, M., Katayama, T., Yachi, N., Hasui, A., Katakuse, M., Atagi, T.: Measurement of large-scale solar power plant by using images acquired by non-metric digital camera on board UAV, ISPRS-international archives of the photogrammetry. Remote Sens. Spat. Inf. Sci. **39**, 435–440 (2012)
19. Hubbard, B., Wang, H., Leasure, M., Ropp, T., Lofton, T., Hubbard, S.: Feasibility study of UAV use for RFID material tracking on construction sites. In: 51st ASC Annual International Conference Proceedings (2015)
20. Gheisari, M., Irizarry, J., & Walker, B.N.: UAS4SAFETY: The potential of unmanned aerial systems for construction safety applications. In: Construction Research Congress 2014@ Construction in a Global Network, pp. 1801–1810. ASCE (2014)
21. Murphy, R.R.: Disaster robotics. MIT Press, Cambridge (2014)

22. BLS: Bureau of labor statistics: census of fatal occupational injuries (CFOI)—current and revised data, November 1st, 2017. Available from: https://www.bls.gov/iif/oshcfoi1.htm#2015
23. Clothier, R.A., Walker, R.A.: Determination and evaluation of UAV safety objectives. In Proceedings 21st International Unmanned Air Vehicle Systems Conference, pp. 18.1–18.16, Bristol, United Kingdom (2006)
24. Bansal, V.K.: Application of geographic information systems in construction safety planning. Int. J. Project Manage. **29**(1), 66–77 (2011)
25. Teizer, J., Allread, B.S., Fullerton, C.E., Hinze, J.: Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. Autom. Constr. **19**(5), 630–640 (2010)
26. Sacks, R., Rozenfeld, O., Rosenfeld, Y.: Spatial and temporal exposure to safety hazards in construction. J. Constr. Eng. Manage. **135**(8), 726–736 (2009)
27. Hassanalian, M., Abdelkefi, A.: Classifications, applications, and design challenges of drones: a review. Prog. Aerosp. Sci. **91**, 99–131 (2017)
28. Shah, S., Dey, D., Lovett, C., Kapoor, A.: Airsim: High-fidelity visual and physical simulation for autonomous vehicles, pp. 621–635 (2018)
29. Craighead, J., Murphy, R., Burke, J., Goldiez, B.: A survey of commercial & open source unmanned vehicle simulators, pp. 852–857 (2007)
30. Koenig, N., Howard, A.: Design and use paradigms for gazebo, an open-source multi-robot simulator, vol. 3, pp. 2149–2154 (2004)
31. Meyer, J., Sendobry, A., Kohlbrecher, S., Klingauf, U., Von Stryk, O.: Comprehensive simulation of quadrotor uavs using ros and gazebo, pp. 400–411 (2012)
32. Rotorsa modular gazebo mav simulator framework. In: Robot Operating System (ROS)
33. Babushkin, A.: Jmavsim. https://pixhawk.org/dev/hil/jmavsim
34. Unreal Engine 4 for game development: https://www.unrealengine.com
35. Gowda, M., Manweiler, J., Dhekne, A., Choudhury, R.R., Weisz, J.D.: Integrating GLONASS with GPS for Drone Orientation Tracking, pp. 77–92 (2017)
36. RealFlight Drone Edition site: https://www.realflight.com
37. Zephyr Drone Simulator site: https://zephyr-sim.com
38. droneSim Pro Drone Simulator site: https://www.dronesimpro.com
39. Choe, S., Leite, F.: Construction safety planning: site-specific temporal and spatial information integration. Autom. Constr. **84**, 335–344 (2017)

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74 Bridge Inspection Using Bridge Information Modeling (BrIM) and Unmanned Aerial System (UAS)

Yiye Xu and Yelda Turkan

Abstract

Bridge inspection is a critical task that is needed to monitor bridge quality and serviceability. Previous studies indicate that road network and bridges in the U.S. are not of high quality and poorly maintained for decades, and the current manual inspection routine is expensive, time-consuming, hazardous, and subjective. Moreover, current Bridge Management Systems (BMS) may not coordinate management of all phases of the bridge life cycle. Also, the dispersed inspection data drastically reduces the effectiveness of the system. Therefore, there is a need to identify cost-efficient and productive ways to inspect and manage our bridges. The objective of this study is to develop a novel framework for bridge inspections and management. The framework implements Bridge Information Modeling (BrIM) and Unmanned Aerial Systems (UASs) technologies in an integrated manner to solve the issues associated with current manual bridge inspection and management practice. The proposed framework was implemented using data collected from an existing bridge located in Eugene, Oregon. Different types of defects were identified automatically using computer vision algorithms from the digital images captured by the UAS. These defects were assigned to individual BrIM elements. BrIM was used as the central database to store the 3D bridge model and inspection data. The framework also enables bridge inspectors and decision makers to access the most up-to-date inspection data simultaneously by taking advantage of cloud computing technology. The proposed framework: (1) provides a systematic approach for accurately documenting the structural condition assessment data, (2) reduces the number of site visits and eliminates potential errors resulting from data transcription, and (3) enables a more efficient, cost-effective and safer bridge inspection process.

Keywords

Building information modeling (BIM) • Bridge information modeling (BrIM) • Unmanned aerial systems (UASs) • Crack detection

74.1 Introduction

The strength and growth of the U.S. economy, and the quality of life of all Americans, depend, in part, on the quality, sustainability, and condition of its infrastructure such as road network and bridges. However, previous studies indicate road network and bridges in the U.S. are not of high quality and poorly maintained for decades [9]. In August 2007, the I-35 W Mississippi River Bridge suddenly collapsed during evening rush hour. The reason behind the collapse was mainly attributed to a design flaw of the gusset plates and vertical clearance. Because of this structural failure and bridge collapse, 13 people were killed and 145 were injured. Similarly, in May 2013, I-5 Skagit Bridge near Seattle collapsed into the river after being struck by an oversized truck. Three people were seriously injured and the incident affected an average of 71,000 drivers who used this bridge to commute daily. Most recently, in March 2018, a pedestrian bridge that connects Florida International University with a neighboring city was also collapsed due to similar circumstances killing six people and injuring more than

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a dozen people [23]. These catastrophes raised the public's attention on the status of the nation's bridges and their maintenance operations. The most recent Infrastructure Report Card that was released by American Society of Civil Engineers (ASCE) reported an overall C+ (mediocre) grade for bridges. Forty percent of U.S. bridges are over 50 years old [4], exceeding their designed life span. In addition, 9.1% of the bridges were classified as structurally deficient in 2016 [4]. Although, structurally deficient bridges do not necessarily indicate that those bridges are unsafe or likely to collapse, it does mean that their critical carrying elements are in poor condition due to deterioration or partial damage. This necessitates frequent monitoring and inspection to eliminate possible and potential structural failure or collapse. However, the back-logged budget for bridge rehabilitation has reached $123 billion [4]. In summary, the U.S.'s aging and deteriorated road and bridge systems and limited budget emphasize the need to develop an efficient and cost-effective bridge inspection process that can reduce or prevent the possibility of structural collapse of bridges.

74.2 Background

74.2.1 Current Bridge Inspection Practice and Problems Identified

Bridge inspections are critical for monitoring bridge quality and serviceability as they provide detailed information regarding the structural stability of bridges. The Federal Highway Administration (FHWA) requires that all states perform biennial routine inspections for each bridge [1] and recommends an inspection at least once a year for those bridges that are rated as structurally deficient [4]. However, current bridge inspection is mainly based on visual and paper-based practices as it requires an inspector correctly identify the type, location and severity of each bridge element, and manually record the damages by using checklists, taking notes, and drawing sketches while on site. They document all this data by using standard inspection reports and update it into Bridge Management Systems (BMSs) after they go back to their office. The system enables bridge engineers to access and compare with previous inspection results, and identify any repair/rehabilitation/ maintenance needs.

There are several shortcomings associated with current visual and paper-based inspection and data management practices. First, inspectors might be exposed to safety risks while performing the evaluation, especially when reaching areas with limited accessibility. Second, equipment used for inspection such as elevating platforms and scaffolding are expensive and can disrupt the flow of traffic. Third, the evaluation process cannot be objectively performed and may be impacted by the experience of the inspector, which may affect the accuracy of the inspection results [7]. Fourth, the process is expensive and laborious. Moreover, current BMSs can be inefficient due to several reasons: (1) stand-alone BMS does not satisfy the increasing need to coordinate management of all phases for entire bridge life cycle [19, 21]; (2) current BMSs provide a 2D database, i.e. does not enable 3D visualization of the data [8]; (3) large amount of inspection data is input from a variety of sources, which can possibly lead to an issue of data dispersion [10]; and (4) the condition of similar types of elements are grouped together to report defects, which might hide the inner reasons for the defects on specific elements [8]. Based on the aforementioned discussion, previous studies have proposed several ideas implementing various technologies to improve bridge inspection and management practices.

74.2.2 Technology Used in Data Acquisition and Processing for Inspection

To overcome the inherent weaknesses in visual bridge inspection processes, previous studies proposed implementation of several non-destructive technologies. Ground Penetrating Radar (GPR) has been used for concrete and masonry bridge inspection, especially for deck condition assessments [2], and has shown high capability to detect size and location of concrete delamination area of bridge decks compared to visual inspection methods [20]. However, the quantitative method to analyze the GPR profile overlook some of the important information in the profile, such as change in reinforcing bar spacing slab thickness [22]. Infrared (IR) thermography is another non-destructive technique for detecting subsurface defects that is available for concrete bridge inspection and evaluation [2]. Being inexpensive and ease of use are the two main advantages of this technology. However, IR Thermography analysis maybe affected by many factors, such as the surface condition and the environment condition [26]. Besides subsurface defects and deteriorations, surface defects such as cracks are important indicators of structure's health and also need to be monitored. Terrestrial Laser Scanners (TLS), which are known for their capability to rapidly obtain accurate surface information of structures and present this information in the form of three-dimensional (3D) high-dense point clouds, have been used in bridge inspection as well. Thruong-Hong et al. proposed a framework that utilized TLS technology in bridge inspections for deformation measurements, damage detection, and reconstruction of 3D models. They concluded that TLS can provide sufficient information for structural condition assessment [24]. That being said, although TLS can produce high resolution and accurate output, the large file sizes and long processing times are the primary barriers of its wider adoption in the Architectural, Engineering and Construction, and Facilities Management (AEC-FM) industry. Turkan et al. [25] developed a novel adaptive Wavelet Neural Networks (WNN) based approach to overcome the drawback associated with using TLS technology for bridge inspections. The proposed adaptive WNN-based approach detects concrete cracks from low-resolution TLS point clouds, which enables 3D point cloud data to be processed quickly and detect cracks automatically. However, even with that, TLS is still not the optimal option from an economic standpoint. In [18], it was shown that the cost for TLS without annual maintenance tend to be six times or more expensive than using photogrammetry [18].

The utilization of UAS to collect aerial images has recently received significant attention in the AEC-FM industry due to its safety benefits, ease of use, mobility, and cost-effectiveness [14]. UAS is considered one of the most trending engineering tools in infrastructure inspection and evaluation. It is frequently used in high risk situations to isolate inspectors from potential workplace hazards. Images collected by UAS are of high resolution and comparable to conventional bridge inspection results [12, 17], especially with respect to identifying potential defects in bridge connections, concrete spalling, and cracks [12]. In addition, using UASs for bridge inspection has little, if any, impact on traffic flow. Furthermore, it eliminates the need to use large equipment, accelerates the inspection process, and provides opportunity to use nondestructive techniques for crack detection [16]. However, due to the low weight of UAS, the quality of images is sensitive to environmental factors such as lighting conditions and wind speed and direction [13], which may be the major hindrance for implementing UAS for condition assessment of civil structures.

74.2.3 Technology Used in Data Management for Inspection

Building information modeling (BIM) is a revolutionary development that has rapidly changed the AEC-FM industry. BIM can be considered both as a technology and as a process that embed all information needed for constructing a facility in a single, virtual 3D model. This 3D model can be transferred and shared with other project teams [5, 6]. BIM enhances project team communication and collaboration through the use of Industry Foundation Classes (IFC), a neutral file format that improves interoperability among applications with different file formats from design to operation and maintenance phases [11]. BrIM is the acronym used for BIM when it is applied to bridge projects. BrIM enables integration of defect information with each component and visualization of bridge conditions. This capability can help overcome the shortcomings in existing paper-based inspection and bridge data management practices. A framework that integrates inspected structural data with a 3D bridge information model was proposed by DiBernardo [10]. Following this work, Al-Shalabi et al. [3] proposed a 3D BrIM enabled inspection framework that implements mobile devices, and cloud computing. In this framework, information regarding bridge elements can easily be accessed using mobile devices during inspection, and inspection data such as crack type, size etc. can be added to the database easily. This framework was tested by Iowa DOT inspectors, who confirmed the benefits of implementing BrIM for bridge inspections. However, there are only a few studies focused on using BrIM for data management. In addition, there exists a gap between onsite inspection data collection for existing bridges and how to apply BrIM to integrate inspection data with virtual models for bridge management.

Previous studies demonstrated various technologies that can be utilized to improve bridge inspection and management practice, it is clear that there is a need for a systematic approach for collecting and documenting bridge inspection data. By building on the framework developed in [3], this study proposes a bridge structural inspection framework combining UAS and BrIM technologies. UAS enable safer and rapid collection of visual bridge inspection data in the form of digital images; whereas, BrIM enable storing all bridge data, including its drawings and 3D models, inspection notes, images, and other related data, in a central object-oriented database that can be accessed both from the office and in the field. This environment combines a 3D representation of the infrastructure and allows the integration of inspection data, such as the presence of damage, type of damage, severity of damage, and previous maintenance decisions.

74.3 Research Methodology

The proposed bridge inspection framework (Fig. 74.1) has three major components: (1) 3D modeling; (2) UAV imaging and processing, and (3) data integration and management.

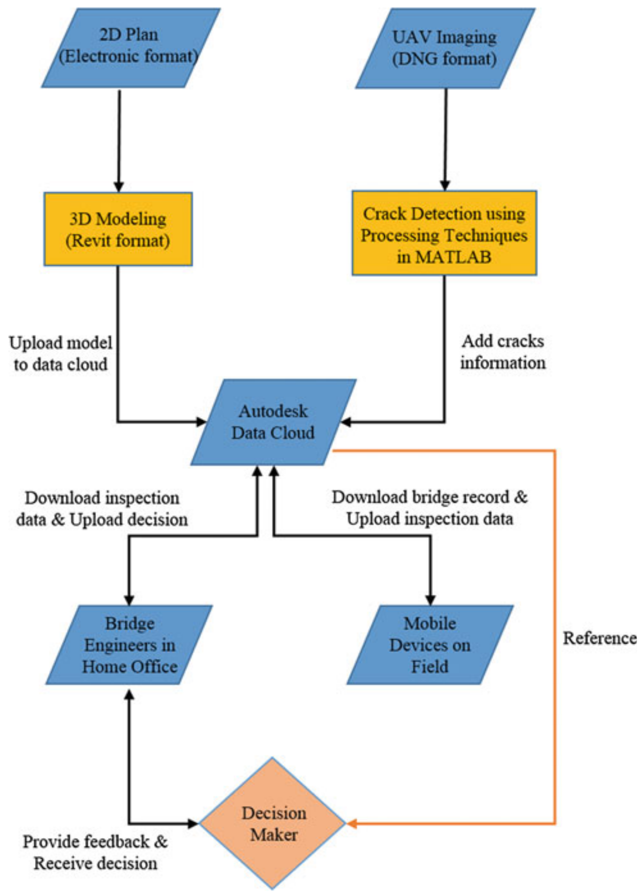

Fig. 74.1 Proposed bridge inspection framework

First, 3D BrIM model of the bridge is built at element-level using conceptual mass in Revit based on the 2D as-built plans. Concurrently, images of both the overall site and bridge elements were captured using a UAS. MATLAB Image processing tools were implemented to detect cracks automatically. From the processed images, crack information such as type, location, and orientation are assigned to individual 3D BrIM elements and uploaded to Autodesk data cloud. The 3D BrIM model integrated with images from the UAS and crack information would enable inspectors quickly locate the region that has defects. In addition, the data cloud can be accessed and updated both from the site and home office, enabling all stakeholders have access to inspection data simultaneously.

For image processing, the following steps were performed using MATLAB image processing tools [15]: (1) colored images were converted to gray-scale images for further processing; (2) contrast adjustment was used for image enhancement; (3) median filter was applied to reduce noise in images; (4) bottom-hat morphological operations were applied to extract dark regions as objects from the background; (5) threshold segmentation was applied to separate cracks from the obtained objects, which results in binary images; (6) morphological area opening was applied to reduce the connected objects, and labeled cracks using bounding boxes based on region properties.

74.4 Data Collection and Preliminary Results

The proposed framework was tested on an existing bridge located on highway I-105 spanning over the Willamette River in Eugene, Oregon, which was constructed in 1967. Its total length and width are 844 and 81.17 ft respectively and has been rated as structurally deficient in the latest available inspection report, mainly due to its poor deck condition.

Fig. 74.2 Aircraft, controller, and pilot

74.4.1 UAS Data Collection

UAS flights were conducted on December 1 and 7, 2017. DJI Mavic Pro Quadcopter with a gimballed camera was used to collect 4 K video and 12-megapixel photography. The aircraft was controlled by the pilot using a remote controller connected to an Android phone (Fig. 74.2). Manual flight mode was used in this study. The pilot flew the aircraft along both sides of the studied bridge and found 5-6 feet as a safe distance while capturing high quality images. The second step of the data collection involved the pilot rotating the gimballed camera to capture high-resolution images of bridge elements from different angles. The interval of hovers was also controlled by the pilot to ensure enough overlap between the images. Real-time images and videos were displayed on the connected phone and the captured images and videos were stored in the memory card in JPEG and MP4 formats respectively.

74.4.2 Preliminary Results

UAS Imaging. 334 high resolution images were successfully collected from the studied bridge. The flight time for each data collection was about 30 min, which drastically shortens the time inspectors spent on site compared to traditional inspection practice. 260 high-resolution images successfully captured defects such as cracking, efflorescence, spalling, and joint leakage. Sample images show some of these defects (Fig. 74.3).

Crack Detection. All original images from UAS were converted to gray-scale images for image processing. The workflow and the results for sample crack detection are shown in Fig. 74.4. After adjusting image intensity values, the contrast between the background and cracks were improved; cracks became darker and the background became brighter. Also, contrast enhancement made material deficiencies around cracks clearer. Next, mean filter was applied to remove Salt and Pepper noise, which smoothed the gray value of pixels while preserving the edges and details of the cracks. Since cracks have lower gray values, bottom hat transformation was performed to enhance dark regions of interest, i.e. cracks. However,

Fig. 74.3 Sample images of defects: **a** cracking with efflorescence on the side of the box **b** spalling area underside the box **c** rust staining on the concrete column

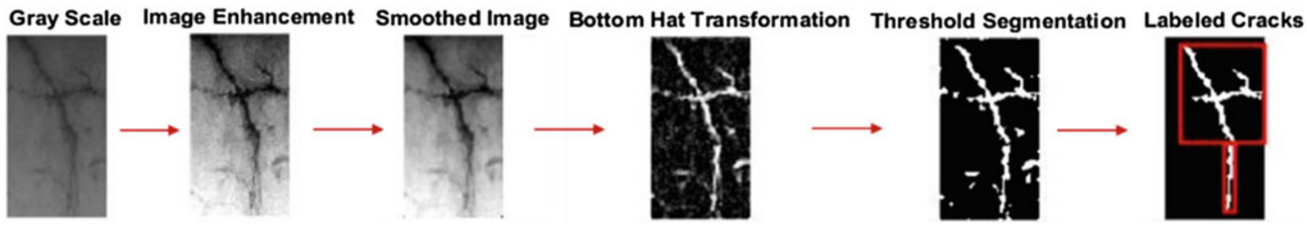

Fig. 74.4 Sample detection results of the workflow

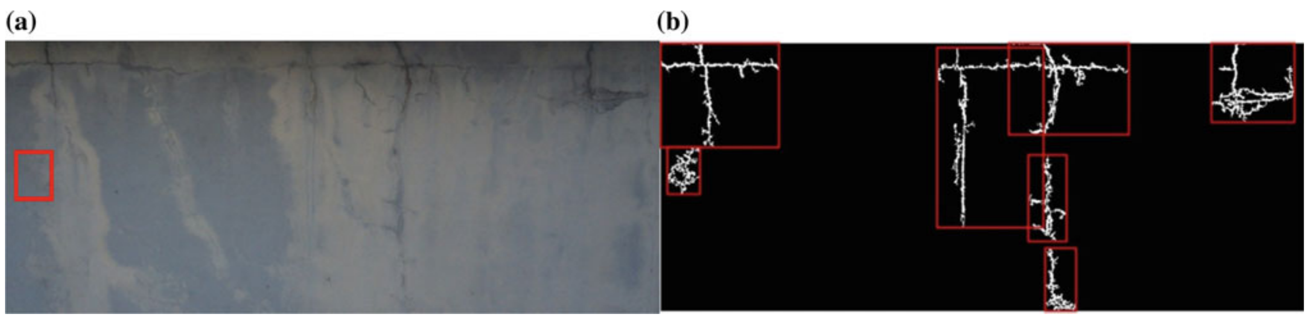

Fig. 74.5 Example of results: **a** original image that was captured by UAS **b** labeled cracks that detected based on the workflow

some dark regions except cracks were also enhanced and extracted after threshold segmentation. Morphological area opening was applied to remove the connected isolated small objects. As a last step, the cracks were labeled on images.

Detection results of an example image revealed that seven hairline flexure objects were detected automatically as cracks (Fig. 74.5b). However, a visual comparison revealed that one crack was falsely detected (false positive) (labeled in Fig. 74.5a). This indicates the need for future research focus on improving classification and machine-learning techniques to improve the detection accuracy.

Data Integration and Management. The 3D bridge model was built using conceptual mass in Revit (Fig. 74.6a). The conceptual massing environment is suitable for modeling irregular shapes that is good for modeling curved bridges. Although the massing environment does not provide shapes that are unique for a bridge, bridge elements can be built by creating custom families. It provides a visual representation of the bridge and enables storing all inspection data in a single model.

For data integration, BrIM model is converted to IFC format (Fig. 74.6b), a neutral file format that facilitates data exchange between different software. Cracks or defects identified during the crack detection step as well as all UAS images can be assigned to individual bridge elements by modifying the IFC file. This is done by updating the line in the IFC text file that represents the specific bridge element with a string containing crack information for that particular element. This information appears in the description field for the specific element when IFC file is imported into Version 2.18.11 of BIM vision software (Fig. 74.6c). For data management, the integrated model along with original UAS images and previous inspection information are uploaded to Autodesk data cloud (BIM 360 Glue was used in this study). The images of individual elements can be linked to that model element as well. Based on the condition of a specific element, different colors are used to represent different condition states (e.g. green: good condition, red: critical condition). This data cloud can be accessed and updated from both the worksite and home office simultaneously, enabling critical, timely decision making.

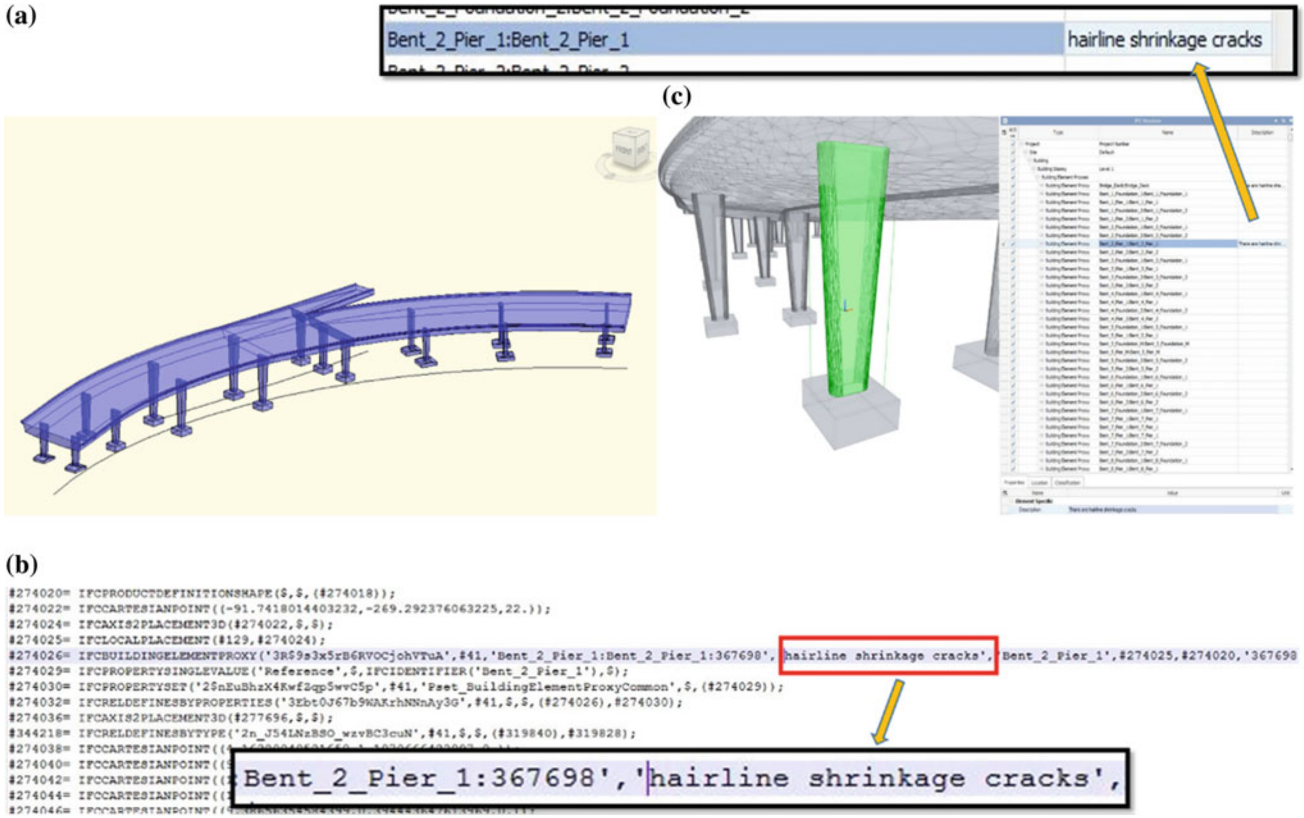

Fig. 74.6 **a** 3D BrIM model in Revit **b** sample IFC text file with crack information **c** integrated BrIM model opened in BIM Vision

74.5 Conclusions and Future Work

Although bridge inspection is a critical task needed to monitor bridge quality and serviceability, current bridge inspection practice is considered inefficient mainly due to its time-consuming, costly, unsafe, and subjective nature. Moreover, current BMS do not satisfy the increasing need to coordinate management of all phases for entire bridge life cycle. Also, the dispersed inspection data drastically reduces the effectiveness of the system. This study proposed a novel framework that uses BrIM and UAS data to improve current bridge inspection practice. This study proposed a novel framework that implements BrIM and UAS data to improve current bridge inspection and management practice. By testing the proposed framework on an existing bridge, the results verified that high-resolution images captured by UAS enable identification of different types of defects, and detect cracks automatically using computer vision algorithms. Furthermore, the results also verified that the use of BrIM enable assigning defects information on individual model elements, manage all bridge data in a single model, and has the potential to reduce the number of visits while eliminating data re-entry with the assist of cloud computing. In addition, the proposed framework has the potential to improve the current inspection practice in terms of safety, cost-efficiency, and effectiveness. Future research will focus on assessing the practicality of the proposed framework through a survey among state DOTs, focusing on Region 10 DOTs (Alaska, Idaho, Oregon and Washington). Furthermore, to increase crack detection accuracy, it is necessary to develop appropriate classification operators to separate real cracks from similar objects. Machine learning algorithms will be investigated to train the classifier on a large database of images containing different types of cracks.

References

1. AASHTO: The manual for bridge evaluation, Washington, D (2011)
2. Abu Dabous, S., Yaghi, S., Alkass, S., Moselhi, O.: Concrete bridge deck condition assessment using IR Thermography and Ground Penetrating Radar technologies. Autom. Constr. **81**, 340–354 (2017)
3. Al-Shalabi, F. A., Turkan, Y., & Laflamme, S. BrIM implementation for documentation of bridge condition for inspection. In Proceedings of the Canadian Society for Civil Engineering 5th International/11th Construction Specialty Conference, University of British Columbia, Vancouver, Canada. June (pp. 7–10) (2015)
4. ASCE's 2017 Infrastructure Report Card (2017)
5. Azhar, S.: Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. Leadersh. Manage. Eng. **11**(3), 241–252 (2011)
6. Azhar, S., Khalfan, M., Maqsood, T.: Building information modelling (BIM): now and beyond. Constr. Econ. Build. **12**(4), 15–28 (2015)
7. Bu, G., Lee, J., Guan, H., Blumenstein, M., Loo, Y.-C.: Development of an integrated method for probabilistic bridge-deterioration modeling. J. Perform. Constr. Facil. **28**(2), 330–340 (2014)
8. Chan, B., Guan, H., Hou, L., Jo, J., Blumenstein, M., Wang, J.: Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. J. Civil Struct. Health Monit. **6**(4), 703–714 (2016)
9. Committee of Economic Development: https://www.ced.org/reports/single/fixing-americas-roads-bridges. Last accessed 6 Jan 2018
10. DiBernardo, S.: Integrated modeling systems for bridge asset management—case study. Structures Congress 2012, Proceedings (2012)
11. Eastman, C.M., Eastman, C., Teicholz, P., Sacks, R.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Engineers and Contractors. Wiley, Designers (2011)
12. Gillins, M.N., Gillins, D.T., Parrish, C.: Cost-effective bridge safety inspections using unmanned aircraft systems (UAS). Geotechnical and Structural Engineering Congress 2016, Proceedings (2016)
13. Morgenthal, G., Hallermann, N.: Quality assessment of unmanned aerial vehicle (UAV) based visual inspection of structures. Adv. Struct. Eng. **17**(3), 289–302 (2014)
14. Liu, P., Chen, A.Y., Huang, Y.-N., Han, J.-Y., Lai, J.-S., Kang, S.-C., Wu, T.-H., Wen, M.-C., Tsai, M.-H.: A review of rotorcraft unmanned aerial vehicle (UAV) developments and applications in civil engineering. Smart Struct. Syst. **13**(6), 1065–1094 (2014)
15. MathWorks: Bioinformatics Toolbox: User's Guide (R2016b). Retrieved September 15, 2016. from http://studylib.net/doc/13513659/bioinformatics-toolbox%E2%84%A2-user-s-guide-r-2016a (2016)
16. Metni, N., Hamel, T.: A UAV for bridge inspection: visual servoing control law with orientation limits. Autom. Constr. **17**(1), 3–10 (2007)
17. Otero, L.D., Gagliardo, N., Dalli, D., Huang, W.H., Cosentino, P.: Proof of concept for using unmanned aerial vehicles for high mast pole and bridge inspections (No. BDV28 TWO 977-02). Florida Institute of Technology (2015)
18. Ravanel, L., Curtaz, M.: Terrestrial laser scanning (TLS)/Photogrammetry (2011)
19. Sacks, R., Kedar, A., Borrmann, A., Ma, L., Brilakis, I., Hüthwohl, P., Barutcu, B.E.: SeeBridge as next generation bridge inspection: overview, information delivery manual and model view definition. Autom. Constr. **90**, 134–145 (2018)
20. Shamsudin, A.M., Senin, S.F., Hamid, R., Yusuf, K.: Concrete delaminations location and its severity detection by visual inspection and ground penetrating radar. J. Eng. Sci. Technol. 10(Spec. Issue on 4th International Technical Conference (ITC) 2014), 1–12 (2015)
21. Shirolé, A.: Bridge management to the year 2020 and beyond. Transp. Res. Rec. J. Transp. Res. Board **2202**, 159–164 (2010)
22. Tarussov, A., Vandry, M., De La Haza, A.: Condition assessment of concrete structures using a new analysis method: ground-penetrating radar computer-assisted visual interpretation. Constr. Build. Mater. **38**, 1246–1254 (2013)
23. TheWashingtonPost: https://www.washingtonpost.com/news/gradpoint/wp/2018/03/16/recovery-efforts-continue-following-florida-bridge-collapse-at-least-6-dead/?noredirect=on&utm_term=.116b39299fcc, last accessed 2018/3/17
24. Truong-Hong, L., Falter, H., Lennon, D., Laefer, D.F.: Framework for bridge inspection with laser scanning. In EASEC-14 Structural Engineering and Construction, Ho Chi Minh City, Vietnam, (2016)
25. Turkan, Y., Laflamme, S., Tan, L.: Terrestrial laser scanning-based bridge structural condition assessment. In Trans Project Reports (2016)
26. Vaghefi, K., Melo e Silva, H., Harris, D., Ahlborn, R.: Application of thermal IR imagery for concrete bridge inspection. In PCI National Bridge Conference, PCI/NBC, Salt Lake City: UT (USA), pp. 1–12 (2011)

Part V

Cyber-Physical-Systems

75

Comparison Between Current Methods of Indoor Network Analysis for Emergency Response Through BIM/CAD-GIS Integration

Akram Mahdaviparsa and Tamera McCuen

Abstract

The main mission of the fire service is protecting life, assets, and natural resources from fire and other hazardous incidents. Geographic Information System (GIS) is supposed to ideally decrease the required time for dispatching first responders to the incident site, while it has some deficiencies in showing and analyzing indoor space and routing. Building Information Modeling (BIM) is a data-rich, potential source for finding the most efficient routes within a building. Researchers have developed the methods, algorithms, and platforms to make indoor navigation analysis easy and understandable for occupants. They have worked on different alternatives of indoor network analysis through a process of applying the different methods to a study model, but it has not been defined which method is more appropriate to first responders' responsibilities. This paper reports on indoor networks analysis for first responders considering the importance of route finding in emergencies. We analyzed the similarities and differences of each method and algorithm, created an indoor network through ESRI's Campus Viewer Tool and conducted interviews with a fire marshal and his team. Participants reviewed eight models, including the indoor network analysis model created by the researchers. Findings revealed the indoor network analyses most compatible with the 3D model, easy to read, and understood by first responders.

Keywords

Computer-Aided drawing (CAD) • Building information modeling (BIM) • Geographic information system (GIS) Indoor network analysis • First responders • Emergency

75.1 Introduction

The mission of the fire service is to protect life, assets, and natural resources from fire and other hazardous incidents. According to the National Fire Protection Association (NFPA) Research, Data, and Analytics Division, in 2016 U.S. fire departments responded to 1,342,000 fire incidents [1]. Statistics from 2016 include 475,500 structure fire incidents, which led to 2950 deaths, 12,775 injuries, and approximately $7.9 billion lost in the property. These statistics prove that structure fires must be taken more into consideration due to the critical and desperate nature of consequences from this type of fire incident. Every second is valuable and any delay in response to a fire can make a difference between saving a life, injury, and even death. It is important that both building occupants and firefighters be secured from injury when a fire incident happens.

For over 40 years the U.S. Fire Administration (USFA) has monitored firefighter fatalities resulting from reported fire incidents. In 2016 a total of 159 firefighters lost their lives in their attempt to extinguish structure fires, the majority of which was a result of the firefighter losing orientation and navigating errors inside the structure during the fire [2]. Search and rescue in unfamiliar buildings is a vital part of firefighters' responsibilities that can lead to a subsequent hazard. Providing

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firefighters with precise building information is a potential solution for mitigating the hazard of getting lost inside the building [3].

Tashakkori et al. [4] emphasize that it is vital for first responders to be aware of the incident environmental situation in a building. They believe that if first responders are prepared with information about interior spaces, number of building occupants in each space, and other critical information about the facility in advance, their capabilities would increase dramatically [4]. Results from a study by Boguslawski et al. [5] revealed the importance of precise evaluation of an incident and how inappropriate decisions can extend the response time. The study concluded it is essential that when arriving at an incident the first responders have actual and reliable information about: (1) the building's interior, (2) surrounding neighborhoods and facilities, and (3) quickest routes to the incident location inside the building [5].

Holmberg et al. [6] reported the importance of an integrated plan to provide emergency responders with building information so they have a comprehensive understanding of the indoor and outdoor environment. Additionally, first responders should have information about the building's interactions with adjacent facilities to decrease the potential for wandering during the response to the incident location. The study recommended remote access to building information would improve the first responder's knowledge about the building and thereby enhance safety and minimize injuries and damages [6]. Unfortunately, most of the required facility emergency information is not provided to firefighters until reaching the scene, which threatens the lives of firefighters and makes their decision making a complex process [4].

Geographic Information System (GIS) is an outdoor environment analysis tool with the potential to supplement the decision-making process at an incident site and even assist with decisions during dispatch to the site. A study by Chen et al. [7] discovered the recommended approach for emergency response is one that analyzes and provides first responders with optimal routes for navigation both outside and inside the building.

Although the capabilities of GIS has advanced in recent years further development to improve on the display and analysis of the indoor environment for the purpose of emergency response navigation during a fire. The negative effect of insufficient knowledge about a building's indoor environment impedes firefighters' capabilities and jeopardizes their safety [8].

While GIS technology has proven capabilities for the outdoor environment, a data rich building information modeling (BIM) is a potential source for finding the most efficient interior routes in the future [9]. The two modeling domains of BIM and GIS are broadly utilized for design and construction modeling, but not so much for use in emergencies.

Vanclooster and De Maeyer [10] suggested that a suitable indoor routing needs a well-defined indoor network, semantic information, and linkage between indoor and outdoor network which may be achieved by the integration of BIM and GIS. The implications of developing an integrated model in which BIM and GIS technology combined with a solution for reliable indoor navigation is important [11, 12].

Indoor network analysis as a part of BIM-GIS integration has gained momentum in recent years with researchers [4, 12–17]. Although new methods, algorithms, and platforms have been developed to make indoor navigation analysis easy and understandable for first responders and building occupants, it is unclear which method best meets the needs of first responders. The study reported in this paper seeks to add some clarity to the topic through its literature review and qualitative analysis of interview responses. The literature review is organized into three sections: (1) Application of BIM in network analysis and navigation, (2) Application of GIS in network analysis and navigation, and (3) Application of BIM-GIS integration in network analysis and navigation. Findings from interviews follow the literature review.

75.2 Literature Review

75.2.1 Application of BIM in Network Analysis and Navigation

BIM remains a dynamic topic in the design and construction fields of research with an increased focus on the integration of information. As result expectations are that BIM will continue to enhance the integration process and interoperability of technologies across disciplines. Industry Foundation Classes (IFC) is a file format developed by the International Alliance of Interoperability (IAI, also known as buildingSMART) for the purpose of interoperability between the many different software platforms potentially accessed for building information during the facility lifecycle [18]. The IFC format provides for the exchange of data rich three-dimensional facility representation that can be accessed by first responders before arrival and entry to an emergency incident. Expectations are this integrated information would enhance their capability and improve their safety in the building at the time of incident [4, 19].

Although BIM can provide a basic model in emergencies there is a need for first responders to have a real-time indoor model to automatically generate navigable indoor networks [5, 20]. In a recent study Li et al. [3] completed interactive interviews with the Los Angeles Fire Department (LAFD) first responders and found the first responders have a low access to BIM, however they anticipate access would increase in the very near future. The opportunities BIM provides first responders offers a possible solution to a gap reported by Ruppel, Abolghasemzadeh, and Stubbe [21] where the development of a BIM based environment with an evacuation route for endangered people and real representation of the building posed challenges for emergency management.

In another study by Xu et al. [22] multiple problems were discovered with current methods for indoor navigation. The first problem is the two-dimensional format of indoor navigation instead of a three-dimensional form of building geometry with vertical networks. (To be concise in this paper, the two-dimensional representation of building as a floor plan is summarized to 2D plans and a three-dimensional form of the building is summarized to 3D models). The other problem is lacking the building semantic information which needs further development. One possible solution to the problems facing indoor navigation is a Variable Density Network (VDN) in which automated egress paths are constructed [5]. VDN is utilized to determine an indoor routing including an entire 3D model with topology attributes which represent the connection between spatial elements. In comparison between VDN and other navigation approaches, researchers claim VDN is more accurate in the way finding.

In 2010 Ruppel et al. [21] developed a method for first responders to find the quickest route in a complex building. The Their study concluded that generating a BIM for the indoor network is a time-consuming task with an intricate data structure not necessary for the purpose of emergency response [21]. A similar conclusion was reported by Wu and Zhang [12] who found that while all semantic and geometric information supports interoperability, however data redundancy should be reduced in the BIM model with data transformation specific to the goals for first responders. Another study on this topic by Tashakkori et al. [4] emphasized the simplicity of methods used to present building information due to the limited time first responders have after dispatching until arrival the scene to get information from the model. Therefore, the information included in the building model must be chosen with enough knowledge and care [4].

Xu et al. [22] used BIM as the 3D model for mapping inside the building and focused on indoor routing around known obstacles such as furniture in a multistory structure. With a new methodology Vandecasteele et al. [8] proposed an outline based on semantic information and computer technology to develop navigation and route finding under fire emergency hazards. Their method was novel because of semantic relationship between BIM and the objects captured by visual and thermal imaging cameras [8].

75.2.2 Application of GIS in Network Analysis and Navigation

GIS provides many tools and data related to the exterior properties of a facility. Taking advantages of some tools and extensions, like network analysis, firefighters could arrive at the incident location well prepared. The need to model the indoor environment for routing has led researchers to use a variety of technologies, such as laser scanning and CAD data to build the 3D model of the facility, however many are not helpful for firefighters due to the lack of semantic information like material types, doors, and windows properties. In 2016 Jamali, Abdul Rahman, and Boguslawski presented indoor modeling with Dual Half Edge (DHE) data structure and integrated it with the outdoor network from Open Street Map (OSM). They gained 3D data and modeled the building through Trimble M3, which is a surveying tool that does not include a BIM model of the building [23]. To generate a 3D model of the building, Tsiliakou and Dimopoulou [24] used CityEngine for the exterior of the building and ArcScene for indoor elements, both tools are commercially available through Esri. Although BIM was not used to create the building model, the study referenced BIM as a technology with features to represent the indoor environment both semantically and geometrically [24].

75.2.3 Application of BIM/CAD-GIS Integration in Network Analysis and Navigation

Zverovich et al. [14] proposed a new approach to find the safest indoor route that considers a hazardous event like fire with some epicenters are happening. Their concern was finding the shortest route considering proximity to hazard and they could find the safest route which is a trade-off between length and closeness to hazard. Their new algorithms were based on algorithms introduced by Boguslawski et al. [5] and they used an integrated BIM-GIS model as an underlying 3D model of the building [5, 14]. The other research conducted by Tashakkori et al. [4] presented a new method for indoor way finding. They developed their method in three parts: (1) indoor building information, (2) semantic information of building, and (3) outdoor emergency information and connecting outdoor to indoor information [4].

Teo and Cho [17] proposed a multi-purpose geometric network model (MGNM) based on BIM and made a link between indoor and outdoor routes. They converted IFC to MGNM and then created the topological relationship of MGNM to GIS Geodatabase [17]. Early researchers such as Isikdag et al. [18] investigated the approach of transferring BIMs into the geospatial environment and focused on fire emergency response. Li and He [15] tried to link BIM model and 3D GIS system and developed the 3D building with a route-oriented semantic model. They built a topological relationship through the medial axial transformation algorithm and created an indoor network with the Dijkstra's algorithm [15].

Furthermore, IndoorGML as a new approach to indoor navigation is an "Open Geospatial Consortium (OGC) standard for representation and exchange of indoor navigation models (geometry and network). It provides a framework to represent indoor spaces and their topology (connectivity), which are needed for the components of navigation networks. It is seen as a complementary standard to CityGML and IFC" [25]. Alattas et al. [26] concluded that the IndoorGML goal is to represent the principles of indoor navigation through a comprehensive framework to depict 3D models for the indoor network.

Xu et al. [16] developed two navigation methods. In the first method, they created routes inside a building by its 2D floor plans and limited semantic information and linked with GIS technology. For creating an indoor network, they utilized Triangulated Irregular Network (TIN). As the second method, they imported BIM model into ArcGIS™ through the Data Interoperability Extension in ArcGIS™. This means that using Data Interoperability Extension, they could translate IFC to a file geodatabase which is required for routing in ArcGIS™ [16]. Another recent study by Wu and Zhang [12] presented BIM-GIS integration for indoor geo-visual analytics. They used BIM just for visualization and did not consider semantic information in the integration process [12]. As a recent navigation tool, ESRI's Campus Viewer Tool is a set of tools for converting indoor CAD to GIS and creating a 3D network [27].

Tashakkori et al. [4] concluded that the current approaches in BIM-GIS integration for indoor navigation suffer from "(1) they emphasize the architectural elements, (2) they are designed for visualization purposes only, (3) the lack of necessary emergency information required about the incident and its area" [4]. However, this research does not consider what information can help first responders to meet their goals to save lives and properties using BIM-GIS technology and it will be for the future research.

The following sections further investigate the usefulness of these methods and approaches previously tested by researchers in an attempt to find which one could best assist first responders. The result of the comparison is summarized in Table 75.1.

75.3 Methodology

In this study, we conducted a literature review on BIM/CAD-GIS integration for indoor network analysis and compared and categorized the scholars' approaches towards indoor navigation. A building was then modeled through the recently-published Esri tool (Campus Viewer Tool) for indoor navigation and a focus group meeting with a fire marshal was conducted. The 2D plans and 3D models of buildings, the results of eight research papers mentioned in Table 75.1, were given to first responders. We wanted them to compare the 2D plans and 3D models to find the level of readability and understandability of each method. The workflow for creating an indoor network through Esri Campus Viewer Tool is presented in the next section.

75.4 Workflow

This section details the work tasks performed in this study. As shown in Fig. 75.1, we first generated a 3D indoor and building model using ArcGIS Pro from CAD files and building footprints, respectively. In this research we used Esri's Campus Viewer Tool, which is incorporated into the latest update for ArcGIS Pro 10.4 and supports the workflow of producing indoor geodatabase datasets from CAD drawings. Moreover, our input CAD conformed to the American Institute of Architects (AIA) specifications for the indoor environment.

With this tool, a user can find people or places in a 3D model and operate the program in a web browser. A search widget can help to find personal or office numbers and generate 3D routes between any two locations in the scene. The tool supports the use of route restrictions for elevators or stairs and reports a summary of total travel time and distance. We imported the building model, which includes various spaces such as offices, conference rooms, corridors, and interior walls, from CAD to GIS.

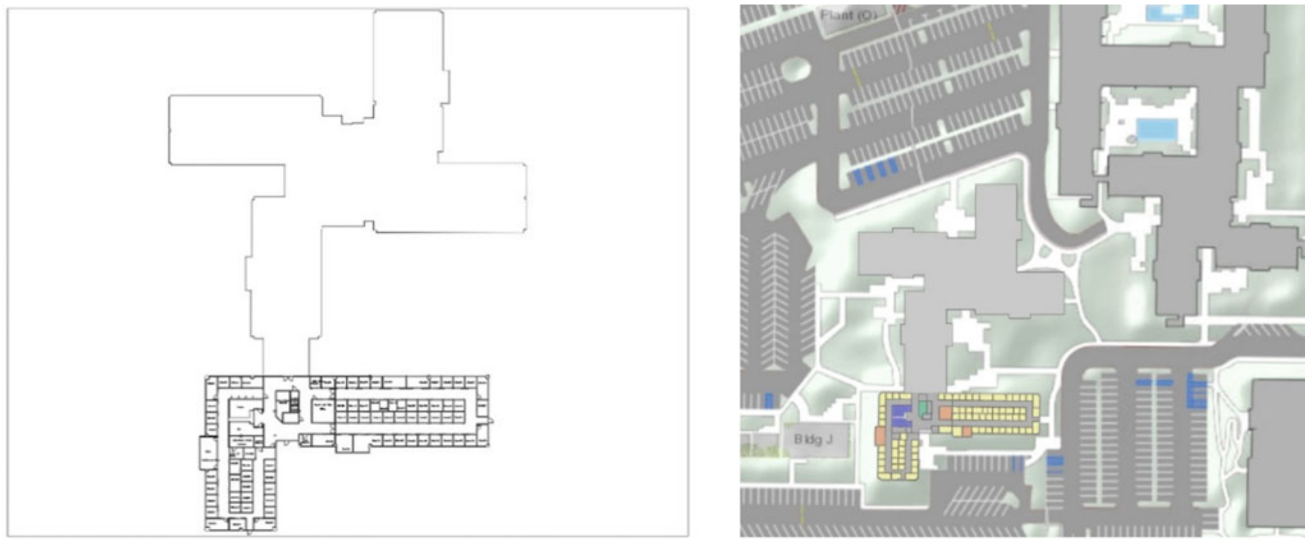

Fig. 75.1 Architectural plans of a part of OOA building. The details of each step using Campus Viewer Tool are discussed in the following section

A portion of building OOA on the Esri campus in Redland, California was used to create the indoor network. The CAD files inserted into ArcGIS Pro included floorplans, building rooms, walls, doors, stairs, and the elevator polygons which were all required for routing (Fig. 75.1).

75.4.1 Geodatabase Creation from CAD Data

We imported CAD data for indoor spaces and building into an ArcGIS™ Geodatabase using the Indoor CAD to GIS geoprocessing tool. The Indoor CAD to GIS tool is designed to work with CAD drawings that have consistent layer naming and are in a real-world coordinate system. This tool is a Python tool and has configuration macro that converts CAD to GIS layers in the Local Government Information Model (LGIM), or to a "generic" indoor dataset. We exported our model to the Esri LGIM directly from the tool as a preferred output.

After running the tool, the output included these layers: Building, BuildingFloor, BuildingFloorplanLine, and BuildingInteriorSpace. Furthermore, the output layers had a Z coordinate system and were enabled to have 3D applications (Fig. 75.2).

75.4.2 Indoor Network

The first step in generating the indoor network was to create a contiguous lattice that covered every floor's extent inside the building, but is cut by any barriers to walking transportation, such as walls or columns. Through the Create Network Lattices

Fig. 75.2 **a** 2D building floorplan, **b** 3D building floorplans, **c** 3D building form with space classification as polygons (The Authors, 2018)

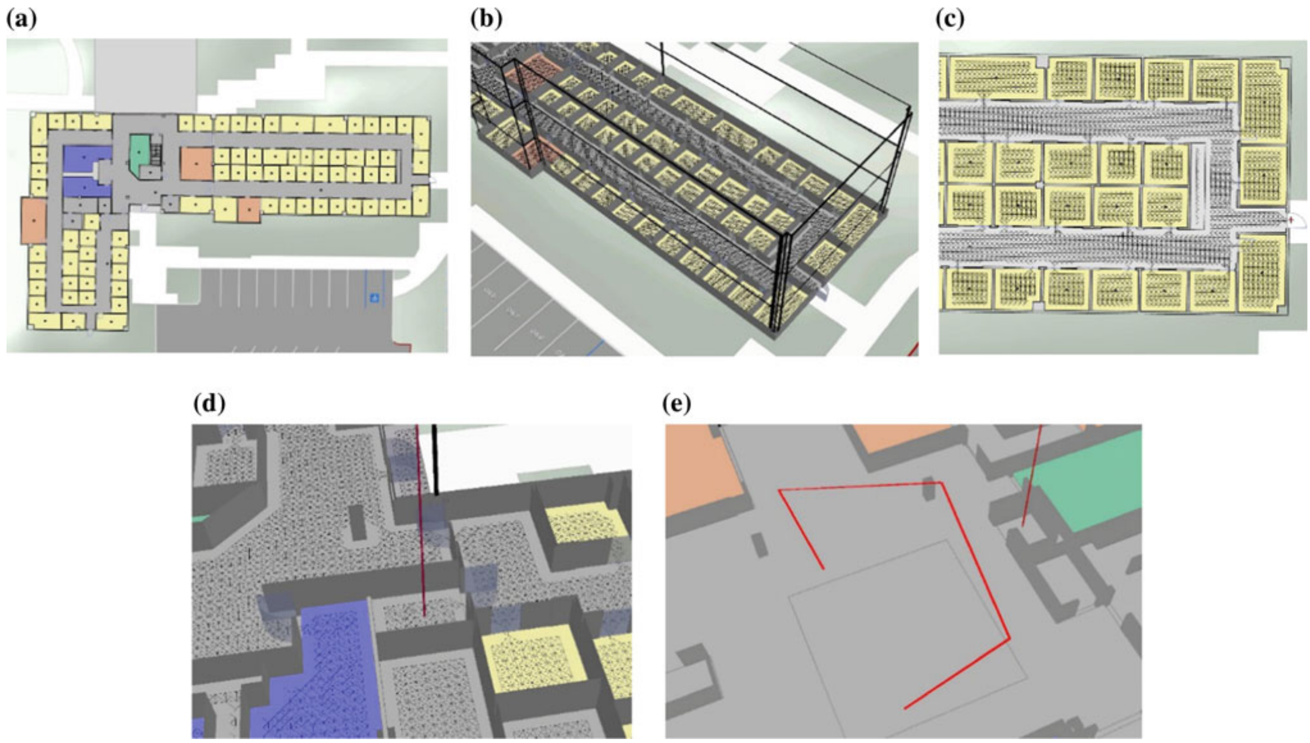

Fig. 75.3 The Indoor Network process, **a** spaces centerlines, **b** lattice, **c** ground floor entry, **d** vertical transition lines—elevator, **e** vertical transition lines—stairs (The Authors, 2018)

tool, part of the Campus Viewer Tool, we created a preliminary network lattice for each floor of a building. It was important to specify the building's entrances from the ground level. To do so we specified entrance doors to the building using Ground Floor Entry Points. Then, for the purpose of transition, we created and added transition lines which were based on vertical routing elements, such as stairs and elevators. The Campus Viewer Tool does not support creating the vertical routes automatically, and the process has to be done manually.

Through running the Network Analysis tool, which is an ArcGIS Pro Extension, the final part of the process can be done. We did not publish the result of Campus Viewer Tool on the web (Fig. 75.3).

75.5 Model Testing and Results

A pilot study was designed to explore a first responder's preferences for 2D or 3D representations to route and navigate through a building in the event of an emergency. This study limited participation to one domain expert with over 20 years of experience as a first responder and fire marshal. The intent was to develop procedures for future research based on testing questions and representations used for this study. A single interview was performed to measure the response for each representation of indoor navigation as shown eight of the thirteen studies in Table 75.1. The other remaining five studies did not include 2D plans or 3D models of the building, therefore they were not included in this study. In addition to the eight representations used in Table 75.1, the representation created as a result of our indoor network analysis in the ESRI Campus Viewer Tool was used as a comparison to each of the other representations. Objectives of this research were to discover: (1) if the 2D and 3D representations for each building "understandable", and (2) if the route finding in each of the 2D and 3D representations was "readable". The term "understandable" was used to measure the participant's response to the navigation information shown in the 2D plans and 3D models.

According to Rensink [28], visualization allows the viewer to understand information at a higher pace as connections and relationships are best conveyed through visual methods. He believed information representation through visualization is the best means to understandability—by using the right visualization techniques for the right dimensions and conveying the information to the viewer at the right time [28]. So, the term "understandable" was used to measure the participant's response to the navigation information shown in the 2D plans and 3D models. A representation is counted as successful where it is

Table 75.1 Comparison between current application of BIM and GIS in navigation methods

Authors	BIM/CAD	GIS	Visualization	Semantic info	2D	3D	Graph algorithm	Application	Fire simulation	Other notes
Zverovich (2016)	Y	Y	Y	Y		Y	Dijkstra, DHE data structure	Evacuation	N	
Li (2008)	Y	Y	Y	Y		Y		Indoor navigation	N	
Choi (2014)	Y	N	Y	Y		Y		Evacuation	N	
Xu (2016)	Y	Y	Y	Limited	Y	Y	Triangulated irregular network (TIN)	Evacuation	N	2 Parts: 2D and 3D
Xu (2017)	Y	N	Y	Y		Y		Indoor navigation	N	
Brown (2013)	IFC	Y	Y	N				Indoor navigation	N	
Wu (2016)	Y	Y	Y	N		Y	ArcScene network analysis	Evacuation	N	
Vandecasteele (2017)	Y	N	Y	Y		Y		Evacuation, indoor navigation	Y	Sensor and thermal Camera
Tsiliakou (2016)	N	Y	Y	Y		Y	ArcScene network analysis	Indoor navigation	N	ArcGIS, CityGML for Visualization
Teo, 2016	Y	Y	Y	Y		Y	Dijkstra	Indoor navigation	N	MGNM
Boguslawski (2016)	Y	N	Y	Y		Y	Variable density network (VDN)	Evacuation	N	Revit > gbXML, DHE data structure
Jamali (2016)	N	Y	Y	N		Y	In(DHE) + Out (OSM)	Indoor navigation	N	
Campus Viewer Tool	Y	Y	Y	N		Y	ArcGIS Pro network analysis	Indoor navigation	N	

able to encode information in a way that the viewers' brains can understand, and eyes can encode. Achieving this goal can be possible by studying human perception and it is a science than an art. Translating abstract information into visualization which can be decoding in an efficiently, easily and meaningfully manner is the goal of understandability [29]. We used understandability concept to measure the first responder's perception of the building model to get how much they can encode the building information presented by 2D plans and 3D models.

Typically, the term "readability" refers to the clarity and speed with which content can be digested over the written text. The definition of readability was expanded by Lambert, Bourqui and Auder [30] to measure the legibility of graphical elements used to represent graphical information like routing and navigation, and is the definition used for this study.

Results from this study indicated a preference to use 2D plans for navigation, and that the elaborated level represented in the 3D models initially had a negative impact on understandability. According to the results from this study, the greatest importance for first responders is to fully understand the building's layout; access points; room and corridor locations; hazardous material locations; and location of occupants. Although the preference was for the 2D plan to navigate routes through the building, there was evidence that a 3D model of the building contributes to further understanding the building's overall volume, vertical adjacencies, and boundaries. Further research is needed to explain the discrepancies between the results reported from this study. It appears that the difference in the quantity of information represented by 2D plans and 3D models had an impact on the cognitive load required for processing, which may have impacted the understandability and readability reported in this study.

75.6 Conclusion

The indoor network was created for a building and tested by first responders in a campus environment. An analysis of opinions communicated about the 2D plans and 3D indoor network of the building representations. Participants claimed that the indoor location information is one of the most important items in all stages of building emergency response operations, and having a ready to use, simple and quick access platform can help first responders to safely meet their goals more efficiently. It is also vital to provide first responders with accurate, robust, and real-time indoor location information so that first responders can prioritize spaces that are more likely to have occupants when planning the search and rescue routes and protect their own safety during the operations. This would help first responders avoid the possibility of getting lost in buildings, as well as avoiding the associated fatalities and injuries.

The results of this research show both 2D plans and 3D models of the building are useful for first responders. It was also reported by participants that fire stations are in the process of switching from the traditional paper-based 2D representations to digital interactive representations of routes and buildings for reference during an incident. Ultimately it was revealed that the 3D model of a building is an appropriate method for providing an understandable overview of the building and its spaces for first responders, while the 2D floor plans are more readable for the purpose of navigation. Expectations are both 2D plans and 3D forms of buildings with automatic route finding will enhance the capabilities and decision making of first responders in hazardous situations.

References

1. Haynes, H.J.G.: Fire loss in the United States during 2016, National Fire Protection Association, Data and Analytics Division (2017)
2. USFA: Fire-related firefighter injuries reported to the national fire incident reporting system (2012–2014). Top. Fire Rep. Ser. **17**(6), 1–12 (2016)
3. Li, N., Becerik-Gerber, B., Soibelman, L., Krishnamachari, B.: Comparative assessment of an indoor localization framework for building an emergency response. Autom. Constr. **57**, 42–54 (2015)
4. Tashakkori, H., Rajabifard, A., Kalantari, M.: A new 3D indoor/outdoor spatial model for indoor emergency response facilitation. Build. Environ. **89**, 170–182 (2015)
5. Boguslawski, P., Mahdjoubi, L., Zverovich, V., Fadli, F.: Automated construction of variable density navigable networks in a 3D indoor environment for emergency response. Autom. Constr. **72**(2), 115–128 (2016)
6. Holmberg, D.G., Raymond, M.A., Averill, J.: Delivering Building Intelligence to First Responders. NIST, Gaithersburg (2013)
7. Chen, L.C., Wu, C.H., Shen, T.S., Chou, C.C.: The application of geometric network models and building information models in geospatial environments for fire-fighting simulations. Comput. Environ. Urban Syst. **45**, 1–12 (2014)
8. Vandecasteele, F., Merci, B., Verstockt, S.: Fireground location understanding by semantic linking of visual objects and building information models. Fire Saf. **91**, 1026–1034 (2017)

9. Gao, X., Chen, Y.: Research on BIM technology in construction safety & emergency management. In: Advances in Engineering Research. 112, Proceeding in 4th International Conference on Renewable Energy and Environmental Technology (ICREET) (2016)
10. Vanclooster, A., De Maeyer, P.: Combining indoor and outdoor navigation: the current approach of route planners. In: Advances in Location-Based Services, Lecture Notes in Geoinformation and Cartography, pp. 283–303 (2012)
11. Hor, A., Jadidi, M., Sohn, G.: BIM-GIS integrated geospatial information model using semantic web and RDF graphs. In: ISPRS Annals of Photogrammetry, Remote Sensing, and Spatial Information Sciences. III-4, pp. 73–79 (2016). https://doi.org/10.5194/isprsannals-iii-4-73-2016
12. Wu, B., Zhang, S.: Integration of GIS and BIM for indoor geovisual analytics. In: Halounova, L., Li, S., Šafář, V., Tomková, M., Rapant, P., Brázdil, K., Shi, W., Anton, F., Liu, Y., Stein, A. (eds.) XXIII ISPRS Congress, Commission II, pp. 455–458. (2016)
13. Isikdag, U., Zlatanova, S., Underwood, J.: A BIM-oriented Model for supporting indoor navigation requirements. Comput. Environ. Urban Syst. **41**, 112–123 (2013)
14. Zverovich, V., Mahdjoubi, L., Boguslawski, P., Fadli, F., Barki, H.: Emergency response in complex buildings: automated selection of safest and balanced routes. Comput. Aided Civil Infrastruct. Eng. **31**(8), 617–632 (2016)
15. Li, Y., He, Z.: 3D Indoor navigation: a framework of combining BIM with 3D GIS. In: Proceedings of the 44th ISOCARP Congress (2008)
16. Xu, M., Hijazi, I., Mebarki, A., El Meouche, R., Abune'meh, M.: Indoor guided evacuation: TIN for graph generation and crowd evacuation. Geomat Nat Hazards Risk **7**(1), 47–56 (2016)
17. Teo, T., Cho, K.: BIM-oriented indoor network model for indoor and outdoor combined route planning. Adv. Eng. Inform. **30**(3), 268–282 (2016)
18. Isikdag, U., Underwood, J., Aouad, G.: An investigation into the applicability of building information models in a geospatial environment in support of site selection and fire response management processes. Adv. Eng. Inform. **22**(4), 504–519 (2008)
19. Brown, G., Nagel, C., Zlatanova, S., Kolbe, T. H.: Modelling 3D topographic space against indoor navigation requirements. In: Progress and New Trends in 3D Geoinformation Sciences, pp. 1–22. Springer, Berlin, Heidelberg (2013)
20. Choi, J., Choi, J., Kim, I.: Development of BIM-based evacuation regulation checking system for high-rise and complex buildings. Autom. Constr. **46**, 38–49 (2014)
21. Ruppel, U., Abolghasemzadeh, P., Stuebbe, K.M.: BIM-based immersive indoor graph networks for emergency situations in buildings. In: Proceedings of the International Conference on Computing in Civil Engineering and Building Engineering, pp. 65–72 (2010)
22. Xu, M., Wei, M., Zlatanova, S., Zhang, R.: BIM-based indoor path planning considering obstacles—ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. IV-2/W4 (2017)
23. Jamali, A., Abdul Rahman, A., Boguslawski, P.: 3D topological indoor building modeling integrated with open street map. ISPRS—International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-4/W1(October), pp. 111–117 (2016)
24. Tsiliakou, E., Dimopoulou, E.: 3D network analysis for indoor space applications. In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W2 (2016)
25. Open Geospatial Consortium: OGC IndoorGML. Retrieved from http://www.opengeospatial.org/standards/indoorgml. Publication Date 23 Aug 2016
26. Alattas, A., Zlatanova, S., van Oosterom, P., Chatzinikolaou, E., Lemmen, C., Li, K.: Supporting indoor navigation using access rights to spaces based on combined use of IndoorGML and LADM Models. ISPRS Int. J. Geo Inf. **6**(12), 384 (2017)
27. ESRI Homepage: http://3dcampus.arcgis.com/EsriCampusViewer2017. Last accessed 10 Apr 2018
28. Rensink, R.A.: Internal vs. external information in visual perception. In: Proceedings of the 2nd international symposium on Smart graphics (pp. 63–70). ACM. (2002)
29. Soegaard, M., Dam, R.F.: The encyclopedia of human-computer interaction. The Encyclopedia of Human-Computer Interaction. (2012)
30. Lambert, A., Bourqui, R., Auber, D.: 3D edge bundling for geographical data visualization. In: Information Visualization (IV), 14th International Conference (pp. 329–335). IEEE. (2010)

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76 Instrumentation and Data Collection Methodology to Enhance Productivity in Construction Sites Using Embedded Systems and IoT Technologies

Alejandra M. Carmona, Ana I. Chaparro, Ricardo Velásquez, Juan Botero-Valencia, Luis Castano-Londono, David Marquez-Viloria, and Ana M. Mesa

Abstract

Construction projects are dynamic environments which are hard to monitor in real time conditions. Thus, traditional practices for productivity estimation, such as historical data analysis, do not provide enough information for decision making. This project proposes a new methodology to instrument and collect data in construction sites using embedded systems and IoT technologies. This solution is efficient in terms of energy, range, costs, and security of the data. In particular, it deals with one of the main challenges of implementing a Real Time Location System (RTLS). That is, we use an indoor technology and adapt it to the unfavorable conditions of constructions sites. The designed network is implemented in three different type of construction projects. Results show that our methodology can be used to determine the level of productivity of personnel in site and to record, analyze and rank their performance in different types of construction activities. This allows decision makers to promptly present alternatives to improve productivity, thus, achieving a positive impact in the fulfillment of the scope, schedule, budget, and quality of the projects.

Keywords

Instrumentation • Data collection • Embedded systems • IoT • Productivity • Construction sites

76.1 Introduction

Construction projects are complex and dynamic environments which are hard to monitor in real time conditions. Thus, preserving safety and accomplishing acceptable levels of productivity has become a main priority and challenge for Engineering and Construction [1]. In addition, traditional practices for productivity estimation, i.e, historical data analysis,

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do not provide enough information for decision making. Therefore, using new technologies to monitor variables in real time (personnel productivity and equipment usage) is essential to improve the design, analysis, planning and control processes in construction fields, as well to create programs to guarantee the workers' welfare at the workplace. Projects with automatization and information technologies (IT) integrated to their processes, could increase their productivity levels between a 31 and a 41% [2]. Moreover, using IT in working zones to enhance workers productivity, could also help to reduce the shortage of skilled workers in the construction industry [3]. According to studies conducted by McKinsey & Company for the Colombian Chamber of Construction [4], Engineering and Construction productivity levels in Colombia are behind global indicators. This is mainly because the adoption rate of new technologies is about 14%, in contrast to the international indicator that is around 48%. Other industries have tried to incorporate Internet of Things (IoT) technologies as a solution for real time measurement, analysis, and data management, which have been adapted to the construction industry, i.e the use of QR codes to identify workers and register their entry time to a productive zone. However, this is not an automated system because it requires human intervention, so the accuracy of the measurements is not guaranteed [5]. Other systems collect data automatically by using different kinds of wearable devices using Bluetooth o UHF Bluetooth and RFID technologies. Furthermore, there is a particular interest in tracking assets using Global Positioning Systems (GPS), Real-Time Location Systems (RTLS), and other geo-positioning technologies [6] and some laboratory prototypes have been presented combining Bluetooth technologies and WiFi networks for indoor location and real time tracking. Nonetheless, these laboratory tests were done within a controlled environment and conditions such as weather, network availability, and security were not taken into account [7]. Regarding the networks used for this kind of applications, the Low-Power Wide-Area Network (LPWAN) has transformed the way connections are made under the 4th Industrial Revolution because in contrast to the other similar solutions available in the market, they are low-cost, consume low energy and are wide range networks [8]. In [9], a review of different works related to RTLS in construction projects such as GPS, RFID, UWB, WLAN, Ultrasound, Infrared (IR), and Computer Vision System is presented. Additionally, there are other techniques that use the proximity of a Bluetooth Low Energy (BLE) device to different nodes with known positions in order to obtain the location of the device by triangulation methods [10]. This technology is known to be extremely accurate indoors and low cost, but it only provides positioning data in two dimensions. Other solutions have been identified worldwide for productivity measurement and analysis through embedded systems, using different types of sensors or hardware [3, 11–13]. However there is no evidence of their application in construction projects. For this reason, more efforts are needed regarding the control and planning of activities in construction sites [14].

This work presents a new methodology for data collection and analysis in dynamic environments using embedded systems and IoT technologies, including indicators to determine productivity levels of workers and equipment. It deals with one of the main challenges of implementing a RTLS in environments other than indoor locations. That is, we use an indoor technology and adapt it to the unfavorable conditions of constructions sites.

76.2 Methodology

We designed a wireless sensor network using Long Range (LoRa) technology for the communication between devices. This proposed system was designed to evaluate the productivity of people in work zones and includes BLE devices, sensor nodes to receive and transmit data, a brain or central node to integrate information between the sensors and the cloud and a platform in which information can be displayed, as described below and depicted in Fig. 76.1.

- Personnel and minor equipment devices: These are BLE devices installed on workers helmet and minor equipment, identified with a 32 digit hexadecimal number named universally unique identifier (UUID). The devices transmit a signal that can be used to determine the distance through the Received Signal Strength Indicator (RSSI), which is the measurement of the power present in the received signal at the sensor node.
- Sensor node: they scan the UUID and RSSI from personnel and minor equipment BLE devices detecting their presence in the working area. These sensor nodes communicate with the central node via LoRa.
- Central node: they work as a gateway that sends the information to an IoT Hub via WiFi or Ethernet. To ensure that the data collected can be transmitted to the cloud, the central node is located in the project offices and connected to a reliable WiFi network.
- Cloud service platform: After data is processed, the platform displays information such as the time that workers spend in specific areas of the project, the time spent on specific activities by zone and occupation, among others.

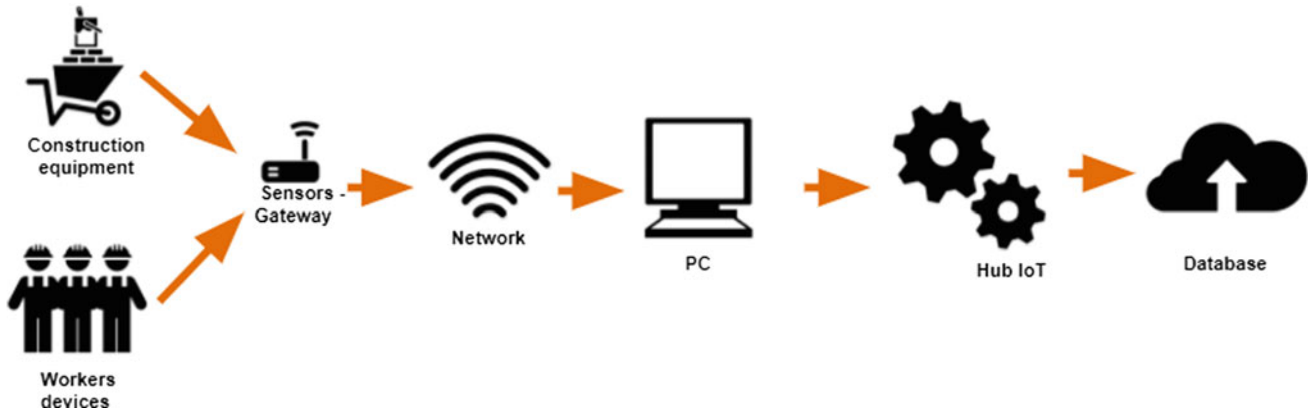

Fig. 76.1 Network design

Table 76.1 Projects specifications

Project	Dimensions	Construction system	Number of workers
Commercial building	8 floors, 4 basement plants 2 towers	Conventional column—beam—slab frame system	246
Residential building	26 floors, 672 apartments 4 towers	Conventional column—beam frame system	480
3D printed house	25 m^2	Additive manufacturing	7

Field measurements are made automatically, monitoring productive times of workers and usage levels of minor equipment. The designed network was implemented in three different types of construction projects: a commercial building, a residential building and a 3D printed concrete house. These projects are located in Colombia, South America, where normally the reliability of wireless connectivity and stable energy availability is not fully guaranteed. Table 76.1 presents some characteristics of the projects.

The system was implemented within the framework of a productivity methodology that's been recently used in all the projects of the company which enhances the measurement of labor hours in construction sites. For this reason, our complete designed system is being used as a tool for the aforementioned methodology as an input to generate performance indicators.

76.2.1 System Evaluation Procedures

Prior to the installation on field, laboratory tests were carried out to validate the operational and communication performance between all network elements in a controlled environment.

Stability laboratory test: Laboratory tests were conducted in order to verify the signal stability of the acquired devices and to validate data acquisition. For this purpose, 4 BLE devices were placed at a known distance, in line of sight, and RSSI values were read every 5 s. The standard deviation was expected to be less than 2.8 dBm for all cases.

Signal noise evaluation on laboratory: Also, normality tests were performed in the laboratory to characterize the noise present in the RSSI signal of the BLE devices. In addition to the laboratory tests conducted to validate communication between nodes and devices, field tests were carried out to evaluate the performance of the equipment and the entire system under construction conditions.

Reliability evaluation on field: A reliability test was performed to verify that nodes in production areas were constantly receiving information from installed devices. For this purpose, two fixed BLE reference devices were left on each of the nodes installed on site. Thus, a signal was expected to be received constantly and with the same strength. The data sent by the devices and received by the collector, was sent to the central node which then uploaded it to an assigned database. The data of each reference device was analyzed to evaluate the deviation between the power strength and frequency of the signal on each of them.

Sensors precision evaluation on field: This test consists in placing two nodes (A and B) at the same place within the construction site to identify whether the information received by node A is the same as the received by node B. In order to verify that both identify the same number of devices, a portion of the database was evaluated. The number of devices detected by each one of these nodes in a given period of time was compared.

Devices precision evaluation on field: Three BLE devices are positioned at the same place on the construction site for a time interval of more than 30 min at three known distances within the range of coverage of one of the nodes. The collector node located at a known distance from these devices receives the data and sends it to the central node, so that the RSSI values for each of the devices and the difference between each of them can later be verified in the database.

Distance and signal power evaluation on field: These tests allowed us to evaluate the level of congruence between the distance calculated through the received signal and the real distance. The information obtained from precision device testing is used to determine the signal strength at a given distance.

76.3 Results and Discussion

In general, results show that our methodology can be used to determine the level of productivity of personnel in site and to record, analyze and rank their performance in different types of construction activities. Tests results in laboratory are described first and then results for the system performance on field and analysis of the data are presented.

76.3.1 Test Results

Panel A in Fig. 76.2 shows an example of the reliability tests performed in laboratory, where the RRSI values obtained for a group of four BLE devices at two different distances are observed. Upper lines belong to devices placed at 30 cm of the node, the lower lines depict devices at 6 m. The standard deviation for devices at 30 cm was 2.2 and 1.7 dBm for devices at 6 m. Therefore, the precision is improved with the distance. Considering the dimension of construction projects, this test is useful to validate the accuracy of the data that can be obtained with the designed system.

Panel B in Fig. 76.2 shows a histogram for one of the devices at the two different control distances used in the test. The x axis represents the magnitude of RSSI and y axis the frequencies. The data accumulation shows the reliability of the signal for each distance.

Results for field tests carried out at the different types of projects show that there are similarities in the way how the elements of the network should be managed but the installation conditions are independent of each type of project. For example, in a commercial project with larger open spaces and fewer divisions, less nodes are required than in a residential project, which has more divisions or walls that could interfere with the signal, thus affecting the measurements. In a first phase of the project, a SigFox network was installed with good communication results during the construction of the

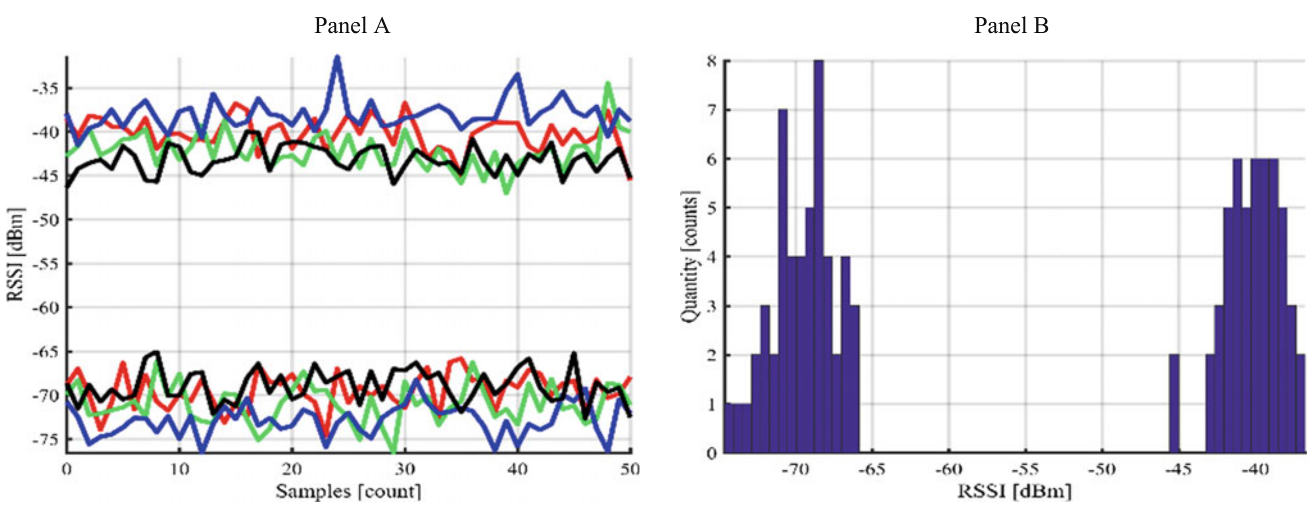

Fig. 76.2 BLE devices RSSI and FDP

foundations of the project. However, once the building started to grow vertically, communication problems arose due to the interference generated by the structure. For this reason, the network was replaced by a LoRa network, improving performance and achieving a coverage range up to 10 m underground. System field test results were kept within the tolerance levels described in the methodology.

76.3.2 System Performance

We designed a solution which is efficient in terms of energy, range, costs and security of the data. On the one hand, to ensure the interoperability of the system, personnel devices were set to transmit data at 1 Hz frequency and the nodes were allowed to receive multiple data at the same time. Arrays of twenty data were sent to the coordinator, which also sent a message to the sensor, verifying the reception of information.

From a technical perspective, the developed system performed well. LoRa networks were used for this application to support long-range communications between objects connected to the network. In general, other existing solutions (i.e RFID, GPS, UWB, WLAN, among others) require higher implementation costs when compared to our system, because they combine different technologies to reduce the influence of the construction environment to the accuracy of the evaluated systems. In terms of the internet upstream speed required to upload data to the IoT Hub, the system can reach maximum levels of approximately 1.2 MB during a day. This is low, considering connectivity conditions in construction projects in Colombia.

Devices installed on workers have a battery life of approximately 1 year, this means that they don't need to be charged. This enables the device to be changed only when the helmet needs to be replaced due to Health and Safety regulations. Each device is associated with a worker ID, their name, his contractor name, and the activity they perform on the job site. This way, it is possible to know personnel working trends. Worker's devices are the same as the ones installed on the minor equipment, so their management and operation is similar.

Designed sensors are transportable, that is, they can be relocated according to the construction program. Their configuration is adaptable so they can be connected to any project network and also they can be taken and installed in other projects. Thus, the system can be adapted to any particular design, size and progress of each project. Also, the designed nodes are composed of simple elements. They are located in hard access places, improving the security of the system.

Many project monitoring systems, whether manual or (semi-) automated, cannot be implemented due to economic constraints [3]. It is essential to emphasize that the designed network uses low cost components, reducing the costs mainly in the sensors manufacturing, increasing the chance of installing more of them on the construction sites and therefore improving the coverage in productive zones.

76.3.3 System Adoption and Implementation

The implementation of the system was made initially with construction engineers and workers that were aligned with productivity strategies in the company. This was useful in order to break adoption barriers principally with construction workers that could be resistive to this kind of measurements. At the beginning, this was a major challenge considering cultural barriers in construction workers. For this reason, workers were instructed on the importance of this project, the sensors functioning and the care that all devices needed so the system could be used to increase their welfare, as it can be linked to safety programs. This improved their acceptance towards the implementation of the sensors. The training sessions were led by the construction foreman who helped us transfer this information to the crew and during the implementation. In terms of the customer experience on field, workers manifested that the device is small, lightweight and it doesn't interfere with their activities.

Regarding the platform, it could be used by Project Managers, Construction Engineers and Productivity Department personnel.

76.3.4 Productivity Measurements Analysis

Figure 76.3 shows the probability of finding a worker in a productive zone in a day. In this figure each panel represents a different type of project. Panel A shows results for the residential building, panel B for the commercial building and panel C for the 3D printed concrete house. Regarding the functioning of the entire system for productivity purposes, results show that for a working session from 7 am to 5 pm, there is a reduction in the work activity for residential buildings at 9 am and at 12 m, which coincides with the break hours for breakfast and lunch, respectively. This is more evident in panel A in Fig. 76.3. Our results show that these granted break periods are extended for more than the established hours. This result was linked to the layout of the construction site, implying that decisions could be made so work areas are better distributed, thus guaranteeing conditions of productivity while simultaneously improving the safety and well-being of the employees.

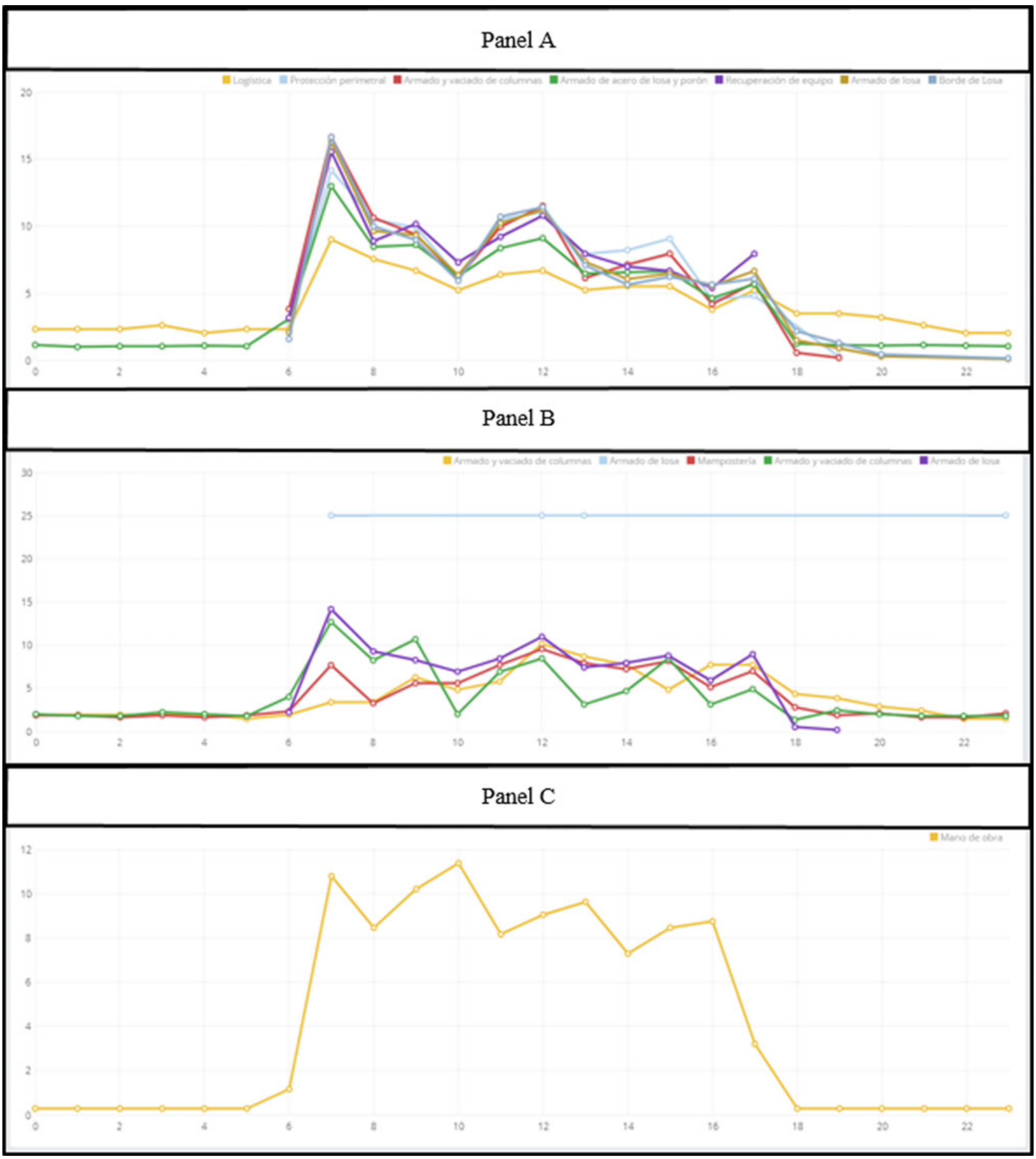

Fig. 76.3 Timeline with activities development in productive areas for residential buildings

Regardless of the differences between construction projects (Table 76.1), there are similarities mainly in the productivity hours during the day. High levels of work activity were evidenced in the early morning hours, while in the afternoon lower rates of work can be observed and a similar distribution of the personnel for the different activities that are executed in the same period of time and zones. This is even more significant for the residential project (Panel A in Fig. 76.3) in which each floor is similar to the other. This encourages a work method divided by productive units with more standardized processes, reducing nonproductive time.

Our results show that 75% of working hours during the construction of the main structure of the building correspond to the slab construction, while 18.3% is used for column construction. Although most of the activities meet the regular working schedule, there are some that are frequently extended beyond planned hours. That is the case of steel slab assembly, column casting and the activities carried out by the logistics teams, including the reception of material on site.

The monitoring of the hours spent by workers in productive and non-productive areas of the project shows that the project's operative personnel spend an average of 16% of their time in non-productive areas, including spaces such as the construction site warehouse, dining rooms, dressing rooms and bathrooms.

One of the main impacts of this project is that we were able to show that it is possible to generate information that helps to implement and evaluate productivity strategies in construction sites. Enhancements in the process of programming the work activities are presented, by supporting the corporate productivity methodologies in the projects with the information provided by the system. Additionally, less man working hours are required for productivity evaluation, due to the automation in the measurement and collection process of this information, increasing the scalability of this process.

76.4 Conclusions

Based on the implemented solution, it is possible to identify the percentage of time spent on each project for each one of the activities within the construction site, validating the certainty of the results with the work schedule. Likewise, the simultaneous monitoring of productive and non-productive zones allows us to identify periods of time that do not add value to the operation, such as waiting times at the warehouse of the worksite.

The versatility of the devices and the designed network was evaluated. The implementation of the system was successful in the different types of projects, proving that it is possible to introduce an instrumentation and data collection methodology with embedded systems for productivity analysis in construction sites, considering all the implementation variables from the technical, social and economic perspectives. This condition supports the system's necessity to be scaled up in a greater number of construction projects in order to obtain enough information to generate strategies for the improvement of the operation.

From the technical perspective, the LoRa network used in the project, is satisfactorily adapted to the construction site's distance and interference requirements, being the most appropriate option in terms of cost and performance for this application. Consequently, the future embedded systems developments applied to our construction projects, could be added to these networks in order to guarantee an accurate transmission of the data collected.

One of the future technological developments proposed for our system is an improvement of nodes, so they can be able act simultaneously as routers. This will allow the network to be implemented in larger projects. Likewise, the viability of implementing an alarm system to detect when devices are disconnected from a power source will be evaluated. Also, integrating the developed system with Building Information Modelling (BIM) methodologies is of interest, since levels of productivity in working areas and the localization of the employees could be carried out within a three-dimensional model of the project.

The obtained results allow us to plan to scale up this methodology to more building projects. In addition, this development will be connected to the personnel access control systems at the entrance of the projects, achieving a complete measurement of man working hours that can be transferred to the company's ERP systems, optimizing project planning processes.

Finally, it is important to point out that with this kind of applications it is crucial to give value to the collected information, turning IoT implementations into income generators that allow the exchange of valuable information to accelerate business innovation processes, as described by [15]. From this perspective, data collected by the devices is an important source of information that can be used with data science methodologies to detect trends in real time. This will allow decision makers to promptly present alternatives to improve productivity, thus, achieving a positive impact in the fulfillment of the schedule, scope, budget and quality of the projects.

References

1. Pradhananga, N., Teizer, J.: Proceedings of the 2012 Winter Simulation Conference. In: Laroque, C., Himmelspach, J., Pasupathy, R., Rose, O., Uhrmacher, A.M. (eds.), *IEEE* (2012)
2. Zhai, D., Goodrum, P.M., Haas, C.T., Caldas, C.H.: Relationship between Automation and Integration of Construction Information Systems and Labor Productivity. J. Constr. Eng. Manag. **135**(8), 746–753 Aug (2009)
3. Costin, A., Pradhananga, N., Teizer, J.: Automation in Construction Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project. Autom. Constr. **24**, 1–15 (2012)
4. de la Construcción, C.C.: Una apuesta en construcción : mayor productividad, menores riesgo (2017)
5. Antonio, J., Montañés, P., Rodríguez, A.M., Prieto, I.S.: Smart indoor positioning/location and navigation: A lightweight approach. J. Artif. Intell. Interact. Multimed. **2**, 43–50 (2013)
6. Perkinson, C.L., Emre, M., Ahmad, I.: Automation in construction the use of computing technology in highway construction as a total jobsite management tool. Autom. Constr. **19**(7), 884–897 (2010)
7. Zhao, J., Olivieri, H., Seppänen, O., Peltokorpi, A., Badihi, B., Lundström, P.: Data analysis on applying real time tracking in production control of construction, *IEEE*, pp. 573–577 (2017)
8. Uglovskaia, E.: The New Industrial Era, Industry 4.0 & Bobst company case study, no. Jan, 2017
9. Chan, G., Kwok, W., Johnny, W., Skitmore, M., Li, H., Chan, G., Kwok, J., Wong, W., Skitmore, M.: Real-time locating systems applications in construction. Autom. Constr. **63**, 37–47, Nov 2017 (2016)
10. Gast, M.S.: Building Applications with IBeacon: Proximity and Location Services With Bluetooth Low Energy. O'Reilly Media, Inc (2014)
11. Vieira, G.G., Varela, M.L.R., Putnik, G.D., Machado, J.M., Trojanowska, J.: Integrated platform for real-time control and production and productivity monitoring analysis. Rom. Rev. Precis. Mech. Opt. Mechatronics **50**, 119–128 (2016)
12. Zhong, D., Lv, H., Han, J., Wei, Q.: A Practical Application Combining Wireless Sensor Networks and Internet of Things: Safety Management System for Tower Crane Groups, no. 30, pp. 13794–13814, July (2014)
13. Reza, A.W., Noordin, K.A., Dimyati, K.: Deployment of a 3D tag tracking method utilising RFID. Int. J. Electron. **99**(4), November 2014 (2012)
14. Seppänen, O., Evinger, J., Mouflard, C.: Construction Management and Economics Effects of the location-based management system on production rates and productivity Effects of the location-based management system on production rates and productivity. Constr. Manag. Econ., 37–41, Jan 2015 (2014)
15. Gardoni, P., Lafave, J.M.: Multi-hazard approaches to civil infrastructure engineering. Springer, Urbana, IL, USA (2016)

A Cyber-Physical Middleware Platform for Buildings in Smart Cities

77

Balaji Kalluri, Clayton Miller, Bharath Seshadri, and Arno Schlueter

Abstract

In the realm of smart cities, tools for intelligent, real-time building energy management at the urban-scale are still evolving. Today, most commercial buildings have a dedicated Building Management System (BMS) to manage operations on-site efficiently; but there is no unified approach involving multiple stakeholders to manage them cooperatively in a district or urban scale. Thus, we formulate the following research question: '*What is a feasible structure and what are the relevant components of a middleware that is easy to integrate within existing BMS/EMS and scalable for application in smart cities?*' To address this knowledge gap, this article proposes a new integrated and non-intrusive approach to cyber-physical middleware design using open-source tools. The implementation of proposed middleware in a case study building-scale project in Singapore is presented. Several features are analyzed to understand the relevance and scalability of proposed middleware as a technology enabler for smart building management in cities. The experiences and lessons learned from this project can be extrapolated to the urban-scale as more buildings are equipped with such systems. For this purpose, middleware code is also made available as open-source.

Keywords

Middleware • Building management system • Cyber-physical • 3for2 office

77.1 Introduction

Understanding the multifaceted nature of cities and their underlying components such as building, transportation, and human-interaction is essential to mitigate the impact on climate and to improve the quality of urban life [1]. In the realm of Internet-of-things (IoT), buildings play a critical role in smart cities. Today, most buildings have a dedicated building management system (BMS) to manage operations on-site efficiently; but these processes are often in silos [2]. Typical use-cases of integrated BMS include periodic scheduling of HVAC or lighting loads in buildings for easy monitoring of the indoor environment and remote maintenance. The energy management systems (EMS) on the other hand are focused on collecting sub-hourly meter readings from various end-uses in build-ings. In general, the vendors of these systems often supplement their platform with add-on tools to process and visualize data, but adoption of these technologies has been limited due to a lack of perception of value. Buildings instrumented with sensors, meters, actuators and a BMS constitutes a

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classic example of pervasive sensor networks in the context of built-environment. However, buildings in future shall additionally require intelligent systems that multiplex the role of BMS/EMS for its universal application in smart cities. 'Middleware' is a software layer embedded between the physical hardware and the building system applications that exploit knowledge from the data. Such middleware serves as an intelligent layer in smart building management at urban-scale.

Motivated by the recent growth of urban mobility systems around the world [2], what can smart buildings community learn? How can information from multiple buildings in the urban-scale be collected and processed to enable an effective engagement of stakeholders managing a smart city? The recent developments in Cyber-Physical-System (CPS) enable multiplexing the role of BMS beyond existing building/campus-level management. In Sect. 77.2, we highlight certain limitations of existing middleware for urban-scale building management. In Sect. 77.3, we introduce an approach to develop a non-intrusive, cyber-physical middle-ware to liberate data from a conventional BMS/EMS system in a real building. It integrates the following: (a) a wide range of sensors, meters, and actuators native to building management infrastructure (b) an appropriate cloud-based, centralized database and (c) an intuitive front-end visualization platform. In Sect. 77.4, we discuss how the proposed middleware architecture overcomes existing limitations through our preliminary experiences in collecting, visualizing and analyzing more than two years data using the middleware implemented in the 3for2 office building [3]. The 3for2 project is a 550 sqm, highly instrumented office located in the United World College South-East Asia (UWCSEA) campus in Singapore with 1600 data points from sensors, actuators, meters across multiple zones. An overview of the building capturing specific vital features such as dedicated outdoor air systems for ventilation and passive chilled beams for space cooling are seen in Fig. 77.1. The purpose of this article is two-fold: (a) demonstrate an approach to building such a middleware using open-source tools that allows scalable implementation across buildings in cities; (b) enumerate specific vital features and explore its future application in smart cities.

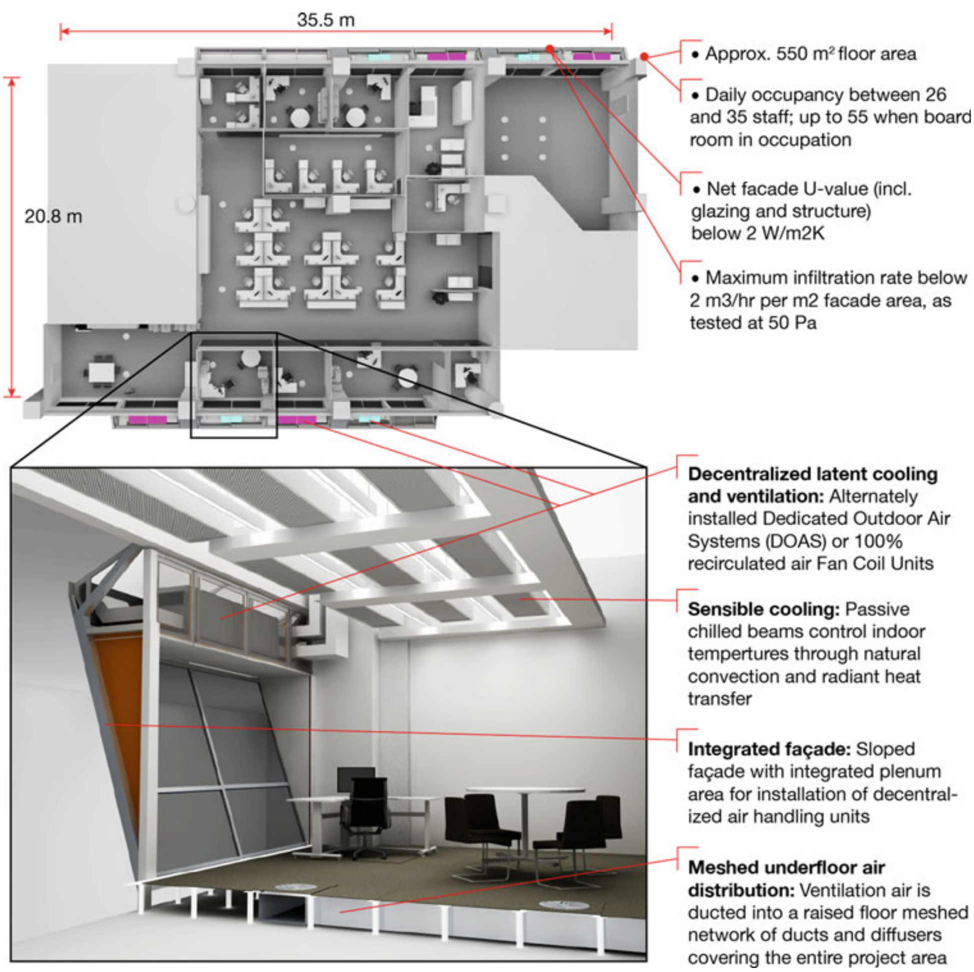

Fig. 77.1 An overview of the 3for2 office space and schematic of the systems installed (adapted from [3] with permission)

77.2 Background and Related Work

Middleware systems for buildings came about the beginning of digital control and automation systems in the 1990s. However, today the growth in IoT and pervasive computing enable cooperation among elements of cyber and physical world leading to a collectively intelligent middleware. Thus, several middleware methods for buildings and cities have emerged in recent years, including but not limited to SensorAct [4] for building energy management and WuKong [5] for virtual IoT/smart city applications. The SmartSantander project [6] is an example of a large-scale implementation of CPS in the city of Santander, Spain. It enables several smart city services such as traffic regulation, monitoring urban environmental quality, parking and irrigation management. However, several challenges still lie open in general.

1. **Lack of integrated middleware:** Building construction and operations management professionals (architects, system engineers, facility managers and technicians) rely on data downloaded from BMS and manipulated spread-sheet programs to visualize spatial and temporal information. The feedback received from them revealed one common concern —'the lack of an integrated middleware' [7]. Some employ multiple BMS and other visualization tools, while other report lack of integration between different building systems, lack of useful visualization of end-use energy data, online dashboard, ability to compare and benchmark multiple building performance ratings.
2. **Data quality and fidelity:** CPS integrates two types of systems which have different assumptions about the lifetime of data [8]. On one hand, data in cyber/computing systems are available until they are modified or deleted, whereas data retrieved from physical systems are valid only at sensed time instance. This situation creates a potential gap in data representation leading to misinterpretation, misuse, and miscomputation.
3. **Lack of open-source, flexible middleware for buildings in cities:** Intelligent building energy management in neighborhood and cities require a scalable data-acquisition, processing, and visualization middleware. Sakakibara et al. [8] elucidates the lack of a flexible middleware whereby the application developers of CPS/IoT systems for smart buildings and cities are constrained by which sensors and how many sensors have to be deployed in buildings. Arjunan et al. [4] demonstrates the application of an open-source, decentralized middleware for buildings called SensorAct, which requires additional dedicated devices (e.g., gateways) for smart energy management. The middleware such as SensorAct, on the one hand, proves appropriate for fine-grained energy management in building-scale, but on the other hand is intrusive and lacks scalability with additional hardware devices for managing several buildings across city-scale.

In some cases, the architecture of these middlewares are developed with a relatively narrow scope: to control systems within buildings [4] or collect necessary information regarding the operation of buildings [8]. These limitations suggest a knowledge gap in existing middlewares towards intelligent energy management (both demand and supply) across several buildings in a city. Motivated by these open challenges, we formulate the following research question '*What is a feasible structure and what are relevant components of a middleware that is easy to integrate within existing BMS/EMS and scalable for application in smart cities?*' with a particular focus on future smart and sustainable urban-scale building management.

77.3 Development of the Cyber-Physical Middleware

Typically, cities have several hundreds of buildings, and every building is made up of several levels and zones. The BMS enables monitoring buildings to improve overall management. Typically, it includes sensors and actuators for monitoring and controlling energy and IEQ. The integrated BMS aid in managing all building services through a unified platform. This approach is generally made at a building or neighborhood-scale. However, managing several buildings in cities require a non-intrusive approach to extract, store, process and visualize essential building information. This section presents an approach to implement such a middleware in the *3for2* office building [3].

A simplified schematic representation of the flow of information from buildings in urban-scale is illustrated in Fig. 77.2. It describes the role of the proposed middleware in creating expert insights about buildings from sensor data together with data-aware end-use applications. The data from several buildings in the UWCSEA campus including the 3for2 office is continuously monitored, collected and stored locally using an integrated commercial BMS from Siemens Building Technologies. The REST API [9] interface of BMS is used for non-intrusive collection of data from multiple building in the campus. The middleware is termed *Cyber-Physical* because it bridges information from the physical world of sensors in buildings with the cyber-world using cloud computing technology. Its *integrated* architecture combines a centralized,

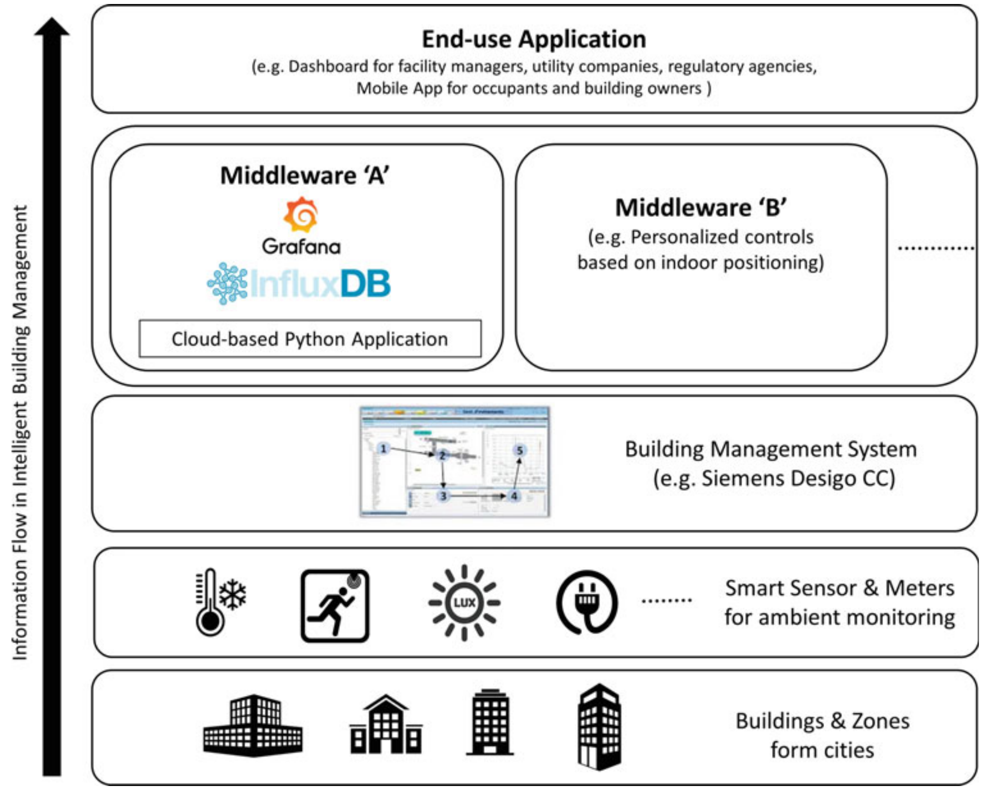

Fig. 77.2 Information flow using proposed middleware: From data to knowledgeable in-sights

cloud-based Python application to collect streaming data from sensors (in the physical world) into a modern time-series database called Influx DB [10], and further visualize using an intuitive open-source platform called Grafana [11]. Several visualization prototypes were developed to interface with the InfluxDB platform, including a time-series monitoring application in Grafana which enables intuitive, fast navigation and visualization of data. Other more customized dashboards were developed using JavaScript. The middleware architecture is *non-intrusive* in the sense that it collects data across multiple buildings without the need for additional devices such as gateways using a secure and straightforward Python application. It is used to create a small query engine that calls the API at a specific frequency, processes the data, and sends it to a cloud database. This database technology was developed specifically for time-series data and is much faster at ingesting and serving these data as compared to conventional SQL technologies. It is also an integrated platform as it converges BMS/EMS capabilities, with efficient cloud-storage and advanced visualization, all from discrete cloud-services onto a centralized platform. This application is made open-source on project GitHub repository[1] for wide-scale deployment and validation.

77.4 Analysis and Discussion

77.4.1 Case Study of 3for2 Office Building

The implementation of the proposed middleware in the *3for2* office building enabled us to overcome particular challenges. The analysis presented in this section help understand them through specific examples.

Flexibility in data representation: Ability to cope with non-homogeneous sampling intervals offered by the underlying hardware, without loss of information is critical to decision-making in IoT enabled smart buildings and cities. The proposed middleware handles this gap diligently. The choice of appropriate components of middleware (e.g., InfluxDB and Grafana) to store streaming data from several sensors help effectively collect, manage and present temporal data streams. The power consumption data of a low-lift chiller (LLC) in the 3for2 office for a week on February 18 is presented as an example for analysis in Fig. 77.3. In this example, estimated weekly energy consumption (in kWh) of LLC based on either 1-minutely or

[1]Siemens-InfluxDB Middleware Repository https://github.com/architecture-building-systems/desigo-influxdb-middleware.

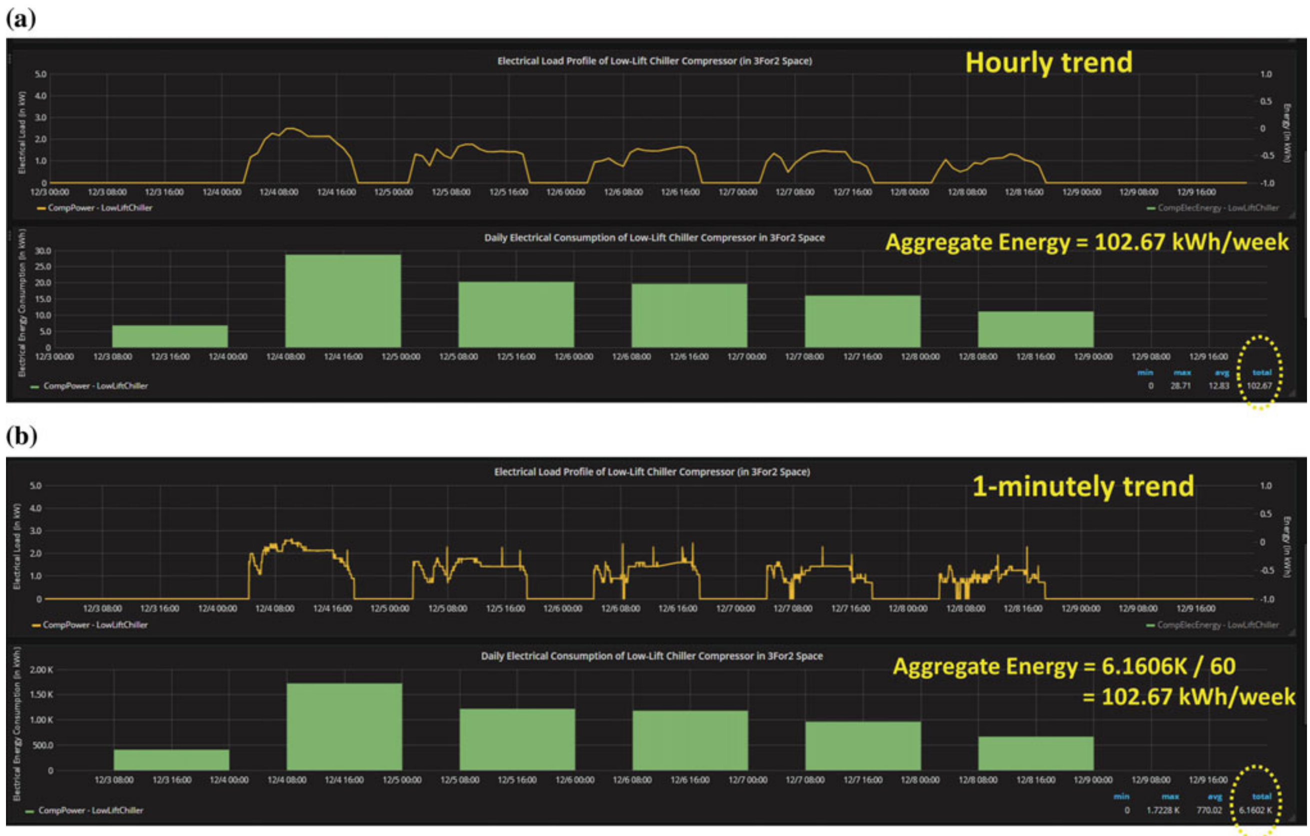

Fig. 77.3 Comparison of electrical power consumption profiles of a low-lift chiller compressor and it's corresponding daily energy consumption represented as bar-charts for a week in Feb.'18 based on **a** 1-hourly trends **b** 1-minute trends

1-hourly sampling is same (approx. 103 kWh). It demonstrates visualizing information (by either minutely or hourly) from a physical system without information loss is possible irrespective of the rate of sampling. Thus, illustrating the integrity of using information retrieved and stored in the middleware.

Ease of managing and querying building information: Physical component such as sensors, meters, and actuators present a meaningful picture of the indoor condition of a building over time. To the best of our knowledge, accessing and managing this information at a city or district scale was previously incomprehensible due to the complexity in organizing various data streams into meaningful hierarchies and understanding them in the right context. The integration of BMS and the middleware in the 3for2 project simplifies this complexity in managing and querying discrete information at either system or component-level in a building. For this purpose, a meta-data file for instrumented physical components in the building is prepared. Such a meta-data file includes information regarding the system it serves together with its digital identity, their physical location within the building, building within a neighborhood/city and so on. Thus, the proposed middleware integrated with REST API of BMS enable automatic retrieval of large volumes of building information on-the-fly. Further, this facilitates dynamic and non-intrusive visualization of building information, without them having to know about sensor placement inside buildings. Examples of such information in building-scale include energy breakdown by end-use/zones and overall daily/weekly/monthly energy-use-intensity. In the future, such a middleware shall enable comprehension and visualization of abstract information of buildings and systems in cities (e.g., the fraction of energy consumed from on-site renewables by different buildings in a neighborhood) which was earlier deemed unmanageable.

Understanding meaning behind data patterns: The proposed middleware integrated with BMS in the 3for2 office building enable using specific meta-data information to configure data dashboards. Some examples include information about the 'nature of end use systems' such as HVAC, lighting and plug-load; or about the 'physical measured quantity' such as energy (in kWh), cooling load (in RT); or about the 'physical location inside a building' such as plant room, Area 3for2, Level 7; or about the 'physical instances' annotating the number of identical sensors in that zone. The front-end visualization tool (Grafana) integrated into the proposed middleware allows easy visualization of temporal data patterns across buildings or zones within buildings. It also improves understanding the data in the right context of built-environment using well-annotated

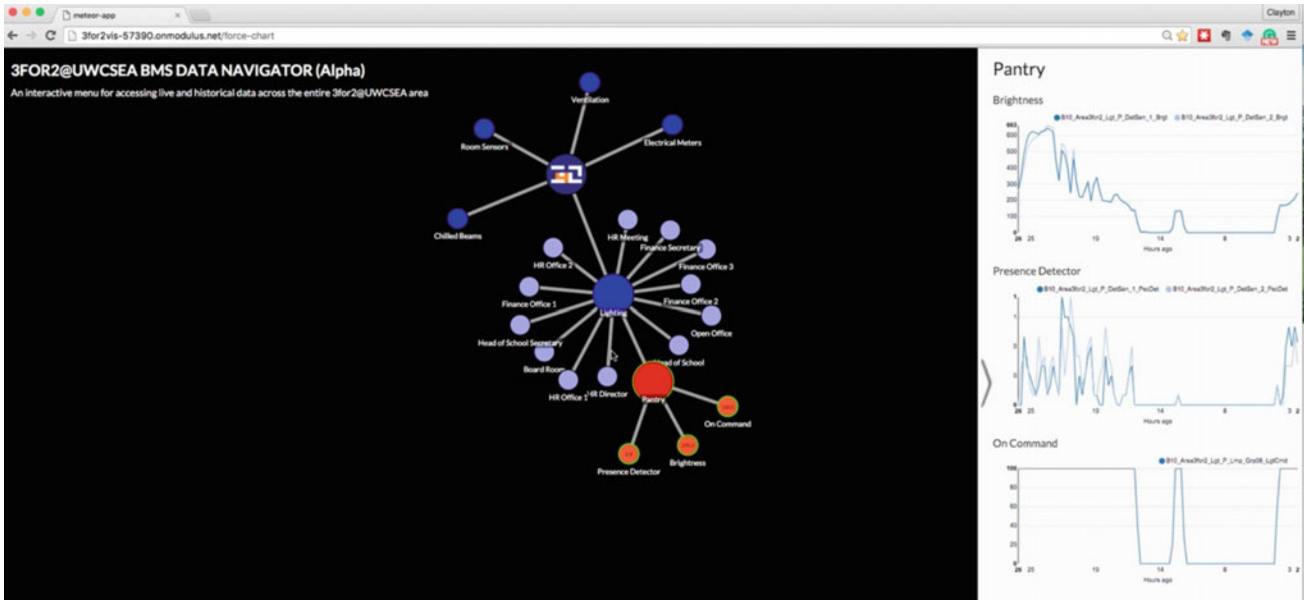

Fig. 77.4 A node-based prototype designed to allow fast navigation of sensor networks

meta-data tags. This approach facilitates stakeholders to take decisions by understanding the implications, limitations, and boundaries of data being collected. Further, a node-based visualization prototype is presented in Fig. 77.4. It was created to test an overview, zoom and filter, details-on-demand concept that is common in the visual analytics community of research, whereby users can select various nodes in the hierarchy and expand them level-by-level. At a certain depth, the detailed temporal data is visualized for the subset of points as a line chart or heat map. These techniques illustrate the notion of 'data-aware' over 'data-driven' design suggested by Bates et al. [2].

77.4.2 Middleware as Smart Building Sensing Service in Cities

In the urban-scale building management, several stakeholders will potentially be interested in the energy-use information. For example, a city/municipal council may use information about on-site renewables together with energy demand from buildings in a neighborhood to device policies, initiatives and rewards to influence communities towards more sustainable and energy-aware lifestyle. Additionally, construction authorities may use the information to classify and benchmark of buildings based on energy demand instead of their end-use type, which is more appropriate and rational. Further, utility companies shall benefit regarding demand-aware generation, distribution, scheduling and pricing of energy such that they avoid black-outs during episodes of peak demands. Finally, building owners can make more informed decisions on when and how much to trade their on-site energy with the grid. The proposed middleware thus enable seamless information flow between buildings and urban systems stakeholders. Based on our experience in successfully implementing a non-intrusive, integrated middleware using open-source tools for a building at neighborhood-scale, we extrapolate sensing and managing buildings to urban-scale using an existing *Smart Building Sensing as Service* (SBSS) model [12] in this section.

A Future Scenario: A Potential Future Application of the Proposed Cyber-physical Middleware

Let us consider a situation where building owner 'C' learns about his building energy information (BIPV generation = 10 kWh, on-site storage available = 25%, end-use consumption = 5 kWh) together with electricity tariffs from the utility grid and his neighbors through SBSS platform (Fig. 77.5). He then decides to sell his excess on-site generated (green) energy and publishes the tariffs to the cloud. Similarly, building owner 'A' also publishes his tariffs. An intelligent cloud-based bidding application sitting on top of the proposed middleware will federate bidding process between several stakeholders. Building owner 'B' predicts her building energy consumption to exceed beyond on-site generated and decides to buy (green) energy from its neighbors over energy from (fossil-based) utility grid for several reasons (e.g., environmental impact, energy pricing). Similar to buildings, a city council which manages operations like street lighting, and public park irrigation may also participate in bidding for (green) energy through the proposed platform (Step 4). It is important to note that entire

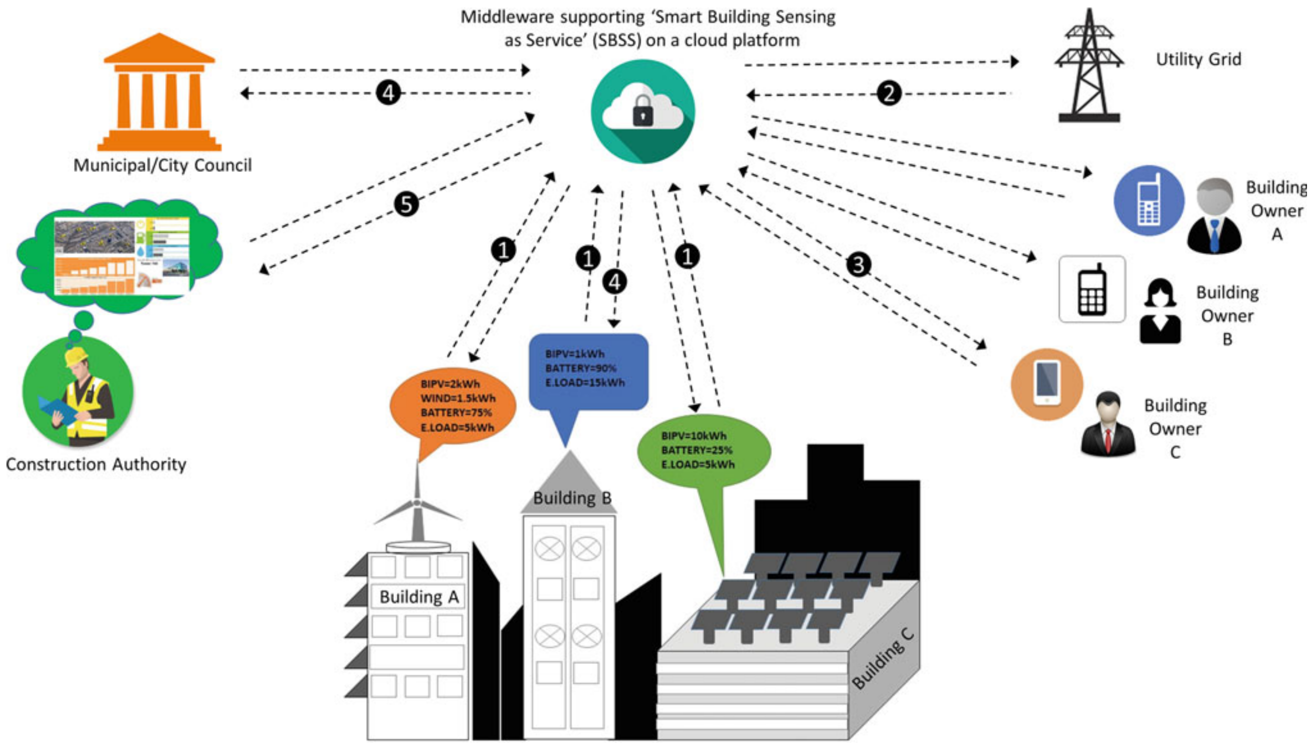

Fig. 77.5 A future scenario—smart building sensing as service model for cities

electrical energy exchange is facilitated jointly by the middleware and bidding application which are part of the smart-grid infrastructure. Finally, construction authorities who plan urban (re)development and public works shall also benefit visualizing key building information (e.g., energy usage, on-site generation, energy purchasing trends) from across several buildings to intelligently rank buildings reflecting their true energy performance. Currently, building authorities rely on rating systems such as GreenMark and LEED which are based on annual energy reports submitted by building owners and ESCO's which in future will be in near real-time.

77.5 Conclusion, Limitation and Future Work

A new cyber-physical approach to develop a non-intrusive and integrated middleware based on open-source tools to manage buildings in future cities is introduced. The middleware extends the capabilities of a commercial BMS into a far more reliable and desirable solution in the building management industry. The potential of the proposed middleware is demonstrated through a successful implementation in the *3for2* office building in Singapore. Several features are analyzed to understand the relevance and scalability of proposed middleware as a technology enabler for smart building management in cities. Collectively, all the features make it suitable for scaling and replicating across more buildings in future. For this purpose, the middleware code is also made publicly available as open-source. The sustainable management of buildings in urban-scale is not far from reality, as building construction industry has already taken steps forward by embracing web-technologies and IoT. We conclude with an example use-case scenario that elucidates how the middleware enables a future potential SBSS model for cities.

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References

1. Crooks, A., Schechtner, K., Dey, A.K., Hudson-Smith, A.: Creating smart buildings and cities. IEEE Pervasive Computing **16**(2), 23–25 (2017). https://doi.org/10.1109/mprv.2017.23
2. Bates, O., Friday, A.: Beyond data in the smart city: repurposing existing campus IoT. IEEE Pervasive Computing **16**(2), 54–60 (2017). https://doi.org/10.1109/mprv.2017.30
3. Schlueter, A., Rysanek, A., Miller, C., Pantelic, J., Meggers, F., Mast, M., Bruelisauer, M., Chen, K.W.: 3for2: Realizing spatial, material, and energy savings through integrated design. CTBUH J. **II**, 40–45 (2016)
4. Arjunan, P., Saha, M., Choi, H., Gulati, M., Singh, A., Singh, P., Srivastava, M.B.: SensorAct: A decentralized and scriptable middleware for smart energy buildings. In: 15th UIC-ATC-ScalCom Conference, pp. 2767–2774. IEEE, Beijing (2015). https://doi.org/10.1109/uic-atc-scalcom-cbdcom-iop.2015.27
5. Shih, C.-S., Chou, J.-J., Lee, K.-H., Lin, K.-J.:Data-Driven IoT applications design for smart city and smart buildings. In: UIC/ATC/ScalCom/CBDCom/IoP/SmartWorld Conference. In-press. IEEE, San Francisco (2017)
6. Sanchez, L., Muoz, L., Galache, J.A., Sotres, P., Santana, J.R., Gutierrez, V., Ramdhany, R., Gluhak, A., Krco, S., Theodoridis, E.: SmartSantander: IoT experimentation over a smart city testbed. Comput. Netw. **61**, 217–238 (2014). https://doi.org/10.1016/j.bjp.2013.12.020
7. Shih, C.-S., Chou, J.-J., Reijers, N., Kuo, T.-W.: Designing CPS/IoT applications for smart buildings and cities. IET Cyber-Phys. Syst. Theory & Appl., **1**(1), 3–12 (2016). https://doi.org/10.1049/iet-cps.2016.0025
8. Sakakibara, S., Saiki, S., Nakamura, M., Matsumoto, S.: Indoor environment sensing service in smart city using autonomous sensor box. In: Computer and Information Science (ICIS), 2016 IEEE/ACIS 15th International Conference on, pages 1–6. IEEE, Okayama (2016). https://doi.org/10.1109/icis.2016.7550871
9. Fielding, R.T., Taylor, R.N.: Architectural styles and the design of network-based software architectures. Doctoral Dissertation, University of California, Irvine (2000)
10. InfluxDB Database Github Repository. https://github.com/influxdata/influxdb
11. Grafana Github Repository. https://github.com/grafana/grafana
12. Perera, C., Zaslavsky, A., Christen, P., Georgakopoulos, D.: Sensing as a service model for smart cities supported by internet of things. Trans. Emerg. Telecommun. Technol., **25**(1), 81–93 (2014). https://doi.org/10.1002/ett.2704

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A Framework for CPS-Based Real-Time Mobile Crane Operations

78

Congwen Kan, Chimay J. Anumba, and John I. Messner

Abstract

Construction machinery have long been associated with high accident rates. Mobile cranes are widely used in construction projects and represent one of the main items of machinery that contribute to a large number of construction accidents. While many of these accidents occur due to inadequate planning and a lack of foresight on the potential hazards on site, few of the mobile crane safety issues have been well addressed. This study seeks to address this problem by leveraging the use of Cyber-Physical Systems (CPS) for planning and monitoring mobile crane operations on the construction site. A framework for a CPS-based approach is developed and the key components and enabling technologies are discussed. With a focus on how the virtual interface of the CPS approach was developed and how the system provides safety assistance in mobile crane operations, the modelling process and analytical algorithms are explained in detail. The capability of enhancing bi-directional communication and coordination between virtual components and their physical representations enables CPS to change the way mobile crane planning and monitoring could be done. By enabling pro-active planning and real-time monitoring of crane operations, CPS manages to provide rich multi-modal feedback to crane operators and workers on site, and thus, helps to reduce/avoid mobile crane failures and mobile crane-related accidents.

Keywords

Cyber-Physical systems (CPS) • Real-time • Mobile crane operations

78.1 Introduction

Over the years, there have been increasing investigations into the use of Cyber-physical systems (CPS). With the ability of integrating computation with physical processes, CPS creates a close relationship between the virtual and physical domains [1]. According to literature, CPS integrates physical devices such as sensors and cameras with virtual components to form a situation-integrated analytical system that responds intelligently to dynamic changes of the real-world scenarios [2]. The definition of CPS reveals its key characteristics: bi-directional coordination and real-time communication. CPS provides a platform for bridging the physical world with its virtual representations, as shown in Fig. 78.1. The physical to virtual bridge is the sensing process, which involves using sensors and data acquisition technologies to acquire information about components or phenomenon. The virtual to physical bridge represents the actuation process which shows how the sensed information affects the system [3].

CPS has yielded improvements in many disciplines, such as transportation [4, 5], health-care [6, 7], navigation and rescue [8, 9]. The successful application of CPS in other industries has attracted attention on how CPS can be applied in the construction industry and what potentially benefit it can bring about. Early attempts at implementing CPS in the construction industry include building energy management [10], construction component placement [11], temporary structures monitoring

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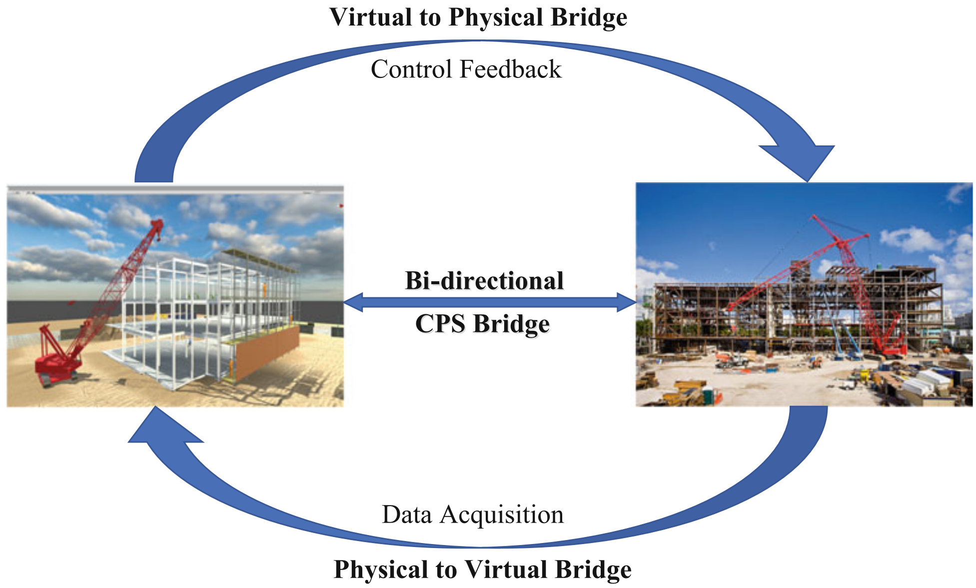


Fig. 78.1 A Bi-directional CPS approach

[12], and planning and monitoring of mobile crane operations [13]. In view of these applications, CPS has been identified as having substantial potential for addressing several problems within the construction industry, particularly given its emphasis on real-time interaction and coordination between the two system representations. It differs from traditional approaches which only monitor the physical world passively by bringing computational resources to bear in the physical world in an integrated fashion.

78.2 Background and Motivation

In the construction industry, machinery safety has long been criticized for being poor relative to other sectors and the associated severe consequences when accidents occur. Accidents caused by the operation of various machineries have posed serious problems as, once accidents occur, economic losses, occupational injuries and fatalities could be substantial [14]. It was reported that collisions, struck-by accidents, and rollovers caused by various machinery account for one quarter of the construction worker fatalities [15]. Cranes, as a central component applied widely in many construction projects, are associated with a large fraction of construction deaths. Construction fatalities in which cranes are involved account for up to one third of the total fatalities [16]. From 1997 to 2014, the number of fatalities in crane-related accidents totaled 566 for the construction industry, of which 306 deaths (54%) were related to mobile cranes [17]. Unlike tower cranes, which have a fixed location and operate within a limited workspace, mobile cranes move freely across a construction jobsite to perform the lifting tasks. Mobile cranes are considered to be riskier in nature than other types of cranes due to their on-site mobility [18].

Although numerous studies have sought to improve crane safety, and more strict regulations have come into effect, catastrophic crane accidents still occur. With the aim of providing real-time safety assistance for mobile crane operations, this paper presents a CPS-based approach to bi-directional communication and coordination between virtual crane models and physical crane operations on construction site. First, the key enabling technologies required for CPS integration of virtual models and physical construction site are outlined. Then, the CPS-based prototype system being developed for real-time mobile crane operations are described. The concluding part of this paper highlights the potential benefits and barriers in implementing the system.

78.3 Bi-directional Coordination in Active Monitoring and Control of Mobile Crane Operations

In this study, the bi-directional coordination involves linking the virtual mobile crane model as well as the site environment model with the corresponding physical site components. This is intended to enable the bi-directional information exchange and to facilitate the communication. The information to be exchanged include two aspects: (1) capturing the mobile crane movement data and site information (such as the location of essential site components and the building structure scheduled to be erected) from the physical interface, and (2) giving control feedback such as warning messages through portable audio devices to the workers and crane operator on site. The following sub-sections highlight the key enabling technologies used in enhancing the bi-directional coordination between virtual models and their physical representations.

78.3.1 Mobile Crane Motion Data Capture

Inertial Measurement Unit (IMU). An IMU is an electronic device assembled with a combination of accelerometers, gyroscopes, and sometimes magnetometers. It measures and reports a body's gravitational forces, angular orientation, and sometimes the magnetic field surrounding the body [19]. With the ability of tracking position changes and reporting inertial measurements, IMU is chosen to monitor the crane load position and sway.

Proximity Sensing System (iBeacon Technology). As one of the primary crane motions, the proximal location of the crane is measured by iBeacons. The iBeacon proximity sensing system is based on Bluetooth-based wireless sensing technology. It incorporates (1) Bluetooth signal transmitter, (2) mobile personnel receivers, (3) crane operator's receiver, and the software on which the system operates [20]. This iBeacon-based proximity sensing system is leveraged to locate mobile crane and to create a hazard detection area so that alerts will be sent to both the crane operator and the workers who enter that area.

78.3.2 Site Information Acquisition

To sense the updates on a construction jobsite, a combination of RFID tags and photogrammetry is proposed. RFID tags are proposed to be leveraged onto relatively small mobile objects which can be treated as a rigid body with fixed dimensions. Examples of such objects include vehicles and workers. For updates on site that require the dimensional data to be considered, photogrammetry is used. 3D geometrical data of such objects would be generated from the photo images. Examples include changes to the site layout such as bulk pieces of newly delivered materials, changes in the jobsite arrangement, and progress made on the building structure being erected. More details concerning site information acquisition can be found in [21].

78.3.3 Mobile Devices for Displaying Control Feedbacks

Mobile devices adopted in this study are portable computing devices which have a screen for displaying information. Examples of such mobile devices include tablet PC and Bluetooth enabled smart phones. A tablet PC is to be installed in the crane operating cab. It has a larger screen which can be used to navigate around the site model as well as the embedded data (such as warning messages triggered and site components which are subject to hazards) in the model. Tablet PCs also have built-in accessories such as Bluetooth signal scanner and RFID reader to capture data. Crane operators can easily use such a tablet to view crane motions and updates of the tagged site components. Smart phones are to be carried by construction workers equipped with RFID tags. Auditory warnings or haptic cues are conveyed to the workers to indicate hazardous behaviors and situations.

78.3.4 Communication Network

The communication network enhances bi-directional communication and coordination between virtual models and their physical representations by enabling the transfer and exchange of information between a tablet PC and local office computer. The communication network adopted in this study includes the Internet and wireless fidelity (Wi-Fi). Data captured on the physical site could be transferred through the communication network to the virtual model on the remote server. With the tablet PC connected wirelessly to the office computer, the status of the mobile crane can be viewed in the model at the office by the project team. In this way, bi-directional information exchange is achieved and the coordination between the virtual models and physical representations are enhanced.

78.4 System Architecture for Real-Time Mobile Crane Operations

The CPS concept is illustrated in the proposed system architecture in Fig. 78.2. The system architecture brings together the functionality and the key enabling technologies discussed previously as a framework for bi-directional coordination between the virtual models and physical representations. The architecture is based on five layers, which are explained in the following sub-sections.

78.4.1 Object Layer

The object layer consists of the physical mobile crane and the as-is site components. At this layer, different modules of a mobile crane and essential site components are identified for the sensing system to be leveraged onto so that the mobile crane movement data and as-is site environment data can be obtained.

Isolated Crane Modules. Mobile crane comes in a great variety of types and configurations. However, it can generally be seen as an entity which comprises several rigid bodies connected by joints [21]. Based on its operating mechanism, a mobile crane can be generally broken down into base, body, boom and load, as shown in Fig. 78.3. To capture crane movement data in real-time, a sensing system incorporating different types of sensors is adopted to measure the critical motions of different mobile crane modules.

As-is Site Condition. The as-is site information to be collected incorporates three parts: (1) geological site environment, such as the terrain and the trees, (2) site arrangement plan including the location of essential site components such as material stacks, site trailer, dumpster, and (3) the building to be erected. The afore-mentioned sensing technologies are to be leveraged on these site components to collect the as-is site condition data.

78.4.2 Sensing Layer

In the sensing layer, the initial crane position and as-is site condition are depicted through the sensing system proposed in the previous section. In addition to the as-is site condition, crane movements and changes on the physical site, such as progress on the proposed building structure, and movement of vehicles and workers are also tracked at this layer. The sensing system presented here was developed for a crawler lattice boom crane as shown in Fig. 78.4, but the application of the sensing system can be extended to other types of mobile cranes by using the same approach to break down the crane into modules as previously discussed. The sensing system collects crane motion information including (1) location of the crane, (2) location of the boom, and (3) location of the load. Sensors adopted for data acquisition include IMU sensor and iBeacons. The locations for sensor installation and the information they collect are shown in Fig. 78.4.

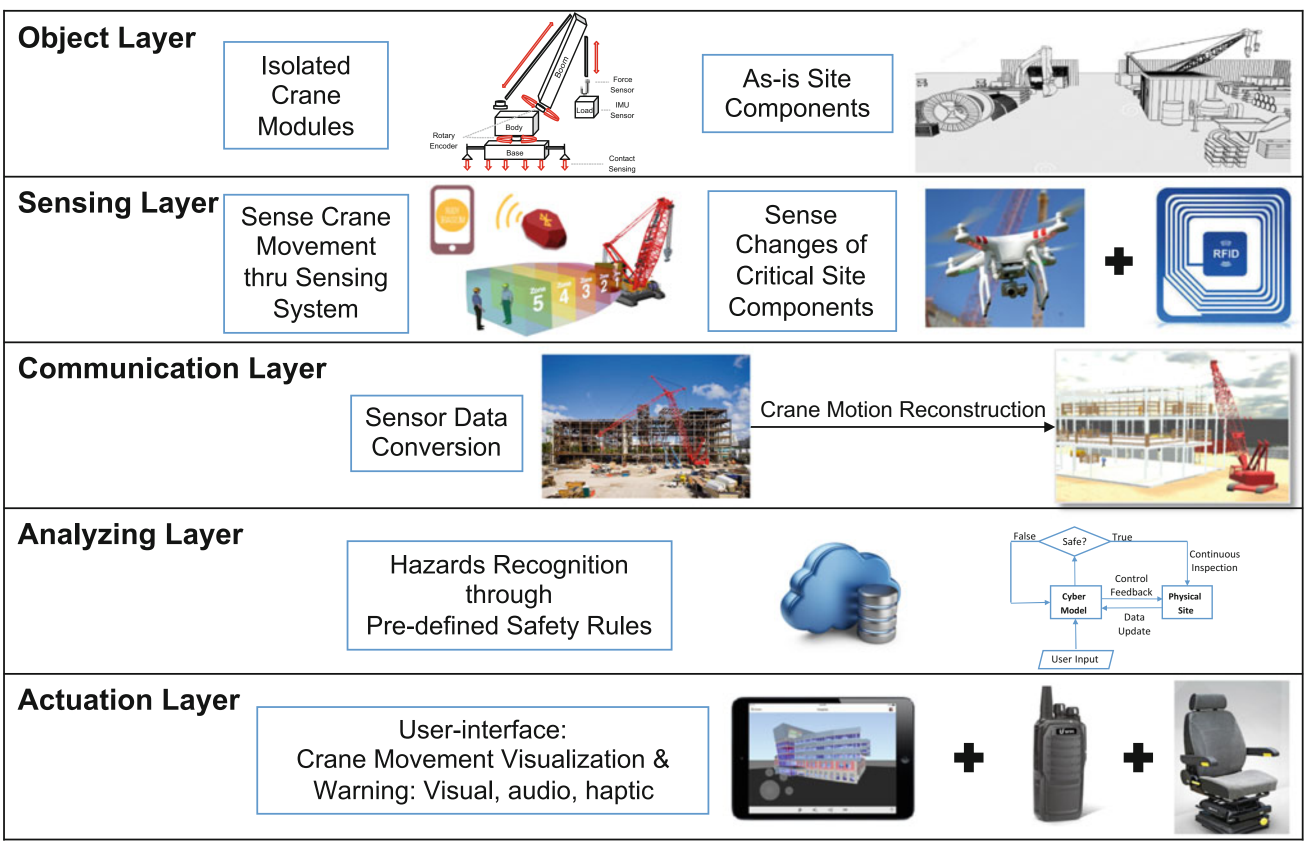


Fig. 78.2 System architecture for CPS-based real-time mobile crane operations

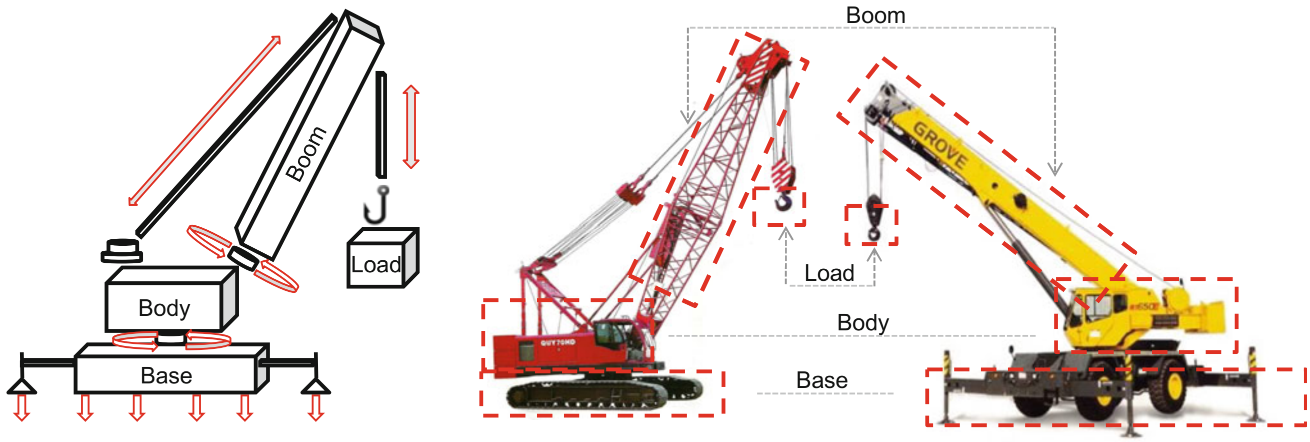
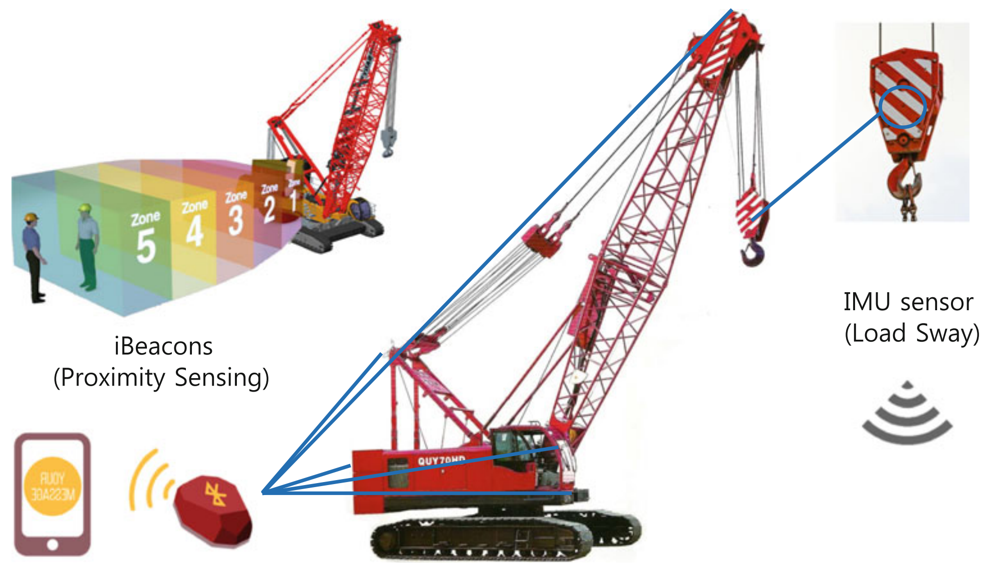


Fig. 78.3 Representation of isolated crane modules

Fig. 78.4 Locations for sensor installation



78.4.3 Communication Layer

The communication layer serves as a data processing unit and it is scripting-based. This unit processes the crane motion data and site environment data collected on the physical construction site through the sensing layer and converts it into software readable packets. These software readable packets are labeled as processed data. The processed data will reconstruct the crane motion and update the changes on site in the virtual site model, which will be discussed in the actuation layer later.

78.4.4 Analysis Layer

Once crane motions and the updates on site have been reconstructed, the processed data will be transferred from the communication layer to the analysis layer for the potential safety hazards to be analyzed. The key steps of how potential safety hazards are identified under the analysis layer are summarized and shown in Fig. 78.5.

In order to identify potential hazards associated with mobile crane, corresponding accident records from Occupational Safety and Health Administration (OSHA)'s website were studied. Based on the information extracted from the database, five potential failure modes including struck by, electrocution, crane tip-over, falls, and failure of boom/cable were identified. After the definition of the potential failure modes, thresholds were set to avoid these potential hazards. Regulations from OSHA, manuals provided by crane manufacturers, and industry best practices were considered while defining the threshold for potential hazards. More details concerning how the potential failure modes were identified and how the safety thresholds were defined can be found in [22].

78.4.5 Actuation Layer

The Actuation Layer consists of the virtual model developed and the user interface which presents the virtual model. In this layer, the mobile crane movement, site environment, the identified hazards, and the warning triggered are visualized simultaneously on a real-time basis. Details concerning how the virtual model is built and how the user-interface is designed are discussed in the following sub-sections.

Virtual Model. Unity 3D was selected as the software environment for virtual site model development. It is a game engine that supports cross platform scripting and can be used to create an as-is site model. Unity 3D was selected in this study for its ability to support cross-platform scripting, 3D modelling and visualization. Other platforms with similar capability would also be practical. Scripts were added to each part of a mobile crane model (e.g. base, body, boom and load) to allow each part of the crane to move freely in the virtual model as they do in the physical world. The motion of the crane model is built to be manipulated through a keyboard initially and later to be updated through the sensory data collected from the physical interface. A baseline construction site model is constructed and updated through the sensory data collected as well. Figure 78.6 shows a screenshot of the virtual site model. Scripts were pre-developed and embedded with the crane model as well as corresponding site components to account for all the five potential failure modes. Warning messages are triggered and shown once any potential hazards are detected based on the safety rules defined in the analyzing layer.

User Interface (UI). The user interface presented in Fig. 78.7 consists of three views: an isometric view shown on the left, a top view on top right and an operator's view on bottom right. The UI shows the re-constructed lifting scene and any warnings triggered in real-time. The detection of potential collision hazard is shown here as an example. Warning messages are triggered and the site components which are subject to the collision hazard are highlighted in red. The UI is proposed to be presented to the crane operator through a tablet PC installed in the operating cab. Workers on site are equipped with a mobile device which provides sound and vibration alerts upon breaching a hazardous area pre-defined with respect to the mobile crane.

78.5 Conclusions

This paper presented a CPS approach for the planning and monitoring of mobile crane operations on a real-time basis. With the aim of providing real-time safety assistance, a system architecture was presented and the key enabling technologies were discussed. The key conclusions that can be drawn from this study are presented as follows:

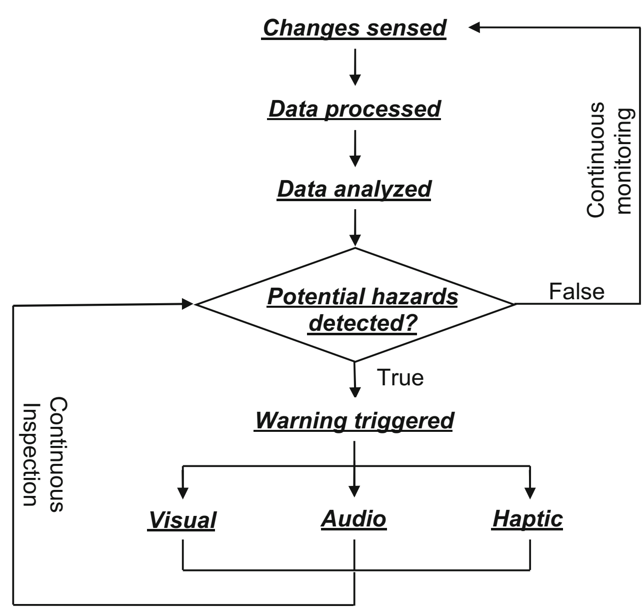


Fig. 78.5 Potential hazards identification [21]

Fig. 78.6 The simulated jobsite in unity 3D

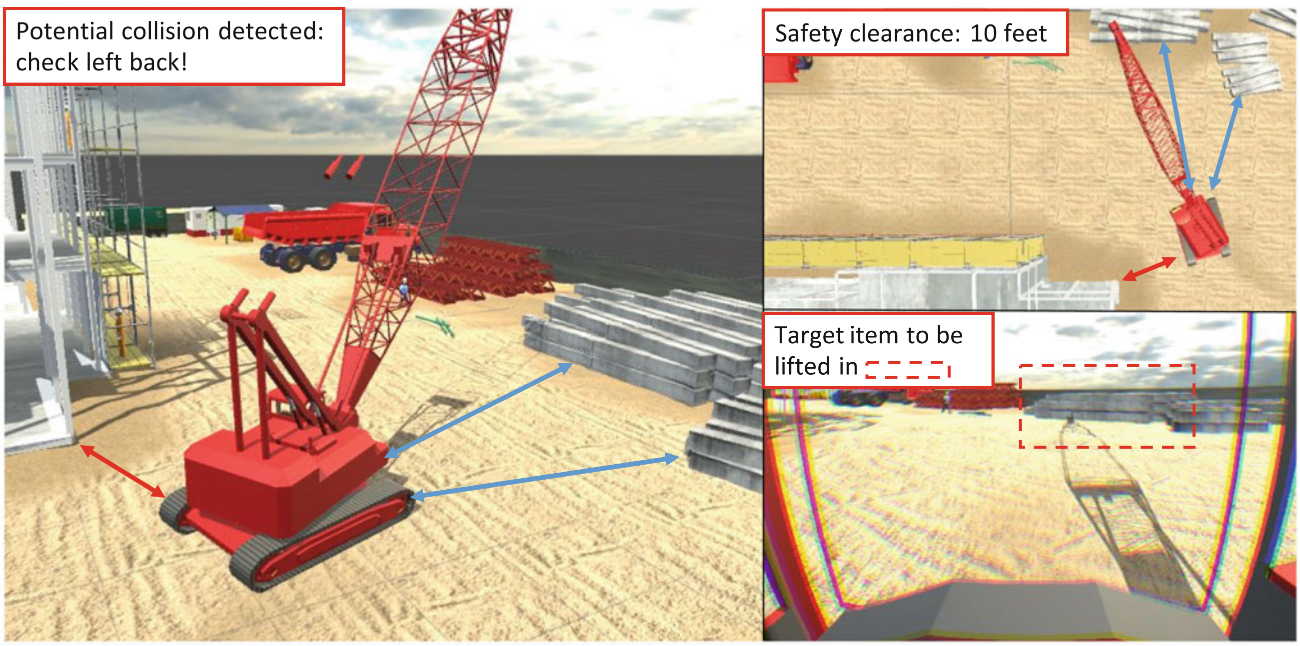


Fig. 78.7 User interface: crane movement visualization [21]

- The application of CPS on real-time mobile crane operations demonstrates how CPS plays an important role in enhancing bi-directional coordination between virtual models and their physical representations. The prototype system being developed is capable of tracking, monitoring the physical crane operations and giving real-time control feedback. It can be seen as an informative approach that provides information on the monitored state of the mobile crane and of the environment.
- The CPS-based approach enhances the communication and coordination between multiple parties. Project team members including the owner, crane manufacturer, project manager, workers and other personnel involved in the routine inspection can obtain information captured by the sensing system from the virtual model interface. It provides better opportunities for problem analysis, hazard avoidance, and collaborative working.
- With the capability of enhancing bi-directional coordination and information exchange, CPS offers advantages in effective planning, pro-active monitoring of crane operations, providing control feedback to both crane operator and workers on site thus ultimately reducing or avoiding mobile crane-related accidents.

However, there are several barriers standing in the way of utilizing a CPS-based approach for real-time mobile crane operations. Future work will focus on making estimation on mobile crane operating state, defining precise safety thresholds concerning each of the failure modes, and protecting the data collected from the sensing system from being tampered.

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References

1. Lee, E.A.: Cyber Physical Systems: Design Challenges. In International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing (ISORC), May (2008)
2. Tang, L., Yu, X., Kim, S., Han, J., Hung, C., Peng, W.: Tru-Alarm: Trustworthiness Analysis of Sensor Networks in Cyber-Physical System. In Proc. ICDM (2010)
3. Wu, F.J., Kao, Y., Tseng, Y.: From wireless sensor networks towards cyber-physical systems. Pervasive and Mob. Comput. **7**(4), 397–413 (2011)
4. Mohan, P., Padmanabhan, V.N., Ramjee, R.: Nericell: Rich monitoring of road and traffic conditions using mobile smartphones. In: Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems (pp. 323–336). New York, NY, USA: ACM (2008) https://doi.org/10.1145/1460412.1460444
5. Thiagarajan, A., Ravindranath, L., LaCurts, K., Madden, S., Balakrishnan, H., Toledo, S., and Eriksson, J.: Vtrack: accurate, energy-aware road traffic delay estimation using mobile phones. In: Int'l Conf. Embedded Networked Sensor Systems, 85–98 (2009)
6. Shi, J., Wan, J., Yan, H., Suo, H.: A survey of cyber-physical systems. In: 2011 International Conference on Wireless Communications and Signal Processing (WCSP). Nanjing, China, 9–11 Nov (pp. 1–6) (2011)
7. Taleb, T., Bottazzi, D., Guizani, M., Nait-Charif, H.: ANGELAH: a framework for assisting elders at home. IEEE J. Sel. Areas Commun. **27** (4), 480–494 (2009)
8. Tseng, Y.C., Pan, M.S., Tsai, Y.Y.: A distributed emergency navigation algorithm for wireless sensor networks. IEEE Comput. **39**(7), 55–62 (2006)
9. Pan, M.-S., Tsai, C.H., Tseng, Y.C.: Emergency guiding and monitoring applications in indoor 3D environments by wireless sensor networks. Int. J. Sens. Netw. **1**(1–2), 2–10 (2006)
10. Zhao, P., Simoes, M.G., Suryanarayanan, S.: A Conceptual Scheme for Cyber-Physical Systems Based Energy Management in Building Structures. 9th IEEE/IAS International Conference on Industry Applications, Nov (2010)
11. Akanmu, A., Anumba, C.J., Messner, J.I., Lee, S.: Component level cyber-physical systems integration: a light fixtures example. In Proceedings of the 2012 ASCE International Conference on Computing in Civil Engineering (pp. 17–20) (2012)
12. Yuan, X., Anumba, C.J., Parfitt, M.K.: Real-time Cyber-Physical Systems (CPS)-based Monitoring of Temporary Structures: a Scaffolding System Example. Available from: http://itc.scix.net/data/works/att/w78-2015-paper-081.pdf (2014)
13. Kan, C., Anumba, C.J., & Messner, J.I.: Potential use of cyber-physical systems (CPS) for planning and operation of mobile cranes on construction sites. In Computing in Civil Engineering 2017 (pp. 139– 146). Available from: http://ascelibrary.org/doi/abs/10.1061/9780784480830.018 (2017)
14. Zhang, J., Zhang, Y., Ji, C., Li, Y. Safety assessment of crane based on FTA and ANP. Proceedings of the Sixth International Conference on Management Science and Engineering Management (Vol. 185, pp. 453–464) (2013)
15. Hinze, J.W., Teizer, J.: Visibility-related fatalities related to construction equipment. Saf. Sci. **49**(5), 709–718 (2011). https://doi.org/10.1016/j.ssci.2011.01.007
16. Neitzel, R.L., Seixas, N.S., Ren, K.K.: A review of crane safety in the construction industry. Appl. Occup. Environ. Hyg. **16**(12), 1106–1117 (2001)
17. Fang, Y., Cho, Y.K.: Effectiveness analysis from a cognitive perspective for a real-time safety assistance system for mobile crane lifting operations. J. Constr. Eng. Manage. **143**(4), 5016025 (2017)
18. Al-Humaidi, H.M., Hadipriono Tan, F.: Mobile crane safe operation approach to prevent electrocution using fuzzy-set logic models. Adv. Eng. Softw. **40**(8), 686–696 (2009)
19. Dissanayake, G., Sukkarieh, S., Nebot, E., Durrant-Whyte, H.: The aiding of a low-cost strapdown inertial measurement unit using vehicle model constraints for land vehicle applications. IEEE Trans. Robot. Autom. **17**, 731–747 (2001). https://doi.org/10.1109/70.964672
20. Gast, M.S. Building applications with ibeacon: proximity and location services with bluetooth low energy. O'Reilly Media, Inc (2014)
21. Kan, C., Fang, Y., Anumba, C.J., Messner, J.I.: A cyber–physical system for planning and monitoring mobile cranes on construction sites. Proceedings of the Institution of Civil Engineers—Management, Procurement and Law, 1–39. https://doi.org/10.1680/jmapl.17.00042 (2018)
22. Kan, C., Zhang, P., Fang, Y., Anumba, C.J., Messner, J.I.: A taxonomic analysis of mobile crane-related accidents in construction industry for cps-based simulation. In 17th International Conference on Computing in Civil and Building Engineering (2017)

79 Drive Towards Real-Time Reasoning of Building Performance: Development of a Live, Cloud-Based System

Ruwini Edirisinghe and Jin Woo

Abstract

Post-occupancy evaluation data on both building performance and occupant comfort can be useful for facility operation and management, and for workspace design but are rarely used in practice due to challenges and research gaps in data collection and analysis. We argue that with the growth of mobile and pervasive computing capabilities, future space design and building management will be based on real-time feedback loops of building performance data—qualitative and quantitative—available through the cloud, at stakeholders' fingertips. We have developed a live, cloud-based system to begin contextualizing fragmented big data sets as evidence to support improvement of workspace management and design, and this paper presents the development process. The proposed system has three functions: data collection, processing, and reporting. A wireless sensor network collects physical environmental data which are then posted to a cloud-hosted server. A smart device-administered survey collects occupants' perception data. Thermal comfort principles, as well as HCI (human–computer interaction) development guidelines and design principles, were followed during development of the app, which was then rigorously tested. The time-stamped survey data are synchronized with environmental data captured by relevant sensors. Pilot data collection is ongoing, as is the correlation analysis of the two data sets used to validate the process. The real-time reasoning and report generation features, supplemented with additional data, will be beneficial to space design, and to facility operation and management. This holistic system is expected to provide a powerful and practical tool for both designers and facility managers.

Keywords

Real time data • Building performance • POE • IEQ mobile app

79.1 Introduction

Post-occupancy evaluation (POE) is the process of evaluating buildings in a systematic and rigorous manner at some point after they have been occupied. The evaluation is intended to discover differences between performance criteria and actual building performance, thus providing insights into the consequences of past design decisions, as well as into the building's actual performance. This knowledge could eventually form a sound basis for creating better buildings in the future, influencing codes, standards and design choices [16].

POEs have typically focused on technical evaluations, such as of HVAC systems or building materials, but the effects of technical performance on occupant health, safety, and physical and psychological comfort need to be considered. In general, POE is a useful technique for assessing how well buildings perform, and its main focus is on building occupants' environmental satisfaction. Indoor environment quality (IEQ) has been measured as a major aspect of POE, and both physical condition monitoring and occupant surveys have been conducted in order to understand building performance, as well as to ensure the validity of other measurements taken. Conventional IEQ assessment approaches have been used to assess building

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performance through feedback on occupants' perceptions of and satisfaction with the environment. IEQ assessment has also been conducted as part of the assessment process for green building certification (e.g., LEED and Green Star) and building performance ratings (e.g., NABERS). The focus of POE was initially on energy and environmental performance, with the intention being to identify successes and failures of green design strategies and technologies. Later, the focus shifted towards building occupants (who are the primary users of buildings) in order to identify opportunities for improvements that would increase productivity in green buildings. As a result, not only buildings' technical capabilities or energy and environmental performance have been assessed, but also feedback provided by occupants to ensure high performance; there is overwhelming evidence of a link between better quality indoor environments and increased occupant health and comfort, which contributes to productivity [9, 12–14, 20].

A large evidence base has been generated concerning elements of workspace design that support the comfort of building occupants [21]. Although POE data can be useful for facility operation and management, they seem to be rarely referred to in building management practice, partly due to the nature of conventional, manual intervention-based data collection. These collection methods continue to be favored, even though the world is moving into the era of mobile and pervasive computing. In addition, systematic correlation of quantitative building performance data and qualitative occupancy evaluation data represents not only a gap in the research, but also in practice.

In this vacuum, the objectives of the present, ongoing research project are three-fold: (i) to develop a live, smart technologies-based platform composed of wireless sensor networks, mobile computing and cloud server for real-time data collection on building performance, representing both quantitative and qualitative data; (ii) to systematically correlate these performance and POE data, and validate the survey for repeated use; and (iii) to develop an analytical algorithm to derive intelligent condition assessment reasoning, alerts and facility management decisions, and provide feedback on workplace preferences and space needs to designers.

As the first step of contextualizing the fragmented big data sets to provide an evidence base for improving workspace design, we developed a cloud-passed wireless sensor network and a POE app to capture building evaluation data in real time. This paper reports on that development process.

79.2 Literature Review

A post-occupancy evaluation (POE) can be conducted using either objective or subjective methods, or a combination of these. Objective methods include physical measurements and utility audits in a numerical format, and subjective methods include occupant surveys, interviews and walk-through inspections. Occupant surveys, either standardized or customized, seem to be the most commonly used method in recent POE projects [7]. Surveys, in the form of self-administered or web-based questionnaires, make large samples feasible, and thus can be useful in describing the characteristics of a large population [2]. They also increase the likelihood of honest responses compared to formats involving interaction with another person, such as a face-to-face or telephone interview [11].

Research has shown that even when physical building conditions satisfy applicable standards or regulations, building occupants often evaluate their indoor environment negatively [8, 17]. This is due not only to their individual preferences, but also to the combined effects of the physical conditions [11, 15, 16, 18].

As a response to this, protocols have been developed in building-related disciplines with which to conduct occupant surveys on indoor conditions. The current protocols use a standardized survey as a subjective method, and numerous sensors and equipment as an objective method. Standardized survey methods have been developed—from a paper-based and face-to-face questionnaire, to a web-based survey—mostly asking questions about occupants' perception of, and satisfaction with, their environment. An apparently typical recent protocol is a web-based occupant survey, with indoor condition measurements taken using a portable monitoring cart (e.g., CBE's Occupant IEQ Survey, the Building Occupant Survey System Australia, or BOSSA). This approach is designed to capture the environmental satisfaction of building occupants as well as the indoor conditions, and usually matches the subjective responses of the building occupants with contemporaneous, objective IEQ measurements. Despite the development of these current techniques and tool kits, the IEQ assessment results seem almost never to have been used in building management practice. Anecdotal evidence suggests that this may be partly due to the manual and intensive nature and practical limitations of these data collection methods, as well as to a lack of knowledge of the best use of such data. These are major challenges for building maintenance and operations professionals.

Yong et al. [23], for their Intelligent Pervasive Spaces approach, envisaged monitoring objective building performance data in real time using wireless sensor networks. Internet access and mobile devices have changed the nature and ways of collecting both subjective and objective data. According to the Australian Bureau of Statistics [1], the number of households with access to the internet increased from 66.6% in 2007–2008 to 86% in 2014–2015. This allows access to a wide range of information, and also provides a crucial means of communication for individuals, communities, businesses and governments. Accordingly, a range of devices, such as desktop or laptop computers, mobile or smart phones, and tablets, are used to access the internet.

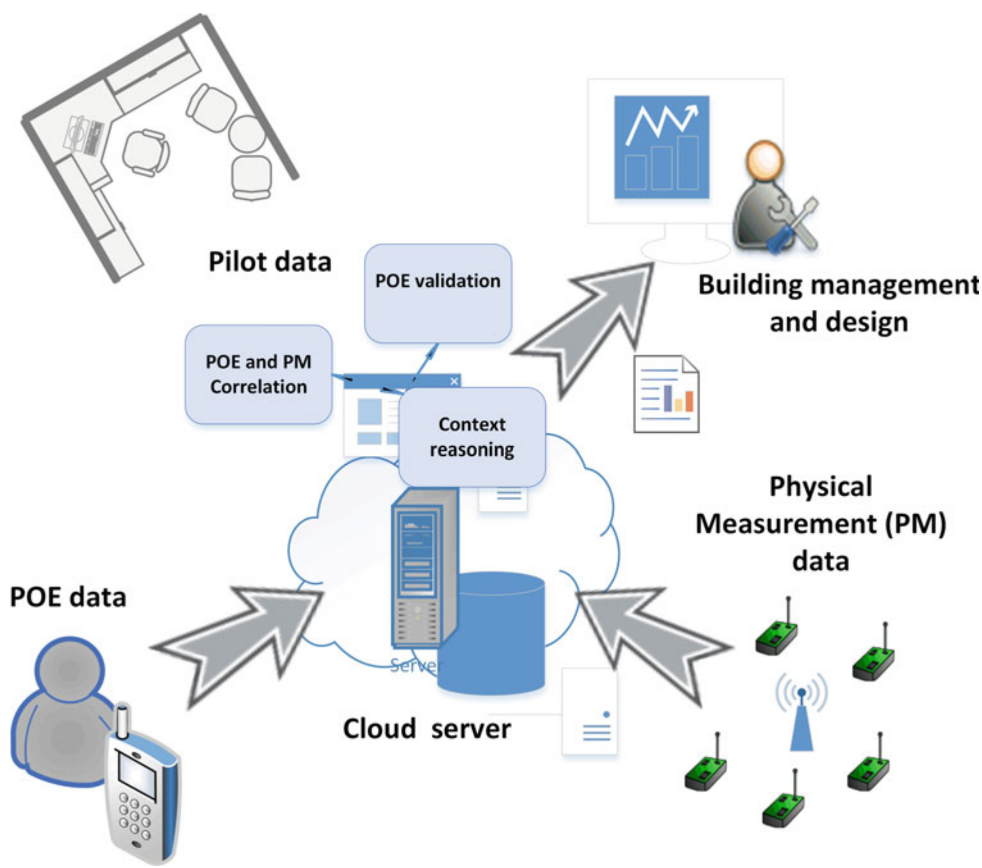
However, gaps exist in data analysis. Data on building occupants' 'functional comfort' have generated a large amount of evidence on both supportive and non-supportive elements of workspace design [21]. A meaningful correlation of the qualitative and quantitative data sets, which is yet to be undertaken, has the potential to bolster this existing knowledge. In addition, analysis and reporting based on the current techniques uses a 'benchmark', a mean score, in order to compare the performance of individual buildings. Although benchmarks can provide an overall indication of building performance, it is unrealistic to expect such a score to be used as a diagnostic or building management tool, due to its lack of generalizability. Real-time data collection and analysis can capture the unique features of each building, which allows the gap between current IEQ assessments and the variability within each building to be filled. Real-time data collection can also enhance building performance, and improve communication between building users and building managers. Cloud computing, integrated wirelessly, has allowed data storage and processing to become cost-effective, and facilitates real-time feedback.

A rigorously validated POE survey systematically correlated with—and supported by—objective building performance data makes effective use of occupancy data. Such quantitative and qualitative data sets (currently fragmented in practice) have the potential to be used again and again to improve serviceability and decision making in facility management, and also as a feedback loop to improve workspaces.

79.3 The Live Platform

The proposed live platform is composed of data collection, data analysis and reporting systems. The system architecture is shown in Fig. 79.1. The system consists of (i) data collection, (ii) data processing, and (iii) browser-based reporting components.

Fig. 79.1 System architecture



The real-time data collection components are: (i) a wireless sensor network to collect physical measurements (quantitative data); and (ii) a smart phone app to collect data on occupants' perceptions (qualitative data). Both components are cloud–connected, and update the data repository in real time. Pilot data are collected to correlate the qualitative and quantitative data sets and to validate the POE survey for repeated use. The use of a cloud server enables real-time context reasoning based on the findings from the validation. This context reasoning generates real-time web browser-based reports, and aids building management and workspace design-related decision making. The web server used in this project is Amazon Web Server (AWS). Other components of the system are discussed below.

79.3.1 Sensor Network

The sensor network used to collect data in the current version of the system is based on the TelosB platform. A TelosB mote has an IEEE 802.15.4 radio with an integrated antenna, a low power MCU, and a 250 kbps data rate. The mote has an embedded 8 MHz TI MSP430 microcontroller with 10 kB RAM. The mote runs the TinyOS operating system, as shown in Fig. 79.2. The mesh network configuration is illustrated in Fig. 79.3. The network is composed of six TelosB motes, including one mote that acts as the central coordinator of the sensor network.

Fig. 79.2 TelosB mote

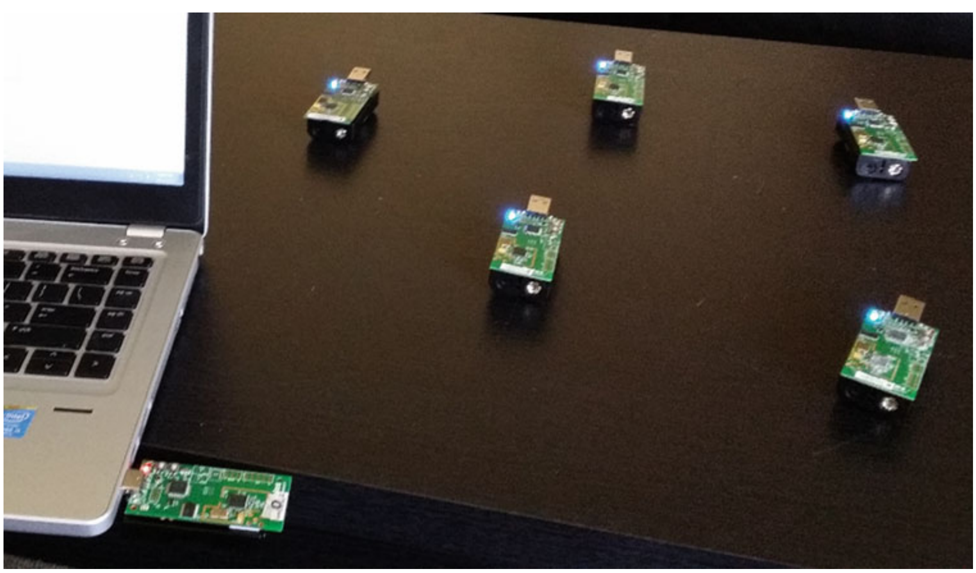


Fig. 79.3 TelosB mesh network

The coordinator of the network (NODE 0) is connected to a central server using a Universal Serial BUS (USB) connection. The coordinator communicates with the server via a C# program. The other nodes (NODEs 1–5) report temperature and humidity values to the coordinator. The coordinator updates the values from all nodes to the cloud server, together with the time stamp and node ID, every 5 s (this was the trial frequency, but others can be set as needed).

79.4 Mobile App

79.4.1 POE Design Principles

To develop an app to capture subjective occupant evaluation data, three parameters on perceived indoor conditions, corresponding with physical parameters, including temperature, humidity and air freshness, were selected. The aim was to achieve a high response rate, so a quick survey was designed, rather than one that would bore or tire recipients. A five-point semantic differential scale using two adjectives with a neutral point (e.g., 1 = hot, 3 = comfortable, 5 = cold) was selected to quantify the occupants' perception of indoor conditions. For thermal sensation, a neutral state means 'comfortable' or 'acceptable', indicating an absence of discomfort due to heat or cold. Participants were also asked to rate their overall satisfaction with thermal conditions. For this overall satisfaction level, a four-point Likert scale was chosen (e.g., 1 = very dissatisfied and 4 = very satisfied). Neuman [12] argues that more specific responses yield more information, but on the other hand, requests for too many specifics can create confusion in the context of a questionnaire.

79.4.2 Human–Computer Interaction (HCI) Design Principles

Human–computer interaction development guidelines and design principles were also followed during the mobile app development process. Initial discussion with POE and facility management experts revealed their needs in terms of the app's practical uses. The top priorities for the app were that it should be simple, easy for occupants to use, and interactive. The fundamentals of successful user-centered design [5] were also considered. Given that the POE design principles recommended that information provided in the app be simple, it was easy to adopt this 'simplicity' as an observational technique, as recommended by Dix [5]. Navigation design elements and global structure [5] were also carefully thought through based on the target users and application areas. We decided upon a maximum of two panels for primary information display, and to include an option button for settings. Direct manipulation [5] was another aspect considered, features of which include: the visibility of objects of interest; the actions used directly manipulate visible objects; and incremental actions within the interface. Dix [5] also argues that it is vital that users experience engagement and fun. The design therefore uses minimal text, and encourages users to enter their perception by means of symbols representing their feelings. For example comfortable conditions are represented by symbols for positive emotions, and uncomfortable conditions by symbols for negative ones. In addition interactive color schemes were used in the design—e.g., hot and dry conditions in red and cold and humid in blue, stale air in red and fresh in green—to: (i) clearly distinguish each option that the user selects, which minimizes errors due to ambiguity, improving the survey's construct validity [10]; and (ii) indicate the measurement being collected.

79.4.3 App Development

The app supports the collection of perception data through (i) a wall-mounted Android device, and (ii) a hand-held smart phone device. Data are then posted to the Amazon Web Server. The first version of the app was developed for Android tablets. Both Android and iOS apps were developed so that the app was compatible with the vast majority of smart phones. The phone apps were built using SDK version 16 (supports Jelly Bean 4.1 and above) for Android, and for iOS version 8.0 or above. The android tab version is SDK version 15 (supports Ice Cream Sandwich 4.00 and above) The Android studio (in Java programming language) and XCode (Objective C programming language) platforms were used for coding and compiling. Adobe Photoshop and Adobe Illustrator (AI) were used as the design tools.

The app's graphical user interface (GUI) is shown in Fig. 79.4. As shown in Fig. 79.4a, the app's settings enable selection of a specific sensor and location. The user is then surveyed about the temperature, humidity and air freshness, as per Fig. 79.4b, and their overall satisfaction, as per Fig. 79.4c. The time stamped perception data are then posted to the AWS. These data are synchronized with environmental data captured through the relevant wireless sensor, based on the initial configuration (physical location and sensor number) and time.

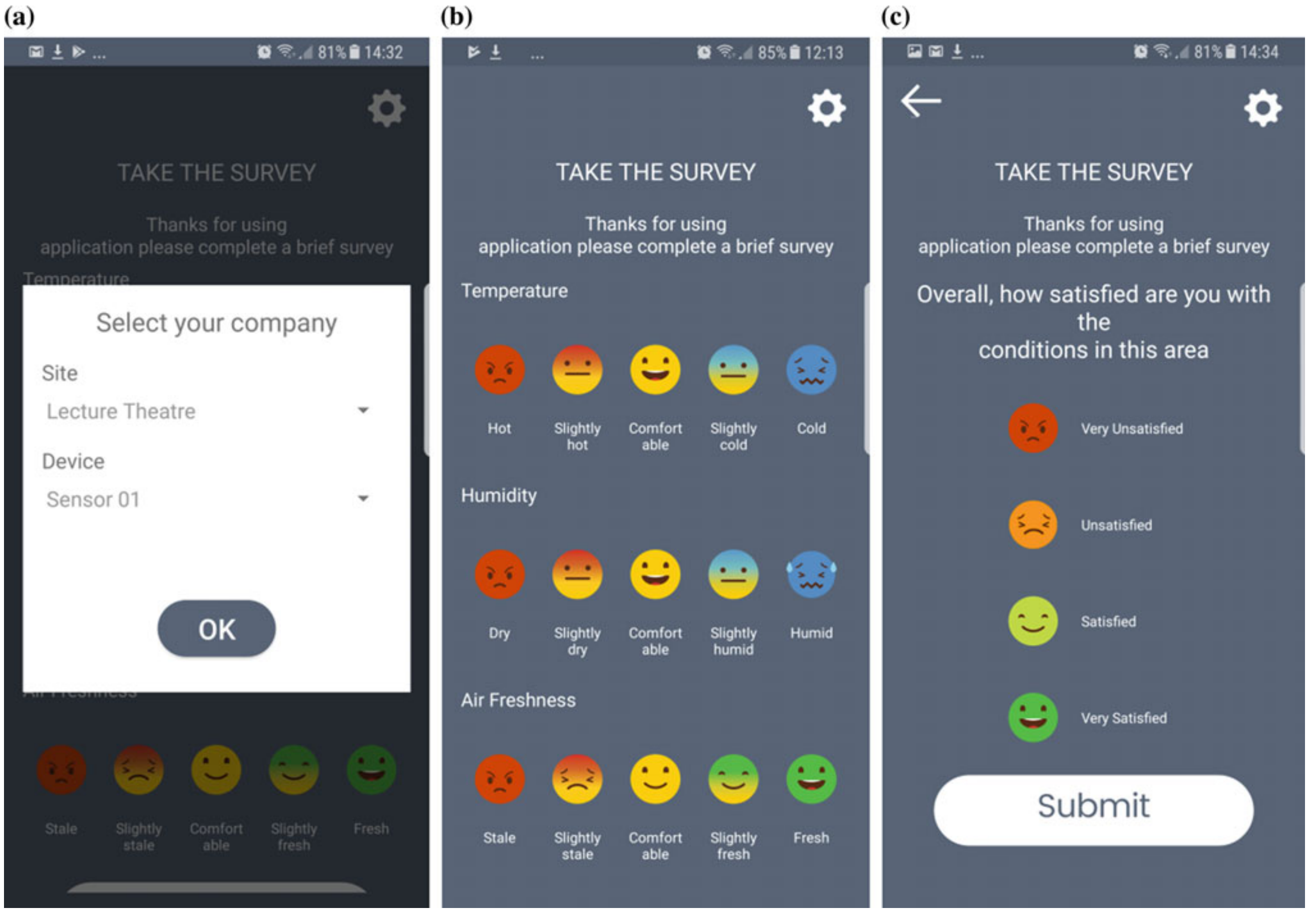


Fig. 79.4 Mobile app GUI

79.5 Testing and Initial Data Collection

The Android tablet app was tested on Samsung Galaxy Tab 4 and Tab A. The Android mobile phone version of the app was tested on Samsung galaxy S8, S7, S6, S5, S4, J7 and J5 phones. The iOS app was tested on iPhone 5, 6, 6s, 7 and 8.

An initial trial data collection using this system will be conducted to capture data in lecture theaters in a tertiary institution. The sensor network will be placed inside the theatre, and students will report their perceptions about the indoor conditions. This proposed trial data collection will also provide anonymous data about space utilization. The app (in its Android and iOS versions) will be hosted publicly during the trial. The University's Human Research Ethics Committee has granted approval for this data collection activity, and the trial is planned to occur in 2018. The lecture theater floor area is 166.33 m^2 with a balcony of 147.12 m^2 and it has the room capacity for 160. The layout of the lecture theatre and sensor placement is shown in Fig. 79.5.

The two types of data is statistically analyzed to investigate whether the two set of data are correlated. Theoretically, within the comfort boundaries of physical conditions, the occupant perceptions of the indoor conditions will remain a comfortable state. If the physical conditions go outside the comfort boundaries, the occupant perceptions will reach a state of discomfort. During this analysis process both quantitative and qualitative data can validate each other.

The data can identify zones that do not meet the set points in physical measurements (standards for indoor conditions); and the occupant perceptions (discomfort/dissatisfaction), which can be directly connected to building management systems to rectify the issues or help building managers to investigate the issues. Additional details about this pilot data collection, data correlation, data analysis and results are reported elsewhere [22].

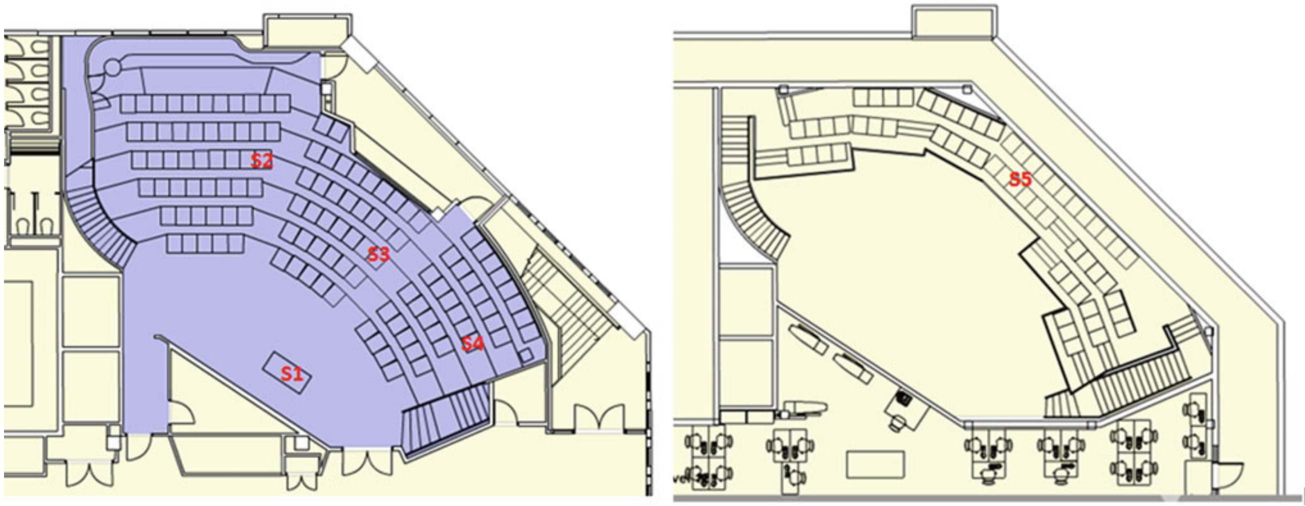


Fig. 79.5 Sensor placement in the lecture theatre

79.6 Conclusions

To fill the gaps in the POE research domain, we propose a holistic system. This system is also expected to provide a practical and powerful tool for both space designers and facility managers. This paper has discussed the development of a live, cloud-based, system for collection of both qualitative data on physical environments, and qualitative data on occupants' perception of building performance. Verification and validation of the survey will be undertaken as part of ongoing work on the project. This cloud-based system will also be extended to include context awareness and reasoning by correlating the qualitative and quantitative data sets. This real-time reasoning feature will be beneficial for space design, as well as for facility operation and management.

Future work will also include expanding the types of environmental sensor to include light sensors, digital microphones, CO_2 sensors, and object/IR (Infra-red) temperature sensors that can provide context-rich information about the use of the space. Given the growing interest in and use of building information modelling (BIM) in facility management, we also envisage linking this system with BIM. The resulting fully functional live system is expected to facilitate a BIM ecosystem integrated with other operational systems [6], and thus collaboration between parties, including planners, designers and facility managers, through live data collection, data analytics and visualization.

References

1. Australian Bureau of Statistics: Household use of information technology, Australia, 2014–15, cat. no. 8146.0, ABS, Canberra, viewed 1 March 2018. http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/8146.0Main+Features12014-15?OpenDocument (2016)
2. Babbie, E.: The Practice of Social Research. Cengage, Wadsworth (2010)
3. BOSSA (n.d.).: The Building Occupant Survey System Australia—BOSSA, Viewed 1 March 2018. http://www.bossasystem.com/
4. Center for the Built Environment (n.d.).: CBE's Occupant IEQ Survey, Viewed 1 March 2018. https://www.cbe.berkeley.edu/research/survey.htm
5. Dix, A.: Human-computer interaction. In Encyclopedia of Database Systems, pp. 1327–1331. Springer, US (2009)
6. Edirisinghe, R., London, K., Kalutara, P., Aranda-Mena, G.: Building information modelling for facility management: Are we there yet? Eng. Constr. Archit Manage. **24**, 1119–1154 (2017)
7. Li, P., Froese, T.M., Brager, G.: Post-occupancy evaluation: state-of-the-art analysis and state-of-the-practice review. Build. Environ. **133**, 187–202 (2018)
8. Leaman, A., Bordass, B.: Productivity in buildings: the 'killer' variables. Build. Res. Inf. **27**(1), 4–19 (1999)
9. Leaman, A., Bordass, B.: Are users more tolerant of 'green' buildings? Build. Res. Inf. **35**(6), 662–673 (2007)
10. Messick, S.: Validity of psychological assessment: validation of inferences from persons' responses and performances as scientific inquiry into score meaning. Am. psychol., **50**(9), 741 (1995)
11. Nagano, K., Horikoshi, T.: New comfort index combined conditions of moderate low ambient temperature and traffic noise. Energy Build. **37**(3), 287–294 (2005)
12. Neuman, W.L.: Social Research Methods: Qualitative and Quantitative Approaches, Pearson Education Inc (2006)

13. Newsham, G., Brand, J., Donnelly, C., Veitch, J., Aries, M., Charles, K.: Linking indoor environment conditions to job satisfaction: a field study. Build. Res. Inf. **37**(2), 129–147 (2009)
14. Paevere, P., Brown, S.: Indoor Environment Quality and Occupant Productivity in the CH2 Building: Post-Occupancy Summary, CSIRO (2008)
15. Pellerin, N., Candas, V.: Combined effects of temperature and noise on human discomfort. Physiology & Behavior **78**(1), 99–106 (2003)
16. Pellerin, N., Candas, V.: Effects of steady-state noise and temperature conditions on environmental perception and acceptability. Indoor Air **14** (2), 129–136 (2004)
17. Preiser, W.F.E., Rabinowiz, H.Z., White, E.T. Post-Occupancy Evaluation, Van Nostrand Reinhold Company Inc (1988)
18. Sekhar, S.C., Tham, K.W., Cheong, K.W.: Indoor air quality and energy performance of air-conditioned office buildings in Singapore. Indoor Air **13**(4), 315–331 (2003)
19. Shneiderman, B.: Designing the User Interface: Strategies For Effective Human-Computer Interaction. Pearson Education India (2010)
20. Thomas, L.E.: Evaluating design strategies, performance and occupant satisfaction: a low carbon office refurbishment. Building Research & Information **38**(6), 610–624 (2010)
21. Vischer, J.C.: Applying knowledge on building performance: from evidence to intelligence. Intel. Build. Int. **1**(4), 239–248 (2009)
22. Woo, J., Edirisinghe, R.: Proceedings of 52nd International Conference of the Architectural Science Association, The Architectural Science Association (Accepted) (2018)
23. Yong, C., Qiao, B., Wilson, D., Wu, M., Clements-Groome, D., Lui, K., Egan, R., Guy, G.: Coordinated management of intelligent pervasive spaces. http://www.thalesresearch.com/Publications/Technical/2007/Documents/Co-ordinated%20Management%20of%20Intelligent%20Pervasive%20Spaces.pdf (2007)

Bayesian Network Modeling of Airport Runway Incursion Occurring Processes for Predictive Accident Control

80

Zhe Sun, Cheng Zhang, Pingbo Tang, Yuhao Wang, and Yongming Liu

Abstract

This paper examines how runway incursion, one of the major risks in aviation system, arise and propagate during communications and operations necessary for air traffic control. Runway incursions (RIs) refer to incorrect presences of aircraft in protected areas designated for landing and take-off of aircraft. RIs can significantly jeopardize the runway safety. Communication errors between air traffic controllers and pilots are major causes of RIs. How to quantify the probabilistic dependence between contextual factors (airport layout, time of the day, etc.) and communication errors that lead to RIs is thus important for real-time alarming and accident prevention. This study presents a Bayesian Network (BN) modeling approach with a focus on modeling the communication errors causing RIs during aircraft take-offs and how different factors contribute to the accidents according to the information from the aviation accident reports. Major findings indicate that the proposed approach can predict the accident occurrences based on the risk knowledge of anomalies captured in the BN produced by the proposed approach. In practice, the proposed approach has the potential for establishing automated and preventive safety management in aviation systems.

Keywords

Runway incursion • Bayesian network modeling • Process model

80.1 Introduction

According to the International Civil Aviation Organization (ICAO), runways are rectangular areas at airports prepared for the landing and takeoff of aircraft. Runway safety is a top priority for the Federal Aviation Administration (FAA) to ensure safe operations of National Airspace System (NAS) [1]. Runway incursions (RIs) refer to incorrect presences of aircraft in protected areas designated for certain landing and take-off of aircraft [2]. RIs, as one category of the most critical accidents, has seriously jeopardized the runway safety, while an average of three RIs occur daily in the United States and cause severe fatalities and property damages [2, 3].

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Air Traffic Controllers (ATCs), who are responsible for safe coordination of air traffic, play a major role in avoiding RIs. ATCs need to communicate with pilots through radio and provide instructions or clearances regarding altitudes, speeds, weather and air traffic conditions [4]. Reliable communications between the pilots and ATCs are critical to ensuring safe coordination in air traffic control. ATC/Pilot communications also need to employ read-back/hear-back procedures for ensuring that the information could be properly understood. However, since the U.S. airspace becomes much more crowded with the increasing air traffic, ATCs are posing a larger workload and prone to human errors despite these procedures ensuring the reliable ATC/Pilot communications [5]. Miscommunication has contributed to more than 60% of RI events [6], which have been identified as one of the most common human error and involved more than 2000 fatalities in the past RIs and are threatening aviation safety [7–9].

Previous studies have investigated miscommunications between ATC and pilots through linguistic analysis using radio communication transcripts [4, 10, 11]. These studies focus on how to reduce misunderstandings in ATC/pilot communications through improving the communication protocols. However, few studies have examined how communication error occurs during air traffic control and lead to RIs. An effective aviation safety control that can reduce RIs is thus necessary, which not can only identify anomalies (e.g. communication error) that may cause RIs but also be able to predict the likelihood of RIs triggered by the propagation of the detected anomalies. This study presents a *Bayesian Network* (BN) modeling approach that first create process models for showing processes of air traffic control that gradually lead to RIs during aircraft take-offs. A Bayesian network-learning algorithm then uses this process model and a large number of accident reports to generate a BN that captures histories about how various contextual and human factors influence the probabilities of certain events and miscommunications that lead to runway incursions.

80.2 Background Studies

Previous research on the RIs focused on two questions (i) what are the contributing factors that cause the miscommunications and the RIs; (ii) what are the processes of accident occurrences. Most studies use Fault Tree Model or Event Tree Model to quantify the causal relationship between contextual factors and communication errors in certain RI scenarios [10]. Some studies examined which factors have more impacts on RIs using Bayesian Network (BN) modeling [11]. Some studies showed that a safety ontology-based framework could help to formalize the safety management knowledge [12]. El-Gohary has developed a set of construction ontologies to better understand the processes of project development [13]. These previous studies showed the potential of using process models along with BN learning methods for synthesizing mechanisms about how RIs occurred. Few studies examined RI processes by quantifying the correlations between accidents, contextual factors, and communication errors, which are critical for the RI prediction. This paper tries to examine how airport RI, one of the major risks in aviation systems, arise and propagate in the process of communications and operations during air traffic control.

80.3 Methodology for Predicting Runway Incursions Using *Bayesian Network* (BN) Modeling

The goal of this study is to understand how communication errors occur in the take-off process of aircraft and how these errors eventually lead to runway incursions. To achieve the goal, the two sub-objectives are: (1) Develop a process model for understanding the process of having runway incursion during aircraft take-off through synthesizing aviation accident reports from multiple sources (NTSB database, ASRS database, etc.); (2) Establish a *Bayesian Network* (BN) model based on the process model to quantify the correlations between events in the process model. This study presents a BN modeling approach with a focus on modeling runway incursions that occur during aircraft take-offs and how different factors contribute to the accident occurrences according to the information from the accident reports.

The proposed BN modeling approach for predicting runway incursions consists of three steps (see Fig. 80.1). The first step is to collect accident/incident reports of runway incursion caused by communication errors from the Aviation Safety Report System (ASRS). The second step is to extract information from the collected reports (i.e. time of the day, number of runways, runway layout, number of people on the same radio frequency, etc.). The third step is to classify the types of communication error and the runway incursion according to the detailed narrative described in the reports. Then, the authors created a process model to represent different phases of an aircraft during the take-off process according to the standard flight take-off procedure. The standard take-off procedure consists of pushback from the gate, start taxiing, hold-short at certain intersections (aircraft cannot across an active runway), line-up and wait at the runway and prepare for take-off, and take-off.

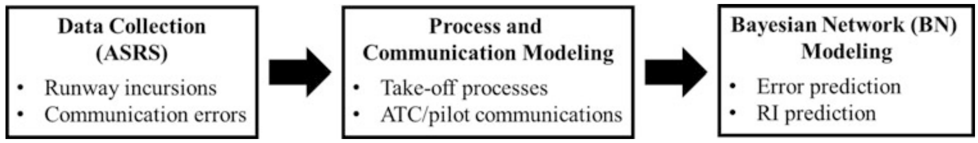

Fig. 80.1 Overall framework

In this process model, the authors also represent the anomalous events by using the error states (i.e. runway crossing, unauthorized take-off, etc.) based on the aviation accident reports. The authors then constructed a *Bayesian Network* (BN) model based on the accident reports of runway incursions to represent how anomalous events arise and propagate that lead to different type of RIs. The model provides the capability to quantify risks during aircraft take-offs by calculating the probabilistic dependence between anomalies based on their relationships represented in the BN.

80.3.1 Data Collection

The Aviation Safety Reporting System (ASRS) is a voluntary confidential reporting system that allows pilots and other aircraft crewmembers to confidentially report near misses and accidents in the interest of improving air safety. It contains a huge amount of accident/incident reports that could help the authors to better understand how runway incursion occurs based on the information provided in the reports. The authors collected data using following the parameters listed in Table 80.1. Since communication errors have been studied as one of the most critical factors that causing runway incursions, the authors are looking for reports of runway incursion that are due to communication errors. A total number of 331 runway incursion cases have been found between 2014 and 2017 under the category communication error, which means that all these 331 runway incursions are due to communication errors. The authors manually analyzed 30 reports and tried to understand the correlation between environmental factors, communication errors, and runway incursions.

Since the air traffic volumes are different at different times, time of the day of specific incident happens allow the authors to understand whether RIs occurred more frequently at dawn, morning, afternoon, or night. Airport layout and its number of runways also provide information on how RIs occurred at airports with a similar design. The authors then picked the *airport name, time of the day*, and *the number of people in the same radio frequency* as major attributes of each RI case for RI prediction. Then, by using *Google Map*, the authors would be able to understand the number of runways and the layout of that airport (interact runway or not, see Fig. 80.2). By retrieving the airport information, the authors could better understand the how RIs occurred at airports with similar layouts that contain a similar number of runways with similar arrangements. Then, the authors retrieve information of how communication errors happen and how many people are in the radio frequency at that time through the detailed narrative of the report. Since ATC and pilots are communicating in the same radio frequency and ATC is required to call out the "call sign" (e.g. AA870—flight number), errors might occur when the frequency is congested. Table 80.2 has listed the major findings from the 30 reports being analyzed (Fig. 80.3).

Table 80.1 Data searching parameters

Data searching parameters	Value
Database	Aviation Safety Reporting System (ASRS)
Date of incident	2014–2017
Event type	Runway Incursion
Human factors	Communication errors
Total number of reports collected	331
Number of reports analyzed in this research	30

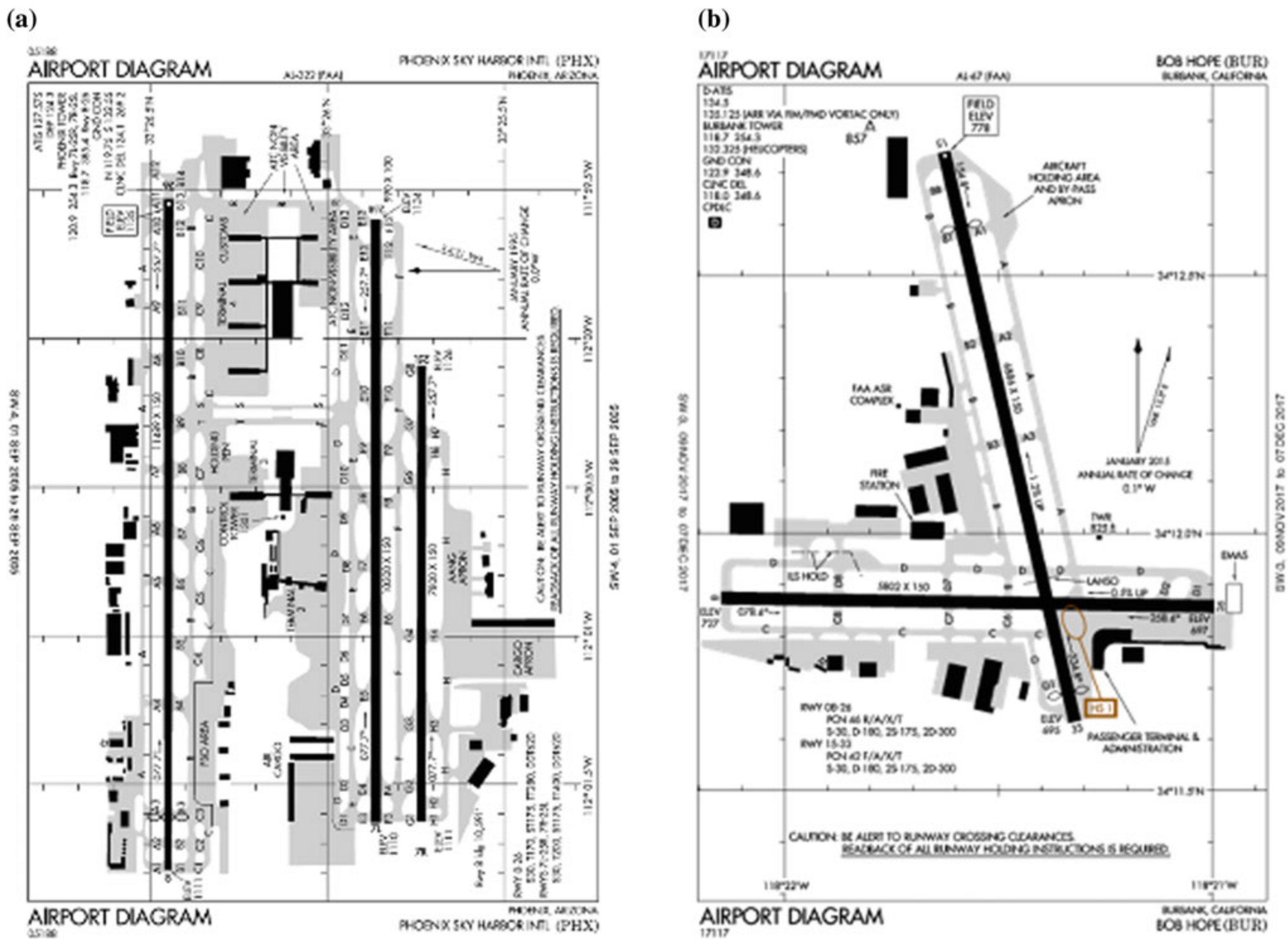

Fig. 80.2 The layout of airports **a** PHX Sky Harbor International Airport—Three runways with no interactions; **b** BUR Bob Hope Airport, CA—Two runways with interaction

Table 80.2 Variables retrieved from the reports

Factors	Variables	Number of cases
Number of runways (R)	2 runways (R^0)	10
	3 runways (R^1)	20
Runway layout (I)	No interaction (I^0)	4
	Interact (I^1)	26
Number of people on the same radio frequency (P)	Less than 4 people (P^0)	17
	More than 4 people (P^1)	13
Time of the day (T)	Dawn (T^0)	3
	Morning (T^1)	6
	Afternoon (T^2)	15
	Night (T^3)	6

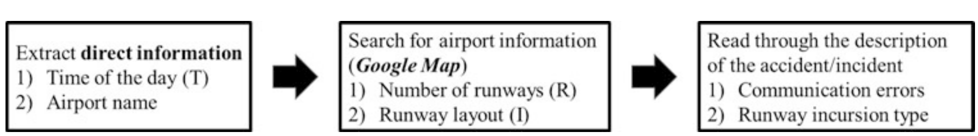

Fig. 80.3 Steps of data collection from the Aviation Safety Report System (ASRS)

80.3.2 Process and Communication Modeling

In this step, the authors created a process model based on standardized take-off procedures to represent how communication errors occurred and contributed to certain RIs at different phases of the take-off process per the reviewed accident reports (see Fig. 80.4). In addition, the BN modeling processes quantified the correlations for enabling risk prediction of RIs.

The authors first create a process model to illustrate the normal take-off processes of aircraft. This take-off process model represents two type of take-off process and is classified depends on whether the aircraft need to cross other active runways on their taxi route to the determined runway for take-off. Runway crossing usually involves more communications between ATC and pilot and induces more risks of communication errors that could lead to RIs. Then, according to the narrative in the reports, the authors found out three types of RIs (see Table 80.3) that frequently occurred before take-off, and incorporate these runway incursions into the process model (see Fig. 80.4). The most common type of RI (RI_1) happens when pilot ignored the "hold short" clearance (stop at the intersection) and cross an active runway without clearance (runway crossing without clearance). The second type of RI (RI_2) happens when pilot cross the hold line at certain interactions on the taxi route (taxi across hold-line of the runway). The third type of RI (RI_3) happens when a pilot attempt to take-off without clearance.

As for the communication errors, ATCs have to issue four types of clearances to inform pilots about the taxi route, hold short (stop) points at certain intersections, and the assigned runway for take-off of a given aircraft. These four types of clearance include (1) *Taxi Clearance* (ATC issue taxi clearance to inform pilot about taxi route from gate to the runway for take-off); (2) *Runway Crossing Clearance* (Pilots are required to stop at intersections and wait until ATC has cleared the runway and give runway crossing clearance to pilot); (3) *"LUAW" Clearance* (ATC issue "line up and wait" clearance to allow the pilot to line up at the runway and wait for take-off clearance); and (4) *Take-of Clearance* (ATC issue take-off clearance to pilot for take-off when runway has been cleared). In the current practice of ATCs/pilots communications, a "three-step" communication protocol is required. In a communication, an ATC needs to issue the clearance to a pilot with specific instructions; the pilot should respond with a full read-back on the clearance, and the ATC needs to confirm the read-back to ensure that the pilot das a clear understanding on that clearance. In total, twelve communications are required for each aircraft before the take-off. However, communication errors do exist and lead to RIs. The authors find out that four kinds of communication errors happen frequently during runway incursions (see Table 80.4).

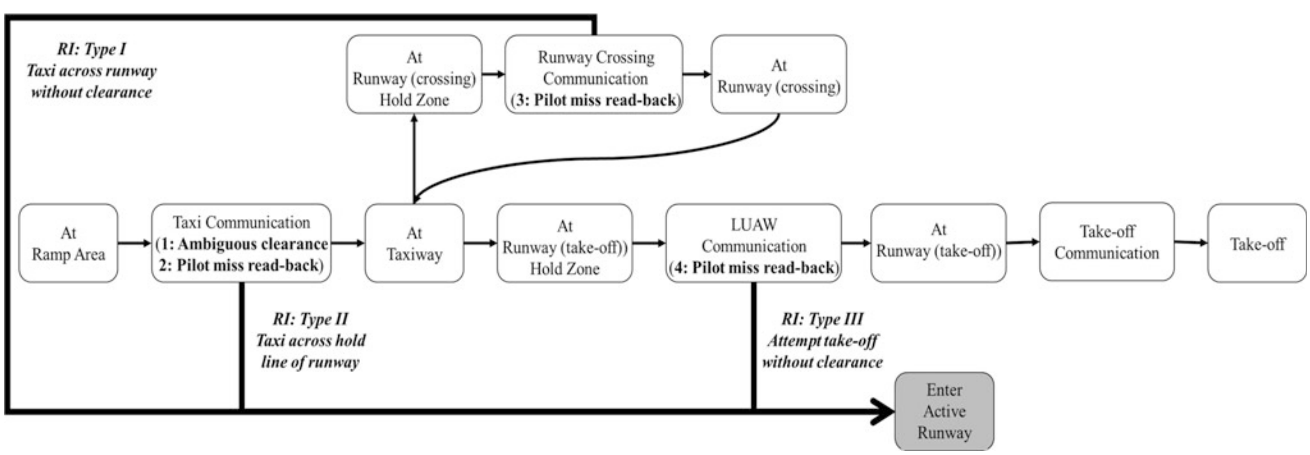

Fig. 80.4 Take-off process modeling

Table 80.3 Types of a runway incursion

Types of runway incursion	Description	Number of cases
Type I (RI_1)	Taxi across runway without clearance	16
Type II (RI_2)	Taxi across hold line of a runway without clearance	9
Type III (RI_3)	Attempt take-off without clearance	5

Table 80.4 Types of communication error

Types of communication error	Description	Number of cases
Type 1 (E_1)	ATC issued ambiguous taxi clearance to pilot	8
Type 2 (E_2)	The pilot missed read-back on the taxi clearance issued by the ATC	16
Type 3 (E_3)	The pilot missed read-back on the runway crossing clearance	1
Type 4 (E_4)	The pilot missed read-back on "LUAW" clearance	5

80.3.3 Bayesian Network (BN) Modeling

The last step of this study is to generate a *Bayesian Network* (BN) model by using the process model that captures conceptual relationships between contextual factors and events occurring during RI arising processes (see Fig. 80.5). Using the accident reports of RIs can serve as data sources for quantifying the strengths of these relationships. More specifically, the BN model uses the information retrieved from the accident reports and try to find out the quantitative relationship between different anomalous events and runway incursions under certain conditions. The quantitative correlation would help the air traffic manager to better understand the potential risks and send out an alarm to the corresponding personnel to avoid a runway incursion.

80.4 Major Findings

This section shows preliminary results of the research methodology presented above. Table 80.5 illustrates the probabilistic relationship between different communication errors and different combinations of the four factors. Table 80.6 illustrates the probabilistic relationship between three types of runway incursions and four types of communication errors. These results quantify the relationship between selected factors, communication errors, and runway incursions respectively.

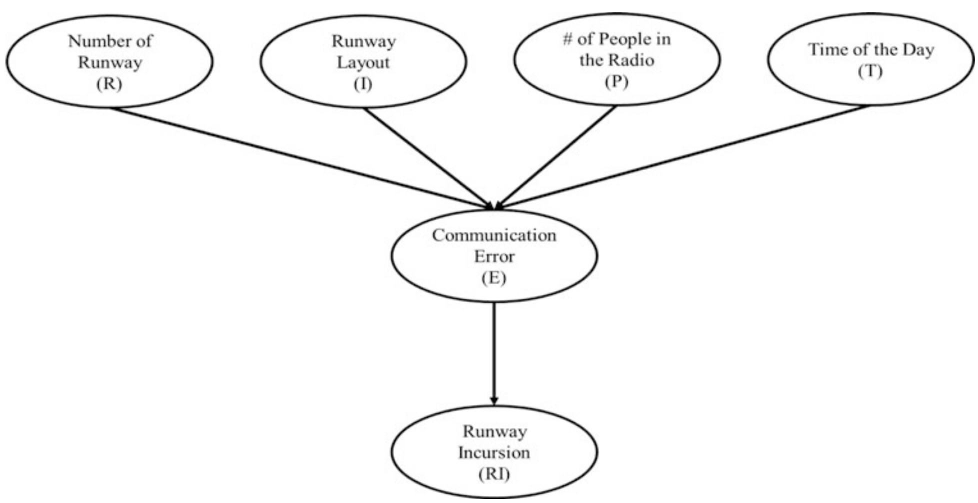

Fig. 80.5 Bayesian Network (BN) modeling of RIs, communication errors, and influencing factors

Table 80.5 The conditional probability of communication errors on factors (see Table 80.2 for a detailed explanation on R, I, P, and T; see Table 80.4 for a detailed explanation on E_1, E_2, E_3, and E_4)

Combinations	Conditional probability (%)
$P(E\_1 \mid R^0I^1P^1T^1)$	79.0
$P(E\_2 \mid R^0I^1P^0T^2)$	45.8
$P(E\_3 \mid R^1I^1P^0T^1)$	94.7
$P(E\_4 \mid R^1I^0P^1T^2)$	67.0

Table 80.6 The conditional probability of runway incursions on communication errors (see Fig. 80.4 for a detailed explanation on E and RI)

P	RI_1 (%)	RI_2 (%)	RI_3 (%)
E_1	62.5	**37.5**	0.0
E_2	62.5	**37.5**	0.0
E_3	**100.0**	0.0	0.0
E_4	0.0	0.0	**100.0**

80.4.1 The Probabilistic Relationship Between Selected Contextual Factors and Communication Errors

Table 80.5 shows that Type 1 communication error (ATCs issue ambiguous taxi clearance) has a higher probability to happen when an aircraft is prepared for take-off on a two-runway (interact) airport in the morning and there are more than four people in the same radio frequency. Type 2 communication error (pilots miss read-back on taxi clearance) has a higher probability to happen when an aircraft is prepared for take-off on a two-runway (interact) airport in the afternoon and there are less than four people in the same radio frequency. Type 3 communication error (pilots miss read-back on runway crossing clearance) has a higher probability to happen when an aircraft is prepared for take-off on a three-runway (interact) airport in the morning and there are less than four people in the same radio frequency. Type 4 communication error (pilots miss read-back on "LUAW" clearance) has a higher probability to happen when an aircraft is prepared for take-off on a three-runway (no interaction) airport in the afternoon and there are more than four people in the same radio frequency. Classification of the communication errors is crucial for predicting the occurrences of communication errors under certain conditions (e.g. airport with complex layout and more traffic volume, etc.). The quantitative relationship between those selected factors and certain types of communication errors can provide additional information to ATCs to discover errors that are more likely to occur so that ATCs could correct those errors in time.

80.4.2 The Probabilistic Relationship Between Communication Errors and RIs

Table 80.6 shows that Type I RI has a higher probability to happen when the pilot has missed read-back to the runway crossing clearance. When pilot issue taxi clearance to inform the pilot about the taxi route, "hold-short" locations at certain intersections and the runway for take-off, it is critical for the ATC to ensure a clear and accurate clearance has sent to the pilot. Especially for the "hold-short" points at certain intersections of runways at the airport that has a complex layout. Read-back is a step that to guarantee that a pilot could strictly follow the instruction given by the ATC. As for type II RI, it has a higher probability to happen when ATC missed information on the taxi clearance or the pilot miss to read-back on the taxi clearance. Taxi clearance contains a lot of information, and increase the risks of communication errors and lead to a runway incursion. For type III RI, it always occurred when the pilot ignored the "LUAW" clearance. When ATC has issued a "LUAW" clearance, it indicates that the pilot is allowed to line up on the runway to prepare for take-off, and can only take-off when he/she receive the take-off clearance.

80.5 Conclusion and Future Work

This research proposed a BN modeling approach to help predict communication errors and runway incursions during the take-off process. By using the accident reports of RI from ASRS, the proposed approach could provide guidance in classifying the communication errors and RIs, and quantify their relationship. The preliminary research findings suggest that the developed BN has the potential of early detections of high-risk runway events and quantitatively assess the associated risk of anomalies captured in the BN. In addition, the proposed approach also has the potential to help with the decision-making of air traffic controllers, and send out alarms to relevant participants about the upcoming risk and thereby reducing the occurrences of RIs.

The results generated from the BN model indicate that the proposed approach could accurately calculate the probabilities of certain anomalous events and predictively reflect the probabilities of runway incursions. However, due to the limited amount of incident reports being analyzed, the structure of the BN model and the results generated by the developed BN could only apply to the selected dataset and might not be representative for all runway incursion cases. In addition, using a large amount of incident report to get a reliable BN model is considered computational expensive. The research team will try to develop an automatic text analysis algorithm to automate the tedious data processing process and ensure the risk prediction based on the BN becomes more reliable and realistic. To sum up, the results showing that the proposed BN could potentially establish preventive safety management strategies for NextGen.

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References

1. Federal Aviation Administration: Runway Incursion Avoidance. Runw. Saf. A Best Pract. Guid. to Oper. Commun., no. Sep (2007)
2. Wilke, S., Majumdar, A., Ochieng, W.Y.: Modelling runway incursion severity. Accid. Anal. Prev. **79**, 88–99 (2015)
3. Chang, Y.H., Wong, K.M.: Human risk factors associated with runway incursions. J. Air Transp. Manag. **24**, 25–30 (2012)
4. Immanuel, B., Candace, F.: Misunderstandings in ATC Communication: Language, Cognition, and Experimental Methodology. Ashgate Publishing (2013)
5. Moon, W.-C., Yoo, K.-E., Choi, Y.-C.: Air traffic volume and air traffic control human errors. J. Transp. Technol. **1**(3), 47–53 (2011)
6. G. Introduction, M. Than, W. To, M. Portfolio, National Runway Safety Report 2013–2014, no. 348, pp. 1–5 (2015)
7. Molesworth, B.R.C., Estival, D.: Miscommunication in general aviation: the influence of external factors on communication errors. Saf. Sci. **73**, 73–79 (2015)
8. Wu, C.-H., Su, M.-H., Liang, W.-B.: Miscommunication handling in spoken dialog systems based on error-aware dialog state detection. EURASIP J. Audio, Speech, Music Process. **2017**(1), 9 (2017)
9. Geacăr, C.M.: Reducing Pilot/ATC Communication Errors Using Voice Recognition. English, 1–7 (2016)
10. Aberdeen, J., Ferro, L.: Dialogue patterns and misunderstandings. Proceedings of Error Handling in Spoken Dialogue Systems, pp. 17–21 (2003)
11. Lu, Y., Shi, Y., Jia, G., Yang, J.: A new method for semantic consistency communication based on LSTM-RNN. 2016 IEEE Int. Conf. Digit. Signal Process (2016)
12. Zhang, S., Boukamp, F., Teizer, J.: Ontology-based semantic modeling of safety management knowledge. Comput. Civ. Build. Eng. 455–462 (2014)
13. El-Gohary, N.M., El-Diraby, T.E.: Domain ontology for processes in infrastructure and construction. J. Constr. Eng. Manag. **136**(7), 730–744 (2010)

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A Low-Cost System for Monitoring Tower Crane Productivity Cycles Combining Inertial Measurement Units, Load Cells and Lora Networks

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Abstract

Tower cranes are one of the most expensive assets inside construction projects and they lead the timing of the planned activities. For this reason, assuring the efficient use of this equipment is essential for the productivity of the project. This work presents a monitoring system for tower crane productivity cycles. It uses an Inertial Measurement Unit (IMU) to calculate jib angles in real time which allows the evaluation of the crane position. In addition, a load cell system measures the lifted load by the tower crane. Data is transmitted via Long Range (LoRa) network. Data is tagged from the origin and sent to the brain, which uploads the information to the cloud. Results show that the system can be used for real time monitoring of the tower crane operation by measuring productivity cycles, average lifted load, and operation hours. This information is organized and displayed in a time series platform that generates inactivity and load alerts to construction managers within the projects.

Keywords

Tower crane • Productivity cycles • Monitoring system • Inertial measuring units • Load cells • LoRa networks

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81.1 Introduction

According to the World Economic Forum the population of urban areas is growing at a rate of 200,000 people per day [1]. Services as housing, transportation and infrastructure are required for communities to carry out their daily activities. Thus, the importance of innovating to optimize time and costs in the Construction sector. While other industries have experienced considerable technology changes, represented in financial and operational benefits, this sector has adopted the changes with lower pace and this situation has affected its productivity [1].

The theory of constraints (TOC), introduced by Goldratt in the 1980s [2], describes the importance of identifying bottlenecks in order to control and measure the flow of materials to increase the productivity of processes. Identifying and optimizing these constraints can be a source for increasing productivity. The main challenge of a construction project is its highly dynamic environment. Thus, programming a construction project involves challenges related to the use of resources. For example, in a building construction project, the structure execution is part of the critical path and the tower crane is a high-cost resource that defines project performance since it allows the transportation and installation of most materials and equipment.

In the past, some systems have been developed to monitor tower crane operation. Most of them aim at improving safety conditions in the construction site, generating alarm signals under hazardous conditions by measuring mechanical and electrical variables, loads, wind speed, among others. These systems use technologies such as RFID, wireless video, black box model, broadband and Building Information Modeling (BIM) [3–7]. Other systems allow measuring variables related to productivity and crane operation. For example, [8] presents a system composed by data acquisition, control, communication and alarm subsystems. The acquisition subsystem consists of four mechanical variables related to crane operation and one for wind speed. The work presented by [9] uses CAN bus and ZigBee technologies to supervise the operating status and tower crane position. In [10] a detailed description of a safety system used for the operation of tower crane groups is provided. Their system uses a sensor that sends information via GPRS or 3G to the terminals. Also, the scheme presented by [11] allows the acquisition, integration, management and control of the data required at a construction site using several communication systems based on ZegBee, 3G and an IoT sensor network connected via a CAN bus, which performs data management through an integrated cloud platform. However, only in a few cases results of the field deployment of the proposed systems are presented. On a commercial perspective, there are crane monitoring systems that provide information of the operational conditions but their high cost is restrictive for its implementation in a larger number of cranes. In addition, they do not provide productivity indicators directly on dashboards and in some cases they are only compatible with cranes from the same manufacturer, loosing flexibility.

This work presents a low-cost, flexible system for monitoring tower crane productivity cycles combining inertial measurement units (IMU), load cells and Long Range (LoRa) Networks. This system allows making informed decisions in real time as well as gathering information for future projects.

81.2 Methodology

A tower crane monitoring and control system was developed and implemented in three types of construction projects:

- An institutional building, developed with a column-beam and slab frame system, with 8 stories and 4 basement and located in Medellin, Colombia.
- A hotel in Bogotá, Colombia with 17 stories, 414 rooms and 2 basements. The construction system consists of column-beam and precast slab frames.
- A 26-story housing project in Itagüí, Colombia built with a traditional beam-column frame system.

81.2.1 System Technical Description

This work presents a system for tower crane productivity cycles monitoring. It uses an Inertial Measurement Unit (IMU) to calculate jib angles in real time. This allows to evaluate the position of the crane at any time. In addition, a load cell system measures the lifted load by the tower crane. This technology offers advantages in terms of power consumption, coverage and

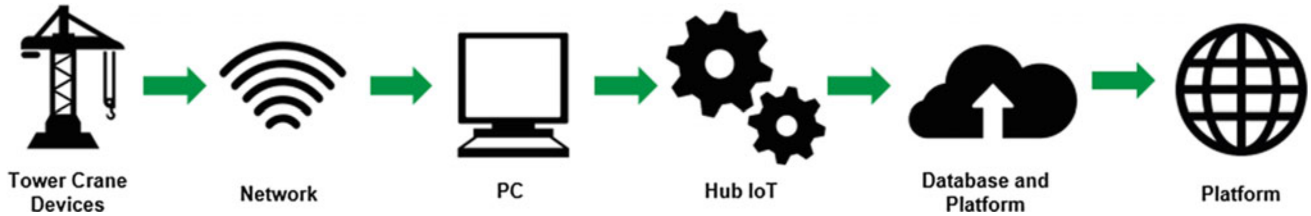


Fig. 81.1 Network overview

Table 81.1 Variables measured by the system

Variable	Units	Description
Jib slewing	Degrees	Generated from 9 variables that are the result of the measurements in the three axes of a magnetometer, gyroscope and accelerometer. Angle is measured in *x*, *y* and *z* axes
Lifted load	Kg	Indicates the load carried by the crane hook
Jib distance	m	Distance between the mast and the crane carriage

interference response [12], it has an estimated range of 12 km and supports the connection of 255 devices to the brain. Data is tagged from the origin and sent to the brain, which uploads the information to the cloud. The network overview is presented in Fig. 81.1. The coordinator receives the system's information through the LoRa network. Then it is redirected to the cloud platform, where it is processed and stored. The coordinator sends the information to the IoT hub. The load cell is powered by a solar panel that is located on the crane hook and guarantees the autonomy of the system. The system also includes a platform in which dashboards with the indicators are displayed. It also includes security and productivity alerts. The system was implemented in different cities, with different weather conditions, thus, allowing us to prove its energy autonomy due to the operation of the solar panel. Internet access and the quality of the WIFI connection also differ according to the project's resources and its location.

The developed system measures the jib slewing, the lifted load and the jib distance as presented in Table 81.1. Using this information, eight productivity indicators were generated, including cycle times, hook position, load capacity efficiency and percentage of use. Time cycle, hitch time, average time cycle and disengage time are used to analyze production based on the crane's operating cycles. The position of the hook is required to determine the material transported and the impacted activity. The percentage of use and the average daily load are required to analyze the overall performance of the crane over a time period defined by the user.

81.2.2 System Calibration

Laboratory and field tests were conducted in order to validate the system performance under controlled and real conditions.

81.2.2.1 Calibration of the Sensors at the Laboratory

Slewing angle error test: The rotation angle was measured combining the results of a magnetometer, an accelerometer and a gyroscope in the *x*, *y* and *z* axes. For this purpose, the IMU device was coupled to a calibration platform based on a robotic arm which was programmed to make turns at certain test angles. A servomotor rotates in the last degree of freedom of the platform and has a resolution of 0.29°. The IMU calibration procedure is described by [13]. The IMU sensors were individually calibrated, the information was used to find the bias and scale factor of the magnetometer and the accelerometer for each axis using the robotic arm position as ground truth. After making the calibration adjustments, the alignment between the axes was verified and the angle estimation was checked for an error of less than ±1°.

Load Cell Calibration: A universal testing machine was used to perform this calibration. The tests consisted on applying five different force values to the load cell, which were equally spaced in a range between 1000–5000 N. Each value was applied for 30 s. The test was repeated twice. The load values of the machine's force sensor were plotted against the ADC converter data of the load pin, getting a linear expression to determine the values of the load pin installed at the tower crane over the entire working range.

81.2.2.2 Field Tests

Load cell power supply using solar energy: A solar charging system was designed and implemented. The charging system allows the load cell to be autonomous. The system was tested over several consecutive days with the purpose of monitoring the actual radiation conditions and its internal energy losses. Battery charging efficiency was also tested using an SOC (State Of Charge) circuit.

Transmission range test: Information is transmitted from the tower crane to the central node (Fig. 81.1), which performs the data uploading. Communication distance tests between these components were performed. The central node was left in the project offices while crane devices were moved to different areas of the construction site. This test was made to determine the performance of the communication in the actual interference conditions. The communication between components was considered to meet the requirements of the system when it is transmitted at a distance of 5 km or less. This distance was defined considering the extension of building projects.

Validation of load linearization value on field: Based on the results obtained from the linearization of the load cell in the laboratory, a field validation was performed by comparing the value received by the system and the actual value of the lifted load. Linearization was considered to meet system requirements if it has an error rate of maximum 3%.

Trolley-operator's cab distance tests: Distance between the trolley and the mast was measured according to the power received by a LoRa sensor node located in the cab from a Bluetooth Low Energy (BLE) device located on the trolley. Power obtained by the cabin system is tested every 10 m. The average power for each control distance was estimated with ten movements of the crane carriage.

81.3 Results and Discussion

Results showed that the system could be used for real time monitoring of the tower crane operation. This information was organized and displayed in the platform as a time series. Figure 81.2 shows the percentage of use, average cycle time and number of cycles per hour for a labor day.

Due to the data uploading method required for the platform, sets of 20 data were sent every two seconds. The dataset transmission rate between towers and the LoRa central node was not constant to avoid collisions between data sent from different devices. Although the amount of data usage per day was just 1.2 MB, the Internet access had to be guaranteed, therefore the coordinator was connected to the access point both by Wi-Fi and Ethernet connection. In general, internet speed for construction projects in Colombia is not homogeneous and the connection is not stable.

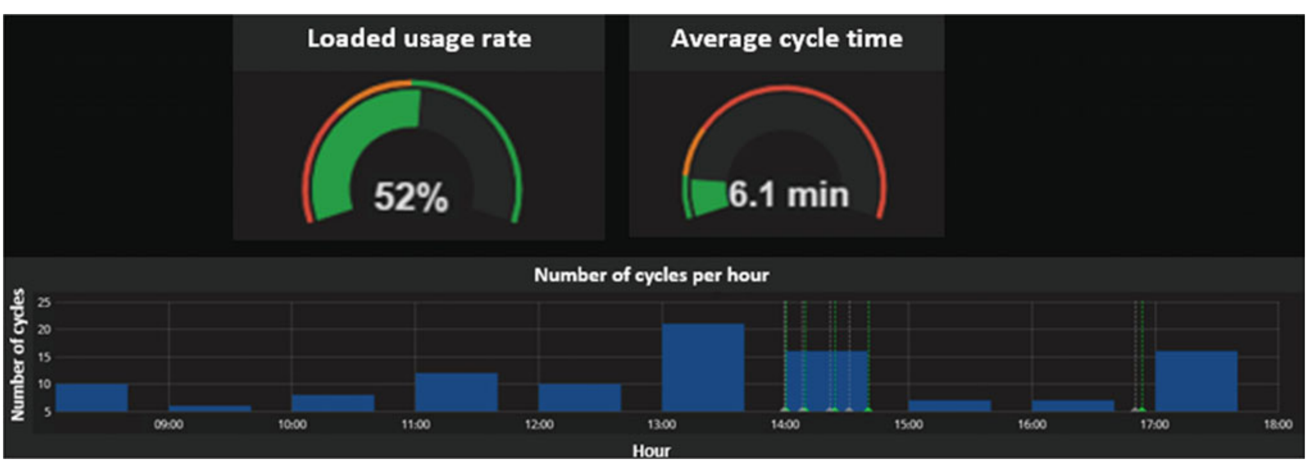


Fig. 81.2 Indicators visualized on the platform

81.3.1 Calibration and Testing

81.3.1.1 Sensors Calibration in Laboratory

Slewing angle error test: After making the calibration adjustments, the alignment between the axes was verified and the angle estimation was checked for an error of less than ±1 degree for the measurement of the obtained slewing angle. Figure 81.3 shows the calibration cycle for one of the magnetometers. Red dotted circles represent the values of the magnetometer while the IMU rotates on the z-axis in the opposite direction to gravity. Black dots indicate the cycle with the inverted z-axis. The upper cylinder represents the raw acquisition data, and the origin-centered cylinder represents the calibrated data.

Load cell calibration: Two plots are shown in Fig. 81.4. The one on the left shows the value read from the load pin through the analog-digital converter. The plot on the right shows the force on the load cell (data supplied by the force sensor). A direct scale relationship is observed between the machine's force data and the value provided by the load pin.

The linearization value was obtained to perform the scale conversion. The procedure is explained above and the resulting linearization equation is showed below (Eq. 81.1). The plot of the data obtained with the load cell and the plot of the function obtained with linearization are shown in the Fig. 81.5.

$$\begin{aligned} L &= 0.114 * A - 1.3e + 04 \\ \text{RMSE} &= 1.321e - 12, \end{aligned} \tag{81.1}$$

where L stands for load, A refers to the ADC value of the load cell and the Root Mean Square Error (RMSE) is used to determine the error of the estimation.

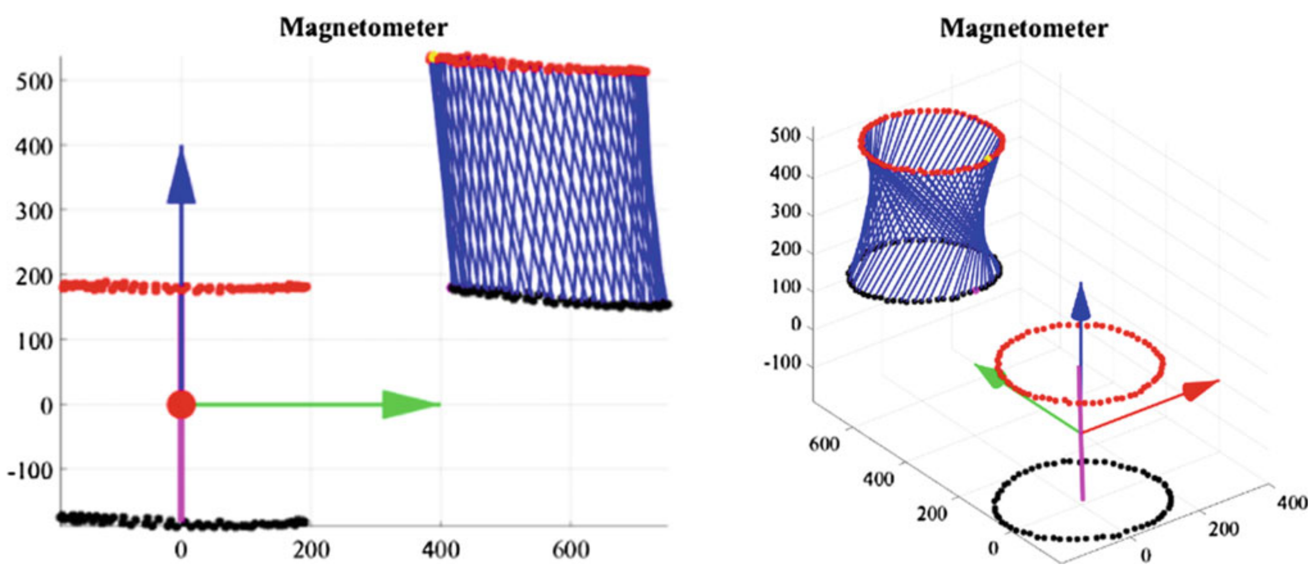


Fig. 81.3 Slewing angle error tests

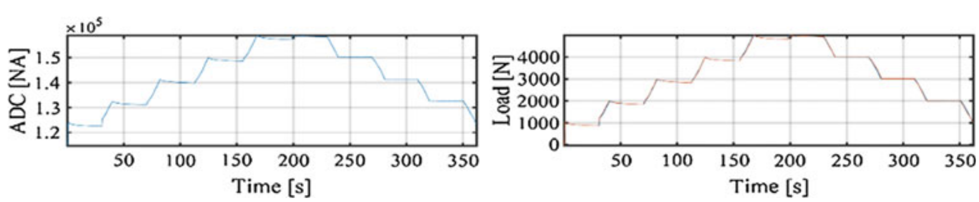


Fig. 81.4 Load cell calibration

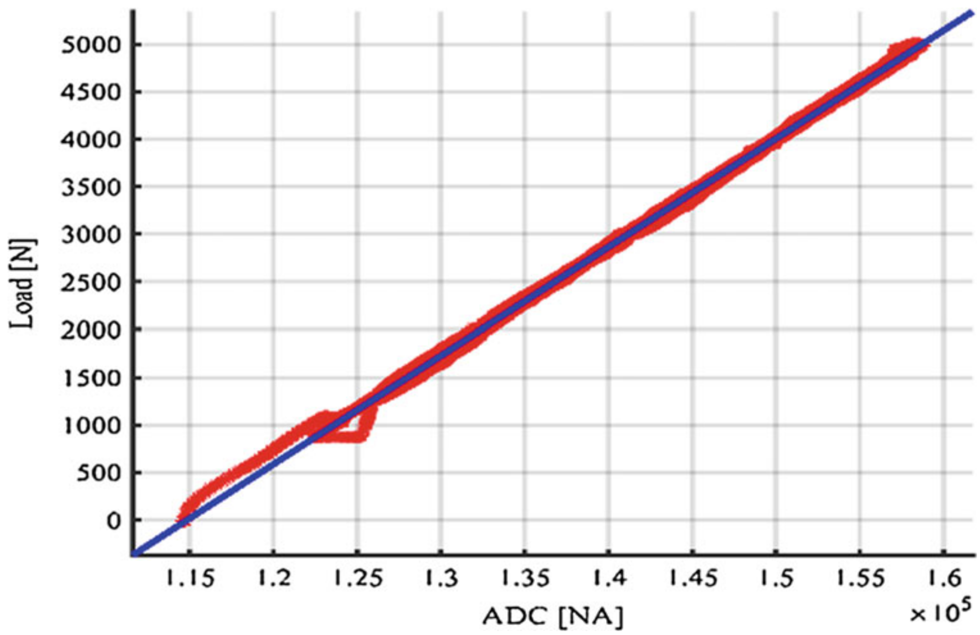
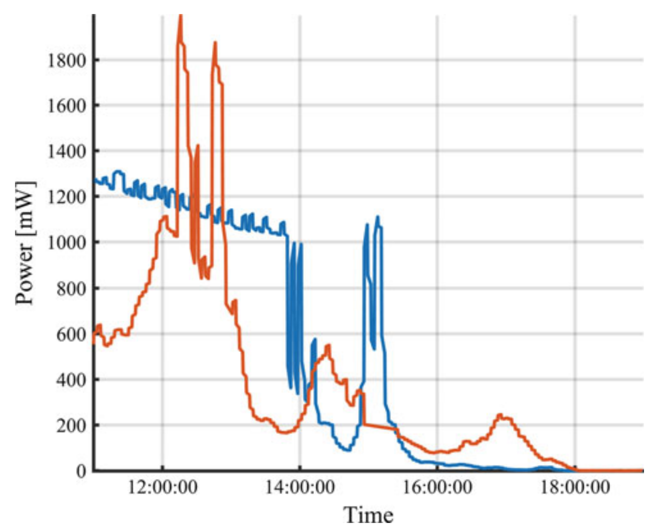


Fig. 81.5 Load cell linearization

Fig. 81.6 Power absorption profile



81.3.1.2 Field Tests

The Validation of the load linearization value on field showed an error of 1.29%.

Load cell power supply: The power profile generated by the solar cell over two consecutive days under actual conditions is shown in Fig. 81.6. The blue line is the profile of the first day, and the red one, the profile of the second day. This test shows that power is a random variable given the number of factors that affect it; however, a dimensioning was made in order to maintain the system functioning up to 5 days under adverse weather conditions.

The behavior of the solar panel during two days under real weather conditions is shown in Fig. 81.7. The blue line is the profile of the first day, and the red line is the profile of the second day. The difference between the state of charge of the battery for one-day to the next is approximately 20%.

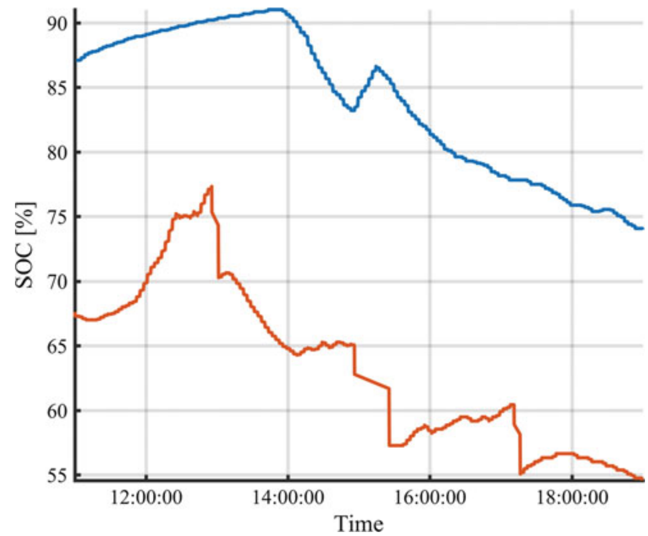


Fig. 81.7 State of chare of the battery for two different days

81.3.2 Comparison with Other Systems

After testing the system, several advantages were identified. The developed system can be implemented at one tenth of the cost compared to commercial systems. This is because the designed system was assembled in Colombia, developed with a local research group, and designed efficiently. Also, the developed system provides more flexibility than other systems, because it can be easily and quickly installed in tower cranes, regardless of their brand and specifications. Also, installation time is reduced about four times, compared to other commercial systems. This is because we use a pre-assembled system, which simplifies welding work, while the other systems need to be totally integrated to the tower crane. Finally, the commercial monitoring system allows the real-time visualization of data. These data must then be processed, which implies a considerable amount of time and work to translate the data into productivity indicators (Table 81.2) as opposed to the system developed in this project, which allows to obtain these indicators in real time directly from the platform that is an integral part of it. Table 81.3 shows a

Table 81.2 Productivity indicators delivered by the system

Indicators	Units
Cycle time	Minutes
Hook position	Meters
Hitch time	Minutes
Average cycle time (daily)	Minutes
Load capacity efficiency	Percentage
Disengage time	Minutes
Percentage of use	Percentage
Average daily load	Kilograms

Table 81.3 Comparison of the indicators measured and visualized by the developed system and by commercial systems

Indicator	Developed system	Other systems
Time cycle	Yes	No
Hook position	Yes	Yes
Hitch time	Yes	No
Average time cycle (daily)	Yes	No
Load capacity efficiency	Yes	Yes
Disengage time	Yes	No
Percentage of use	Yes	No
Average daily load	Yes	No

comparison between the indicators that are measured and displayed directly on the developed platform and the databases delivered by other commercial systems. The indicators are selected based on the productivity methodology implemented in the projects, in which our engineers rely to make decisions.

81.4 Conclusions

The visualization platform which displays real time productivity indicators, allows decision making regarding the actual use of the tower crane and its operation plans for future projects. The information delivered by the developed system is integrated into corporate methodologies which aim to improve productivity of projects. In addition, fewer man-hours are required in the productivity evaluation, thanks to the automation of the measurement and the overall processes.

This work presents a valuable tool for monitoring tower crane's work cycles, which allows improving productivity in construction processes, since this asset sets the rhythm of the project's structure construction phase. The developed system is easy to scale in a large number of tower cranes because it is 10 times cheaper compared to commercial systems. In addition, it is flexible, since it can be customized to the needs of the company and it allows to save time dedicated to information processing. Also, it can be adapted to different tower crane brands, weathers and types of projects. Furthermore, it does not depend on the specifications and type of crane assembly.

The LoRa network used in this project exceeds the initial operating parameters required for the system. The acceptance parameter for the network communication distance was defined with at least 5 km and the accomplished communication was 12 km in line of sight.

Additionally, it was possible to have an adequate data uploading rate (20 data package every 2 s) considering the usage levels of the crane and the need to detect all its movements. This fact makes the LoRa network a suitable cost and performance option for this application. Finally, given the obtained results with the implementation of the system, a second phase of the project is being evaluated. In this new phase the measurement of other relevant variables for monitoring the use of the tower crane, as well as the integration of the information obtained by the system with BIM (Building Information Modeling) is being considered.

References

1. World Economic Forum and Boston Consulting Group: Shaping the future of construction a breakthrough in mindset and technology. Ind. Agenda, no. May, pp. 1–64 (2016)
2. Cox, J.F., Schleier, J. G., JR.: Theory of Constraints Handbook (2010)
3. Lee, U.K., Kang, K.I., Kim, G.H., Cho, H.H.: Improving tower crane productivity using wireless technology. Comput. Civ. Infrastruct. Eng. **21**(8), 594–604 (2006)
4. Hwang, S.: Ultra-wide band technology experiments for real-time prevention of tower crane collisions. Autom. Constr. **22**, 545–553 (2012)
5. Lee, G., et al.: BIM- and sensor-based tower crane navigation system for blind lifts. Autom. Constr. **26**, 1–10 (2012)
6. Wang, M. Zhang, G., Yan, Q., Shen, B., Yuan, L., Liu, L.: Development of a Novel Black Box for Tower Crane Based on an ARM-based Embedded System *. Proc. IEEE Int. Conf. Autom. Logist., pp. 82–87 (2007)
7. Deng, H.L., Xiao, Y. G.: Development of general embedded intelligent monitoring system for tower crane. Appl. Mech. Mater., 394–398 (2012). https://doi.org/10.4028/www.scientific.net/AMM.103.394
8. Zheng, X.J., Zeng, J.B., Zhang, H.: Research of intelligent monitoring system of tower crane based on RFID. Adv. Mater. Res. **706–708**, 990–994 (2013)
9. Zheng, X., Zhang, H., Xie, Z.: Design of wireless monitoring system based on CAN bus and ZigBee technology of tower crane. Lect. Notes Electr. Eng., **1**, 103–110 (2011)
10. Zhong, D., Lv, H., Han, J., Wei, Q.: A practical application combining wireless sensor networks and internet of things: safety management system for tower crane groups. Sensors (Switzerland) **14**(8), 13794–13814 (2014)
11. Bai, L., Sun, Y., Guo, X.: Applied research on tower crane safety supervising system based on internet of things. Adv. Intell. Soft Comput., pp. 549–556 (2012)
12. Augustin, A., Yi, J., Clausen, T., Townsley, W.: A study of LoRa: long range &amp. Low Power Networks Internet Things, **16**(12), 1466 (2016)
13. Botero-Valencia, J., Marquez-Viloria, D., Castano-Londono, L., Morantes-Guzmán, L.: A low-cost platform based on a robotic arm for parameters estimation of inertial measurement Units. Measurement **110**, 252–257 (2017)

82 The Interface Layer of a BIM-IoT Prototype for Energy Consumption Monitoring

Fernanda Almeida Machado, Cassio Gião Dezotti, and Regina Coeli Ruschel

Abstract

This paper aims at describing the interface layer of a BIM-IoT prototype. The prototype addresses the gap of BIM Model Use (BMU) for energy monitoring by the integration of BIM Models with building systems' energy consumption information in real-time. Such integration requires a BIM/Internet of Things (IoT) Interfacing due to the connection between real and virtual environments as well as context awareness demands. Also, the need for a user-centered feedback strategy concerns about the information delivery and display to enhance predictive maintenance activities and facilities managers' decision-making over Energy Management. The BIM-IoT prototype followed the Design, Development and Evaluation (DDE) steps of the Design Science Research. A pilot implementation at an institutional building restricted to a research laboratory enabled a proof of concept and an analytical assessment of the prototype's capacities. The existing BIM Record Model demanded changes comprising geometric and non-geometric modeling issues (e.g., assets registers) to receive sensor-based dynamic and actual information, and assure its 2D/3D views and semantic context. We observe that the BIM-IoT prototype is a feasible system to support operational strategies based on facilities managers-centered feedback. It contributes to the predictive maintenance and facilitates the comprehension of building systems status and performance. The prototype acts as an accessible and interactive option for energy consumption monitoring.

Keywords

BIM/IoT interfacing • Energy management • Operation and Maintenance

82.1 Introduction

Energy use is expected to have a sharp increase until the middle of 2050 in the Brazilian commercial and public building sectors. The adoption of energy efficiency measures that concerns about building use patterns issues may mitigate that increase [1]. This scenario represents an incentive for owners that build for their own use to regard facilities' Operation and Maintenance (O&M) long-term costs [2].

Efforts concerning building use patterns are consistent to achieve improvements in saving energy [3]. Initiatives in that sense comprise building automation, devices upgrade and behavior changing [4]. Energy Management (EM) becomes relevant as well since energy is not a fixed cost [5]. Recognized in the literature as one of the recurrent types of Facility Management (FM) [6], EM requires the process of analyzing the efficiency of building energy consumption and identifying

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if its cost is competitive. Such circumstances lead to ISO 50001 and building energy performance monitoring, which should produce measurable results involving energy efficiency, use, and consumption [7]. Monitoring the built environment improves problem-solving by allowing real-time data collection, visualization, and analysis [8]. Conventional Building Management Systems (BMS) that own EM modules are capable of measuring actual energy consumption periodically. Though they are regularly programmed and depend on outsourced service to update geometric and non-geometric information of a building (e.g., new floor or asset) [9]. BMS display of collected data is usually in tables, charts or texts, on 2D floor plans and isolated from a 3D environment [10–12]. Furthermore, the majority of those systems lacks interconnectivity between their graphical representations, which brings to the segregation of objects from the building context without the appropriate level of detail [9].

Through the rising adoption of Building Information Modeling (BIM) in Architecture, Engineering, Construction and Operation (AECO) industry and its potential link to BMS, owners can benefit from context awareness provided by BIM models [13]. BIM models are 3D and visually accurate digital building representations that embrace semantic and enriched data [14], allowing a wide range of uses in construction domain [15]. A BIM Model Use (BMU) for energy monitoring is less developed than in other applications. Still, there is an acknowledged potential of integrating BIM models with sensor-based information, which may support real-time energy monitoring and building automation [9]. So potential must consider that in the built environment there is a significant amount of data associated with the functioning and behavior of its objects [10, 11, 16]. Such a scenario of monitoring and control should fit into the Internet of Things (IoT) paradigm, which comprises a set of technologies for embedding intelligence in real-world environments. IoT can be defined as a global network infrastructure to interconnect physical and virtual objects aiming at exploiting collected data and its communication capabilities [17].

This paper aims at describing the interface layer of a BIM-IoT prototype. The prototype addresses the gap of BMU for energy monitoring by the integration of a BIM Model with a building system's actual energy consumption information in real-time. Furthermore, there is a focus on a feedback strategy planned for enhancing predictive maintenance practice and facilities managers' decision-making over Energy Management.

82.2 Related Work

According to [2], BIM Models provide a natural interface with sensors and remote FM operations, which highlight their capacity to support Monitoring and Control practices. Such statement reinforces the integration of BIM and Internet of Things that should consist of using a BIM Model as an interface benefited from data provided through a network of equipment, sensors and mobile devices [15, 18]. The outcomes of BIM/IoT Interfacing for Energy Management may improve the consumption monitoring and control through building automation as well as promote the association of BIM objects with actual data for analysis and prediction. Other outputs may comprise the user's feedback employment to reduce consumption, the historical usage reports enhancement for each building environment/zone/occupant, and the ability to relate costs and activities aiming at energy savings [9].

Past studies regarding BIM/IoT Interfacing and focused on Energy Management in O&M phase approached Energy Efficiency Awareness and Indoor Environmental Quality (IEQ) issues. Such studies attended demands from owners, facility managers, occupants, building technicians, and designers [19]. They comprised BMUs such as performance monitoring and real-time utilization to display sensor-based information collected by sensing technologies (e.g., Wireless Sensor Network—WSN), both in web-based platforms [20, 21] and BIM native environments (i.e., BIM tools as Autodesk Revit, Archicad, Solibri Model Viewer) with add-ins [22, 23]. Those applications emphasized BIM Models as persistent virtual resources for building information context, semantic relations, and 3D visualization. Furthermore, it is noticeable the potential outcomes related to assets maintenance support, since integration of BIM and IoT may provide information for preventive actions, increasing stakeholder's knowledge over the real environment [19]. In another perspective, studies such [24, 25] also exploited BIM Models to provide predictive simulation data of energy consumption for comparative purposes with actual data to improve existing operational strategies in retrofit scenarios.

82.3 Methodology

This paper is part of a research that adopted the Design Science approach, which is a prescriptive method focused on solving real-world problems [26]. It aims at describing the interface layer of a BIM-IoT prototype, emphasizing its development and partial evaluation process. The prototype's goal is integrating BIM Models and actual energy consumption data in real-time to contribute to addressing a BMU for Energy Management and Energy Efficiency Awareness issues. Based on [27] and described in the next section, the prototype's architecture embraces four layers: the sensing, network, service and interface layers.

Initially, we defined the facility managers as target users and created a feedback strategy to deliver and exhibit information with the aim of stimulating predictive maintenance and energy consumption monitoring. Then, regarding the scenario of owners that build for their own use, we considered the BIM-IoT prototype's instantiation in a building of the University of Campinas (UNICAMP). Due to the lack of a BMS at the UNICAMP campus, we developed an IoT-side solution for one research laboratory of the building. The IoT-side solution considered the laboratory's lighting system to perform a proof of concept, since [28] states that in commercial and institutional buildings the lighting and HVAC systems, as well as office equipment's are the principal sources of energy consumption. In turn, the BIM-side regarded the BIM Record Model as the primary communication channel between actual information collected from sensing technologies and facilities managers. Both sides required the following steps of the prototype's Design, Development, and Evaluation (DDE):

1. To adapt the BIM Record Model to be the primary agent of actual information delivery and display, concerning both energy monitoring and feedback strategy to attend facilities managers as target-users;
2. To input actual information collected by the IoT-side in the BIM Record Model hosted in a native environment, through a Visual Programming Language (VPL) application;
3. To implement the BIM-IoT prototype in the research laboratory to a pilot instantiation; and
4. To evaluate the BIM-IoT prototype through an analytical technique.

The evaluation step focused on verifying the prototype's performance based on real scenarios, concerning its capacity for monitoring lighting system's energy consumption as well as the interface layer role. In that sense, we considered the benefits, potentialities, and limitations of the BIM/IoT Interfacing through the created solution.

82.4 Prototype System

The proposed architecture (Fig. 82.1) consists of four distinct layers that went through two cycles of DDE. The Sensing Layer includes a WSN that is responsible for collecting, aggregating and monitoring the energy consumption data of the research laboratory's lighting system. The WSN design and development followed the OpenEnergyMonitor guidelines [29], with adaptations to attend implementation needs. The Network Layer consists of an IEEE 802.11 (Wi-Fi) communication protocol required for receiving and transmitting collected data to a Web Server (Apache HTTP Web Server). Such data is processed and stored in an associated Database Server (MySQL) hosted in the Service Layer. The Service Layer allows centralized database queries and data treatment and analysis for generating valuable information on energy consumption monitoring. In addition to MySQL, the Service Layer holds Dynamo BIM tool for extracting the latest information from MySQL Database and populate the BIM Record Model in real-time. Dynamo has the central role of enabling the BIM/IoT Interfacing and transforms the static BIM Record Model in a dynamic environment. That dynamic environment represents the connection of actual and virtual information provided by the prototype. Since Dynamo is a VPL tool that allows easy access to Revit API, we defined Autodesk Revit 2017 in the Interface Layer as the BIM tool for managing the acquired BIM Record Model. Hence, the Interface Layer contains the front-end tools for hosting both BIM Record Model and monitoring charts, the last ones available on a website. The BIM Record Model is the primary agent to display sensor based-information, comprising its delivery and display in BIM objects, schedules, and 2D/3D views. Moreover, the settings over information views regard graphical color overrides for condition monitoring purposes about lighting system's performance. Besides, the creation of an external link allowed the extension of BIM objects to the web-based monitoring charts created from the Database Server.

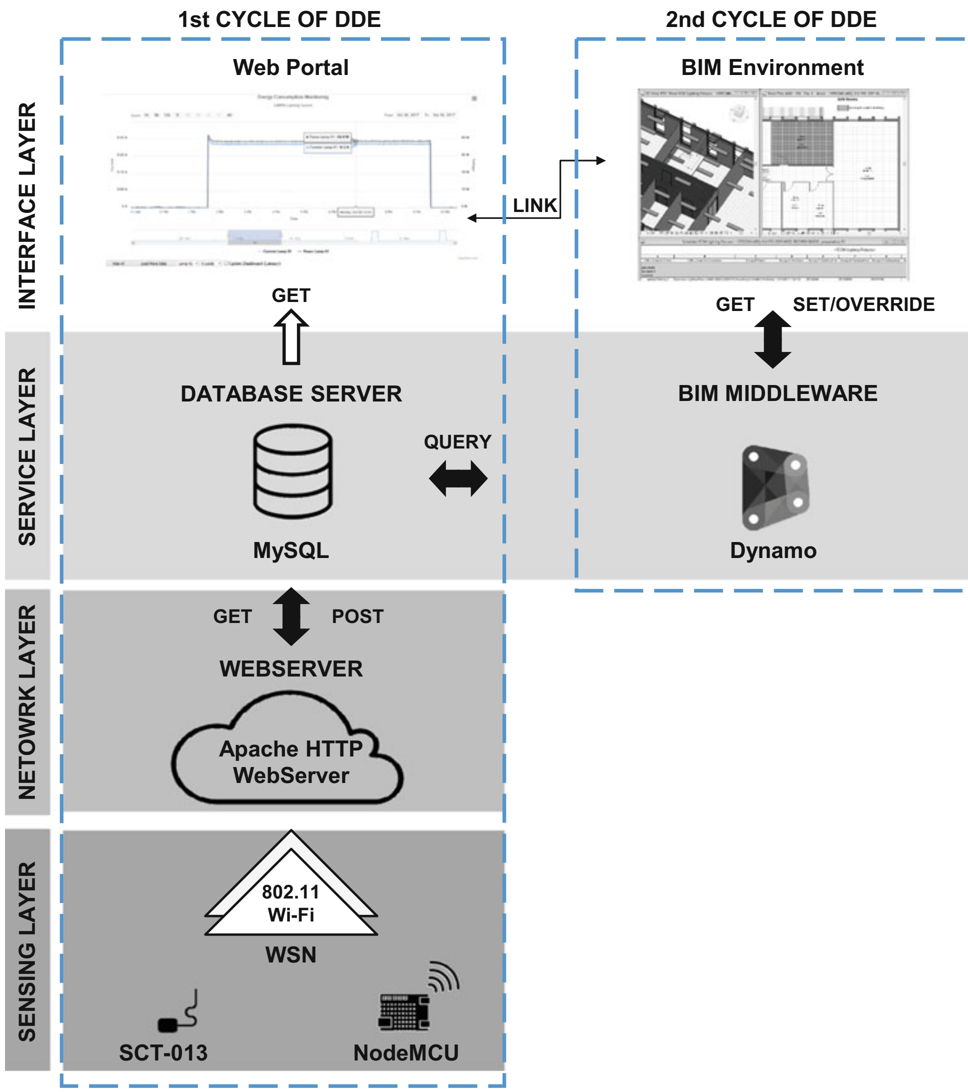

Fig. 82.1 Prototype's system framework

82.4.1 BIM Record Model and Feedback Strategy

We employed the BIM-IoT prototype in an integrated workflow, similarly to existing studies [22, 23], but with different architecture concept and definitions. The use of the BIM Record Model ensured the sensor-based information linked to building context and graphical views. The set of sensor-based information considered the user-centered feedback strategy over facilities manager's roles and responsibilities. As stated by [25] in literature and reinforced through an interview with the FM Department of UNICAMP, FM users act for monitoring and analyzing specific building performance data such as energy consumption about a particular department, zone, user, building system or time interval. The lack of BMS in the existing building of this study reflected on their activities that only involve corrective maintenance by service order and preventive maintenance. Through the implementation of a BIM-IoT solution that sup-ports building performance monitoring, the FM users may incorporate predictive maintenance in their daily practices. Therefore, the user-centered feedback strategy comprised: (i) real-time update frequency for the information delivery; (ii) desegregated (lighting fixtures, circuits or room) and historical information exhibition; (iii) reports based on condition monitoring established for lighting system; and (iv) display of multiple information units display (Watts, R$, kgCO2e/kWh) for extensive user's comprehension and knowledge.

The acquired BIM Record Model consisted of an administrative building containing research laboratories and faculty offices. The model included the accurate representation of architectural and structural systems (i.e., spaces, physical conditions, surrounding). In turn, the MEP systems were missing except for the location of the lighting fixtures. We defined one research laboratory to adjust the following BIM objects for receiving dynamic information from the database server: lighting fixtures, circuits, and rooms. Regarding the BIM Model's adequacy to the feedback strategy and 3D visualization goals, it was necessary to review the highlighted BIM objects and their attributes. The review started with the cable ducts and switches modeling, followed by lighting fixtures positioning check. Due to Autodesk Revit 2017 limitations, we generated rooms for 3D visualization with a Dynamo script. Then, we created shared properties among those BIM objects to receive dynamic information and COBie properties for assets registers to assure semantic contextualization. In addition to BIM Objects, the interface required the creation of dedicated 3D views and schedules for lighting systems' monitoring and control.

82.4.2 Actual Information Input in the BIM Record Model

Updating BIM Record Model for dynamic purposes enabled functional tests with the Dynamo script. Its programming logic initially comprised the selection and filtering of target BIM objects related to their real objects under performance monitoring. Next step involved the establishment of communication between the Dynamo environment and MySQL Database Server, through an Open Database Connectivity (ODBC) standard provided by the Slingshot! Package. It allowed the extraction of sensor-based information from MySQL, its organization in sublists inside Dynamo and its aggregation to meet condition-monitoring requirements, which were configured to generate assets reports. The final steps included the insertion of the actual information into the dynamic properties created on each filtered BIM object as well as the color override in 2D/3D views according to each asset report. Concerning condition-monitoring requirements, they admitted the operational values of each lighting fixtures, according to its specifications. For example, the lighting fixtures are according to condition monitoring considering values between 49 Watts and 64 Watts. Instead, values above or below that range indicate the demand for verifying the asset in place and possible failures in the lighting system.

It is relevant to emphasize that the actual information is a result of transformations over the collection of current data in Amperes by non-invasive current sensors. Such current data becomes active power (Watts) through the application of math formulas. The registered power data is stored in conjunction with its timestamp, which allows the application of functions in MySQL, concerning averages in a determined period or the working hours of each lighting fixture/circuit/room under monitoring. Besides, monthly averages can be applied to valuable correlations with costs and carbon emissions, enriching the feedback for facility managers.

82.4.3 Implementing the BIM-IoT Prototype to Pilot Instantiation

The research laboratory's lighting system consists of two parallel circuits (Circuit A and Circuit B) with three lighting fixtures in each one. The prototype's design to monitor the energy consumption of both circuits and lighting fixtures considered the use of a single NodeMCU microcontroller board and six non-invasive current sensors of SCT-013 family. The addition of an AC-AC adaptor assured the measurement of the actual electric voltage in real-time. A printed circuit board interconnected those electronic components (Fig. 82.2). Such implementation is also represented in the BIM Record Model (Fig. 82.3).

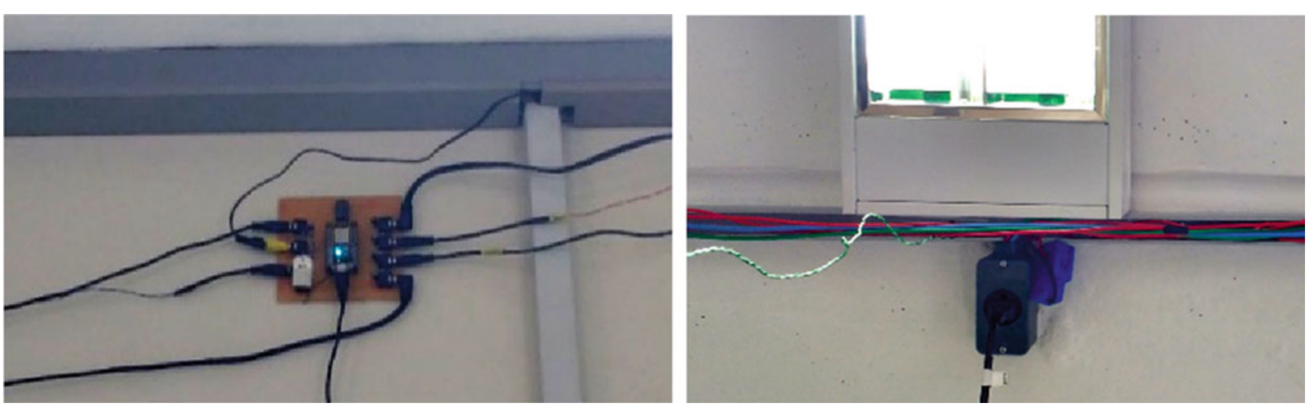

Fig. 82.2 Prototype implemented for lighting system' energy consumption monitoring

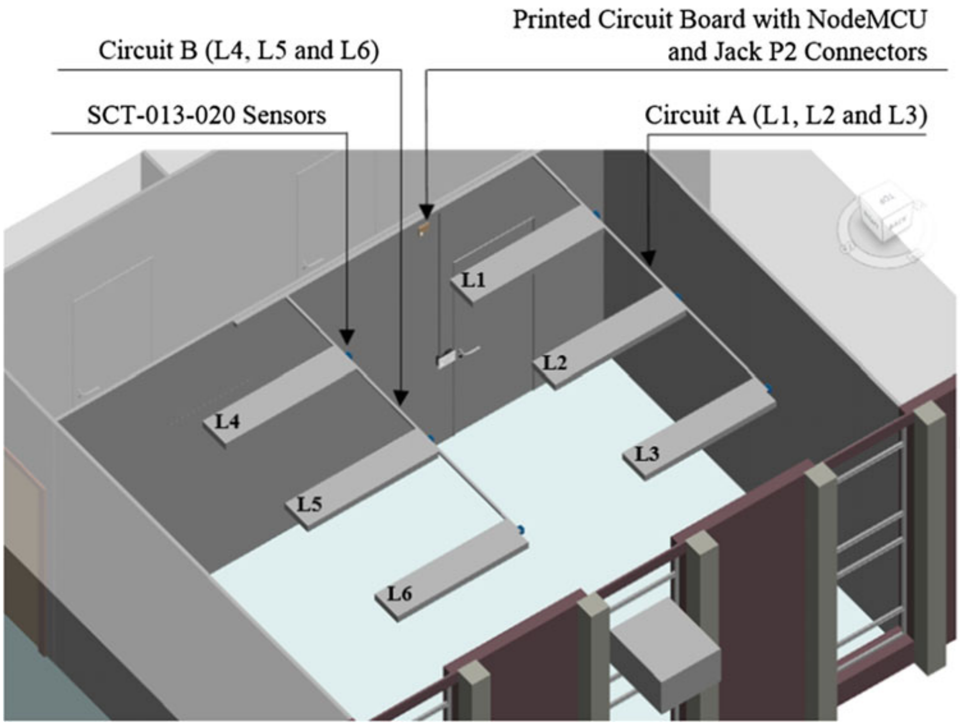

Fig. 82.3 Implementation context

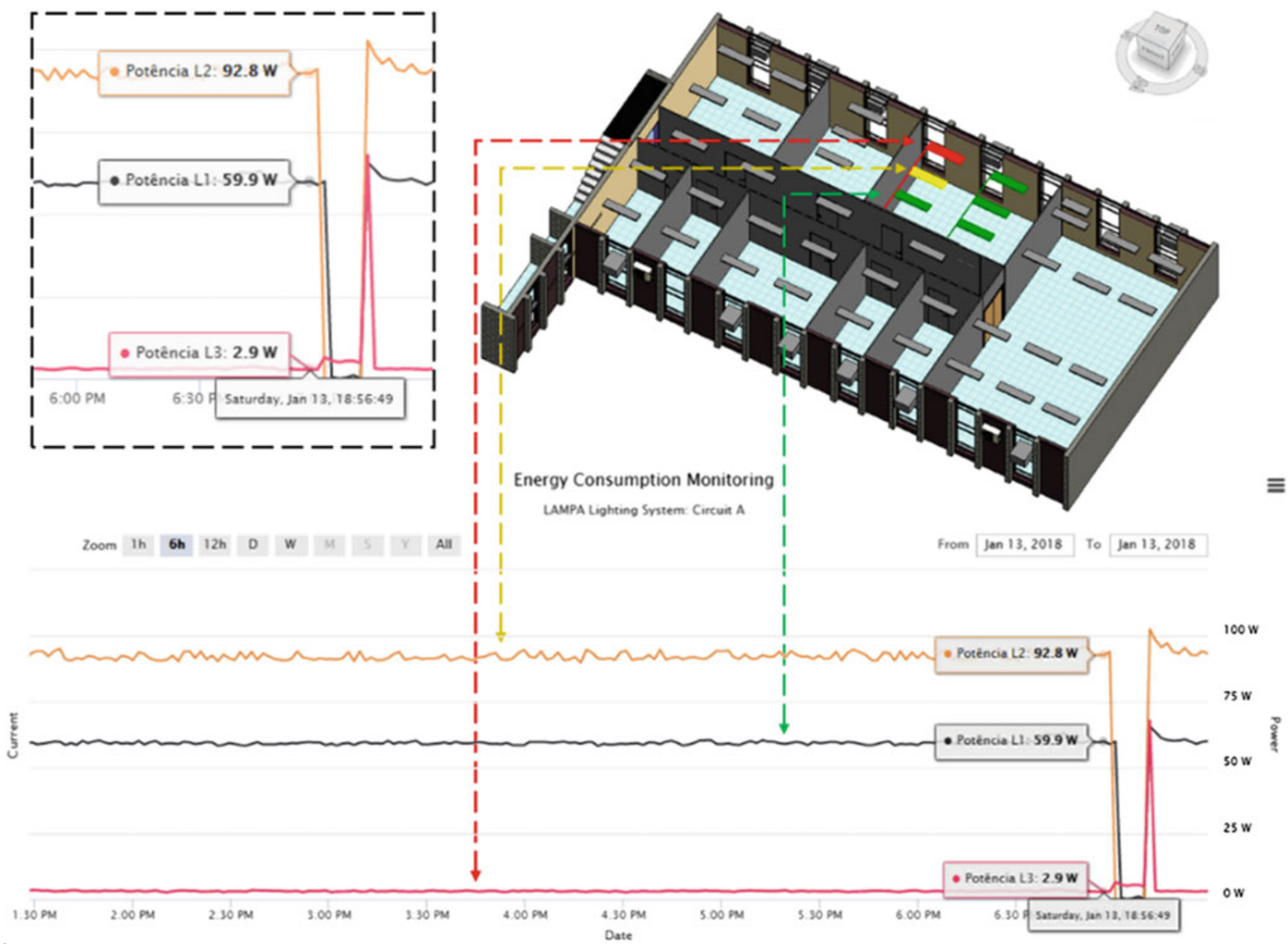

Fig. 82.4 Interface demonstration of running prototype

82.4.4 Evaluating the BIM-IoT Prototype

The BIM-IoT prototype system ran for three months for achieving monitoring results, and refining database query, Dynamo scripts, and the BIM Record Model itself. We considered populating the BIM objects (lighting fixtures, circuits, and room) with real-time power information in Watts; Watts/h per hour; Watts/h per day, month and year. Besides, for room data population we also included Cost and CO2e/kWh properties, considering economic and environmental impacts measurement. Such information met the user-centered feedback strategy considering FM users' roles and responsibilities. Through Dynamo script, it was configured reports based on operational values, favoring predicted maintenance for building performance improvement. We presented these reports in BIM objects properties, schedules and through the 3D color overrides: red and yellow colors for "Check-in Place" and green color for "According to Condition Monitoring". Finally, we created a link between BIM objects and the external web-based charts generated from the database server. As demonstrated in Figs. 82.4 and 82.5, during the period of pilot instantiation it was possible to verify issues over condition monitoring in the research laboratory.

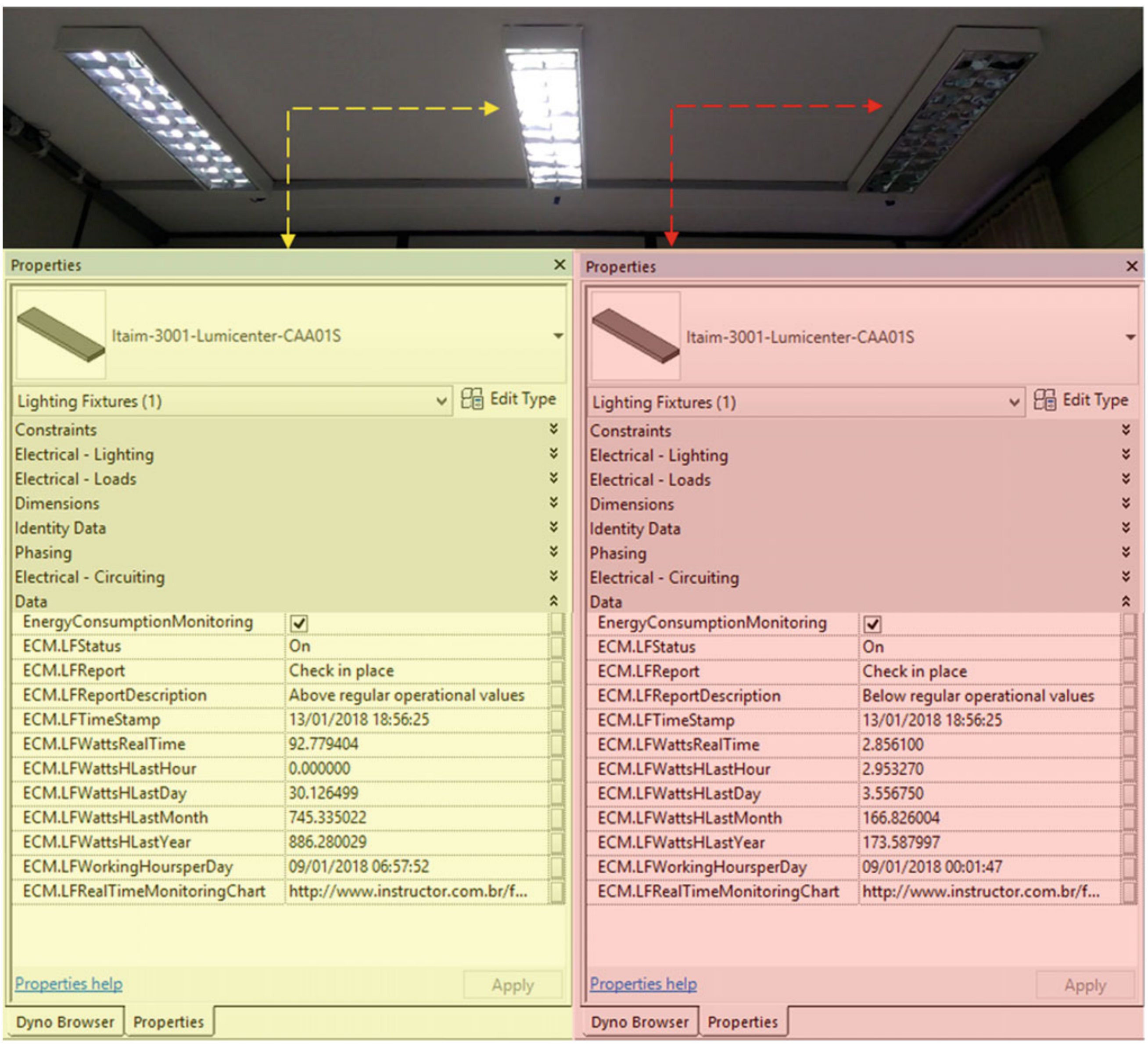

Fig. 82.5 BIM objects in record model with dynamic information: (left) LF 2 and (right) LF 3

The circuit A presented a “Check in Place” report: (i) in lighting fixture 2, power consumption was above regular operational values, which means the requirement of reviewing lighting systems’ installation; and (ii) in lighting fixture 3, it was below regular operational values, which indicates performance failures and replacement demands. Monitored values could be confirmed in external charts with the benefit of historical registers, and in BIM objects properties or schedules. The evaluated scenario indicates that BIM-IoT integration plays a relevant role for increasing facilities managers’ awareness on energy consumption since it acts as an accessible and interactive option for monitoring and visualizing activities.

82.5 Conclusion

This article described the interface layer of a BIM-IoT prototype, developed to promote the integration between BIM Models and building systems’ energy consumption information in real-time. We highlighted by a real scenario the system’s potential for monitoring the environment and stimulating building performance improvements through operational strategies of Energy Management. Prior BIM-IoT applications that employed BIM Models directly for building context and 3D views required the expertise of developing solutions in web-based or Microsoft’s.NET Framework programming languages, the last ones used to create add-ins for BIM tools. Alternatively, considering the BIM Model management in a native environment, we developed VPL scripts to support the integration of BIM and IoT. In building design phase, [30] has already presented experiments with VPL, BIM Models and sensors as well. VPL demonstrated to be an accessible mode of enabling BIM/IoT Interfacing, transforming BIM Models from static to dynamic with the ability to self-update actual information. At first, that scenario emphasizes the demand for programming skills (visual or textual) when considering the development of applications that aim at BIM/IoT Interfacing. Also, that self-update ability indicates a machine-to-machine (M2M) communication trend involving BIM Models. Besides, supporting such dynamic condition, BIM Models potential extension to external databases allows the persistent connection between the real and virtual worlds.

Few before-mentioned studies presented user-centered interfaces. User’s feedback on Energy Management should be appropriately structured according to building users’ roles and responsibilities. We considered a feedback strategy for facilities managers comprising real-time update frequency, desegregated 2D/3D views, instructive reports as well as assets and performance registers. That strategy enriched the use of BIM Models for Energy Monitoring. Thus, BIM-IoT prototype presented itself as a feasible solution to support such strategies and provide feedback to target-users, since it acts as an accessible and interactive option in monitoring activities and supporting predictive maintenance. Regarding the limitations of this study, it is relevant to highlight the potential of BIM/BMS Link and how its lack influenced in the DDE of the BIM-IoT prototype. Also, the presented solution required BIM skills from FM team to manage the dynamic model, an unusual scenario that indicates the need for contributions regarding BIM Models in, or associated with, BMS environments.

References

1. MME – Ministério de Minas e Energia; EPE - Empresa de Pesquisa Energética. Demanda de Energia 2050: Nota Técnica DEA 13/15. Série Estudos da Demanda de Energia, pp. 1–244 (2016b)
2. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: Manual de BIM: um guia de modelagem da informação da construção para arquitetos, engenheiros, gerentes, construtores e incorporadores. Bookman, Porto Alegre (2014)
3. Pisello, A.L., Asdrubali, F.: Human-based energy retrofits in residential buildings: a cost-effective alternative to traditional physical strategies. Appl. Energy **133**, 224–235 (2014)
4. Gulbinas, R., et al.: Network ecoinformatics: development of a social eco-feedback system to drive energy efficiency in residential buildings. J. Comput. Civil Eng. **28**(1), 89–98 (2014)
5. Ferreira, I.: Energy management. In: Teicholz, E. (ed.). Facility Design and Management Handbook 2004, pp. 23.1–23.17. The McGraw-Hill Companies: Digital Engineering Library (2004)
6. Mota, P.P.: Modelo BIM para gestão de ativos. Master Thesis—University of Campinas, Campinas (2017)
7. Associação Brasileira de Normas Técnicas (ABNT).: NBR ISO 50001: Sistemas de gestão da energia – Requisitos com orientações para uso. 1, ABNT, Rio de Janeiro (2011)
8. Lee, Y., Choi, J., Lertlakkhanakul, J.: Dynamic architectural visualization based on user-centered semantic interoperability. J. Asian Archit. Build. Eng. **10**(1), 117–124 (2011)
9. Becerik-Gerber, B., et al.: Application areas and data requirements for bim-enabled facilities management. J. Constr. Eng. Manag. **138**(3), 431–442 (2012)
10. Attar, R. et al.: 210 King Street: a dataset for integrated performance assessment. In: 10 Proceedings of Spring Simulation Multiconference. Society for Computer Simulation International, San Diego, CA (2010)
11. Attar, R et al.: Sensor-enabled Cubicles for Occupant-centric Capture of Building Performance Data. ASHRAE Transactions 117(2) (2011)

12. Hailemariam, E. et al.: Toward a unified representation system of performance-related data. In: 6 Proceedings of IBPSA Canada Conference. IBPSA, Manitoba (2010)
13. Sabol, L.: BIM Technology for FM. In: Teicholz, P. (ed.) BIM for Facility Managers, 1st edn, pp. 17–45. Wiley, New York (2013)
14. NBIMS. National BIM Standard Purpose. US National Institute of Building Sciences Facilities Information Council, BIM Committee (2006). Homepage, http://www.nibs.org/BIM/NBIMS_Purpose.pdf. Accessed 01 June 2016
15. Succar, B., Saleeb, N., Sher, W.: Model uses: foundations for modular requirements clarification language. In: Australasian Universities Building Education, AUBEA 2016, Cairns, Australia (2016)
16. Khan, A., Hornbæk, K.: Big data from the built environment. In: Proceedings of UBICOMP. ACM, Beijing (2011)
17. Casagras, E.F.P.: Casagras Final Report: RFID and the Inclusive Model for the Internet of Things, pp. 1–88 (2009)
18. BIM DICTIONARY, https://bimdictionary.com/en/bimiot-interfacing/1/. Accessed 25 Feb 2018
19. Machado, F.A., Ruschel, R.C.: A integração de BIM e IoT com ênfase em energia na fase de operação e manutenção da edificação. In: 1º Simpósio Brasileiro de Tecnologia da Informação e Comunicação na Construção e 10º Simpósio Brasileiro de Gestão e Economia da Construção, SBTIC + SIBRAGEC 2017, Fortaleza, Brasil (2017)
20. Lee, D., Cha, G., Park, S.: A study on data visualization of embedded sensors for building energy monitoring using BIM. Int. J. Precis. Eng. Manuf. **17**(6), 807–814 (2016)
21. Nakama, Y., Onishi, Y., Ik, K..: Development of building information management system with data collecting functions based on IoT technology. In: 33rd eCAADe Conference Proceedings, Vienna, Austria (2015)
22. Marzouk, M., Abdelaty, A.: A BIM-based framework for managing performance of subway stations. Autom. Constr. **41**, 70–77 (2014)
23. Marzouk, M., Abdelaty, A.: Monitoring thermal comfort in subways using building information modeling. Energy Build. **84**, 252–257 (2014)
24. Habibi, S.: Smart innovation systems for indoor environmental quality (IEQ). J. Build. Eng. **8**, 1–13 (2016)
25. Gokçe, H.U., Gokçe, K.U.: Integrated system platform for energy efficient building operations. J. Comput. Civil Eng. **28**(6), 05014005 (2014)
26. Dresch, A., Lacerda, D.P., Antunes Jr., J.A.V.: Design Science Research: método de pesquisa para avanço da ciência e tecnologia. Ed. Bookman, Porto Alegre (2015)
27. Li, S., Da Xu, L., Zhao, S.: The internet of things: a survey. Inf. Syst. Front. **17**(2), 243–259 (2015)
28. CBCS et al.: Aspectos da Construção Sustentável no brasil e Promoção de Políticas Públicas: Subsídios para a Promoção da Construção Sustentável (2014)
29. OPENENERGY MONITOR, http://www.springer.com/lncs. Accessed 01 Apr 2017
30. Kensek, K.M.: Visual programming for building information modeling: energy and shading analysis case studies. College Publishing **10**(4), 28–43 (2015)

Predicting Energy Consumption of Office Buildings: A Hybrid Machine Learning-Based Approach

83

Kadir Amasyali and Nora El-Gohary

Abstract

Improving building energy efficiency requires an understanding of the affecting factors and an assessment of different design and operation alternatives. In this context, accurate prediction of building energy consumption gained a lot of research attention. In recent years, a significant number of building energy consumption prediction models, with various intended uses, have been proposed. However, existing data-driven models are mostly based on outdoor weather conditions, but do not take occupant behavior into account. Towards addressing this research gap, this paper presents a hybrid machine-learning and data-mining approach to develop prediction models that learn from both real data and simulation-generated data. Real data were collected from an office building, including data about building energy consumption, outdoor weather conditions, and occupant behavior. Simulation-generated data were created through simulating an office building in EnergyPlus. A feature selection algorithm was used to determine the critical features in predicting energy consumption for office buildings. A set of regression models were then trained for predicting the hourly values of an outdoor weather-related factor and an occupant behavior-related factor based on these features. Then, an ensembler model—which takes the outputs of the outdoor weather-related factor and occupant behavior-related factor models—was trained to predict cooling energy consumption. In training the models, several machine learning algorithms—such as Gaussian Process Regression (GPR), Support Vector Regression (SVR), Artificial Neural Networks (ANN), and Linear Regression (LR)—were tested. The predicted energy consumption levels showed agreement with the actual levels. This indicates that the proposed regression models can help support decision making related to office buildings.

Keywords

Building energy efficiency • Energy consumption prediction • Machine learning

83.1 Introduction

Energy consumption is on the increase. Numerous research programs and initiatives for reducing energy consumption and improving energy efficiency have been proposed to cope with the climate change and resource depletion issues caused by the increase in energy consumption and associated CO_2 emissions. Building energy consumption represents a significant portion of the primary energy consumption [1]. In recent years, the concern about the rapid increase in energy consumption of buildings due to improved living standards and economic development has triggered building energy efficiency-related researches. Energy efficiency in existing buildings can be achieved in several ways, such as building retrofitting, appliance and equipment upgrade, and improving occupant behavior. Occupant behavior is the actions and decisions taken by building occupants that affect building energy consumption [2]. In this regard, improving occupant behavior comes forward as one of the best ways for reducing building energy consumption, because it aims to improve the efficiency of energy use without sacrifice in people's demands.

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Previous studies [e.g., 3–7] investigated the impact of energy use behavior through empirical and theoretical methods and showed that behavior has a significant impact on building energy consumption. The prediction of building energy consumption that takes occupant behavior into account is thus fundamental for discovering more efficient building operation and occupant behavior-related strategies. However, existing data-driven building energy prediction efforts did not sufficiently take occupant behavior into account, and therefore cannot be utilized for improving occupant behavior.

There are two main approaches in developing data-driven prediction models: learning from simulation-generated data (e.g., using building energy simulations such as EnergyPlus and eQuest to generate data to train models) and learning from real data (using meters, sensors, and building management system data to train models). However, each approach has its own limitations and strengths. On one hand, simulation-generated data, in many cases, are limited in representing the complexity and stochastic nature of occupant behavior but can significantly reduce the data sensing efforts to collect energy consumption-related data. On the other hand, developing data-driven models that learn from real data requires a significant amount of training data to develop an accurate model, but can better capture the occupant behavior and therefore can better incorporate the impact of occupant behavior on building energy consumption.

Towards addressing the limitations of each approach, the authors are proposing an occupant behavior-sensitive energy consumption prediction model. To leverage the strengths of the both approaches in developing data-driven prediction models, a hybrid model learns from both simulation-generated data and real data was developed. The hybrid model consists of three base models: (1) a machine learning model that learns the impact of outdoor weather conditions from simulation-generated data, (2) a machine learning model that learns the impact of occupant behavior from real data, and (3) an ensembler model that predicts cooling energy consumption based on the outputs of both models.

83.2 Background

A body of research efforts has been already undertaken towards developing data-driven building energy consumption prediction models. On one hand, some research efforts utilized simulation generated data to train the models. For example, Li and Huang [8] developed short-term load prediction models using the data generated by TRNSYS simulations. On the other hand, some other research efforts utilized real data. For example, Wang et al. [9] developed hourly electricity consumption prediction models using the data collected from two educational buildings. Despite the importance of all these efforts, two primary knowledge gaps are identified. First, there is a lack of studies on data-driven and occupant behavior-sensitive building energy consumption prediction. The majority of existing efforts in the area of data-driven building energy consumption prediction either did not take occupant behavior into account at all or they did some limited efforts (e.g., taking schedules into account). Occupant behavior, as a result, still remains as one of the greatest uncertainties in building energy consumption prediction [10]. An accurate prediction model that can incorporate the impact of occupant behavior can be utilized for both discovering more efficient building operation and occupant behavior-related strategies. Second, the existing efforts either utilized simulation-generated data or real data to train the prediction models. Given that both approaches have their own advantages and disadvantages, a hybrid model that is trained using both simulation-generated data and real data can leverage the advantages of both approaches.

83.3 Methodology

A hybrid machine learning model, which learns both form simulation-generated data and real data, was developed. The hybrid model consists of three base models: (1) a machine learning model that predicts the hourly values of the weather-related factor, (2) a machine learning model that predicts the hourly values occupant behavior-related factor, and (3) an ensembler model that predicts cooling energy consumption based on the predicted values for both factors. The weather-related factor represents the impact of the outdoor weather conditions on cooling energy consumption, at a specific hour. The occupant behavior-related factor represents the impact of the occupant behavior on cooling energy consumption, at a specific hour. The simulation-generated data was utilized to train the weather-related factor prediction model, because a simulation environment allows for generating data in which the consumption is impacted by outdoor weather conditions only. On the other hand, the real data was utilized to train the occupant behavior-related factor prediction model, because the stochastic and complex nature of occupant behavior can be better captured in a real-world setting. Finally, an ensembler model that takes the weather-related and occupant behavior-related factors as features was developed to predict cooling energy consumption, and was evaluated in terms of prediction accuracy.

83.3.1 Weather-Related Factor Prediction Model Development

The development of the weather-related factor prediction model included three primary steps: energy simulations, data preprocessing and feature selection, and factor prediction model development.

EnergySimulations. A simple, one-story square office building with five thermal zones was modelled to generate the data needed for training the weather-related factor prediction model. The building model was simulated using EnergyPlus [11], a widely-used whole building energy simulation program. To understand the impact of outdoor weather conditions on building energy consumption, all the other energy consumption-related parameters (e.g., occupant behavior, operation schedule) were kept constant throughout the simulation period—the outdoor weather conditions were the only variables. The simulations were conducted from June 1 to August 31 using the typical meteorological year 3 (TMY3) weather data of Philadelphia, PA. In order to have an undisturbed consumption pattern throughout the simulation period, the holiday schedules in EnergyPlus were removed. For this pilot study, Philadelphia was chosen to match the location of the building where the real data were collected (see Sect. 83.3.2).

Data Preprocessing and Feature Selection. Four data preprocessing and feature selection steps were conducted: data cleaning and aggregation, feature selection, data normalization, and data splitting. First, the weekend and non-working hours on weekdays, where the building is unoccupied and cooling energy consumption is zero, were removed from the dataset. Also, the outdoor weather condition variables (e.g., solar radiation) that are not available for real data were removed from the simulation-generated data as well. Second, using the remaining variables, feature selection was carried out, using a Neighborhood Component Analysis (NCA), to remove the redundant and non-discriminating features from the dataset. As a result, the final, remaining features were: temperature, dewpoint temperature, wind speed, wind direction, and atmospheric pressure. Third, the features were normalized using their means and standard deviations to avoid overflowing of an individual feature. Then, in order to obtain a factor representing only the impact of weather conditions on building energy consumption, the hourly cooling energy consumption levels generated by the EnergyPlus simulations were normalized from 0 to 1, where 0 represents the minimum weather condition impact and 1 represents the maximum weather condition impact on cooling energy consumption. Fourth, the real data were split into training (90%) and validation (10%) datasets.

Factor Prediction Model Development. A weather-related factor prediction model was developed using the training dataset. In developing the model, the following four algorithms were tested: gaussian process regression (GPR), support vector regression (SVR), artificial neural networks (ANN), and linear regression (LR). The parameters of all these algorithms were tuned through parameter grid search using the validation dataset to maximize the prediction performance.

83.3.2 Occupant Behavior-Related Factor Prediction Model Development

The development of the occupant behavior-related factor prediction model included four primary steps: building instrumentation, data collection, data preprocessing, and factor prediction model development.

BuildingInstrumentation. The real data were collected from the Philadelphia Business and Technology Center (PBTC) building between October 5, 2015 and March 31, 2018. The PBTC is a 6-story masonry office building with an estimated total floor area of 272,000 ft^2. The west wing of the 4th floor was already instrumented for empirical data collection as part of an earlier research project by the Consortium for Building Energy Innovation (CBEI) [12]. The instrumented area is 10,000 ft^2, which consists of 12 offices and two thermal zones. The instrumented area is occupied on weekdays from 8 am to 5 pm, mostly. The building uses electricity for cooling.

Data Collection. Cooling energy consumption was metered in 15-min intervals using the power meters installed on the air handling units (AHUs) and monitored using the PI CoreSight web-based application. There are two AHUs. Each thermal zone has an AHU for cooling. Outdoor weather condition data were gathered from a weather station at the Philadelphia International Airport in hour intervals [13]. Occupant behavior data were captured through a preference monitoring application (PMA) [14]. The PMA was developed using an online survey tool to capture the actions taken by the occupants. The actions included turning on/off a portable heater, opening/closing a door, opening/closing a shading device, and turning on/off a light. The occupants were asked to provide feedback whenever they have taken an action.

Data Preprocessing. Five data preprocessing steps were conducted: data cleaning, data aggregation, data integration, data transformation, and data splitting. First, the data instances that have missing and/or outlier values were removed from the dataset. Non-summer months were also removed from the dataset. Second, the hourly cooling energy consumptions of the instrumented area were calculated by summing the hourly energy consumptions of the AHUs; and the 15-min cooling energy consumption data intervals were aggregated into hourly consumption levels. Third, data from multiple sources—including energy consumption data, outdoor weather conditions data, and occupant behavior data—were integrated using their date and time. Fourth, a principal component analysis was conducted to estimate the weather-normalized cooling energy consumption. The weather normalization aimed to remove the impact of weather conditions on energy consumption, and therefore all the energy consumption levels were transformed into the estimated energy consumption at the outdoor temperature level in the center of the first principal component (PC1). For the transformed cooling energy consumption levels, the outdoor weather conditions are expected to have minimum impact on cooling energy consumption due to the weather normalization. Since weather conditions have minimum impact on the transformed energy consumption data, the variance in the transformed energy consumption data can mostly be explained by other energy consumption-related parameters (e.g., occupant behavior). Finally, the real data were split into training (70%), validation (10%), and testing (20%) datasets.

Factor Prediction Model Development. An occupant behavior-related factor prediction model was developed using the training dataset. In developing the model, the same aforementioned four algorithms (see Sect. 83.3.1) were tested, and their parameters were tuned through parameter grid search.

83.3.3 Ensembler Model Development

An ensembler model was developed to predict cooling energy consumption. The weather-related factor and occupant behavior-related factor predictions were preprocessed and an ensembler model—which takes these predictions as features—was developed. Prior to the machine learningprocess, both types of features were normalized. In developing the ensembler model, the same algorithms (see Sect. 83.3.1) were tested, and their parameters were tuned through parameter grid search.

83.3.4 Performance Evaluation

The performances of the two factor prediction models were evaluated using the validation datasets. The hybrid model was evaluated using the testing dataset. The prediction performance was evaluated using coefficient of variation (CV). According to the ASHRAE Guideline 14, an hourly prediction model is considered as calibrated if hourly CV values fall below 30%. CV was calculated using Eq. (83.1).

$$\text{CV}\ (\%) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_{predict,i} - y_{data,i})^2}{n}}}{\bar{y}_{data}} \times 100 \qquad (83.1)$$

where $y_{predict,i}$ is the predicted target at hour i, $y_{data,i}$ is the actual target at hour i, n is the number of hours in the validation/testing dataset, and $\bar{y}_{data}$ is the average target data.

83.4 Preliminary Results and Discussion

83.4.1 Weather-Related Factor Prediction

The simulation of the building model generated 2208 h of cooling energy consumption data. Table 83.1 presents the summary of the simulation-generated data, after feature selection but prior to data normalization and splitting. The fine-tuned GPR, SVR, ANN, and LR models achieved 18.78, 20.19, 20.42, and 31.01% CV, respectively, in predicting the values of the weather-related factor. Although the GPR model was the most accurate model, and was therefore selected, there was no clear outperformer across the GPR, SVR, and ANN. The predicted weather-related factor was used as one of the features of the ensembler model.

83.4.2 Occupant Behavior-Related Factor Prediction

As shown in Fig. 83.1, the data is scattered along PC1; there is more variation on PC1 than PC2. This can be explained by the very dominating impact of temperature on cooling energy consumption. As expected, the cooling energy consumption increased as the temperature increased. As illustrated in Fig. 83.1, all the data were transformed to the dashed vertical line which crosses the temperature in the center of PC1. The transformed data represent the occupant behavior-related factor. The upper levels of the vertical line indicate the higher occupant behavior-related factors, and vice versa. The fine-tuned GPR, SVR,

Table 83.1 Summary of the simulation generated data

Feature	Min	Mean	Median	Max
Temperature (F)	53.96	74.84	75.02	98.06
Dewpoint temperature (F)	42.08	63.31	64.94	78.08
Wind speed (mph)	27.00	70.14	72.00	100.00
Wind direction (deg)	0.00	206.72	220.00	360.00
Atmospheric pressure (mb)	0.00	8.35	8.05	21.92

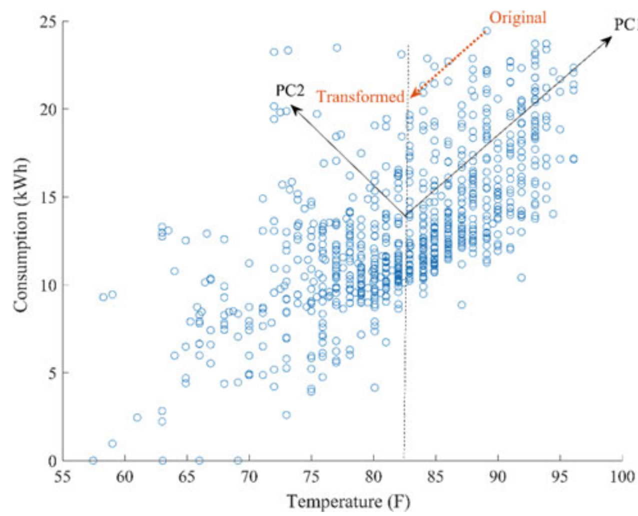


Fig. 83.1 Illustration of principal components and weather normalization

ANN, and LR models achieved 18.55, 18.19, 18.24, and 34.58% CV, respectively, in predicting the values of the occupant behavior-related factor. Similar to the weather-related factor prediction, there was no clear outperformer across GPR, SVR, and ANN. The predicted occupant behavior-related factor was used as one of the features of the ensembler model.

83.4.3 Ensembler Model Prediction

As shown in Fig. 83.2, the predicted cooling energy consumption (predicted by the proposed hybrid model) showed good fitness with the actual consumption (collected from the office building). The fine-tuned GPR, SVR, ANN, and LR models achieved 18.89, 18.78, 19.01, and 19.55% CV, which is considered calibrated according to ASHRAE Guideline 14.

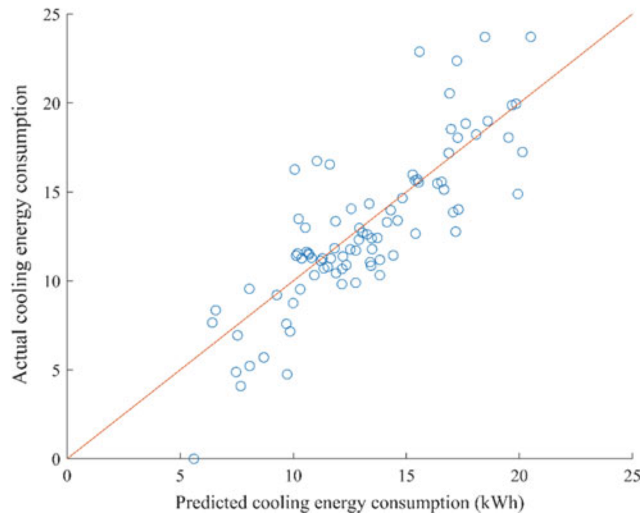
For comparative purposes, a typical prediction model, which does not take occupant behavior into account and learns only from real data, was also developed (using the same dataset). The model achieved 30.21% CV, which is significantly lower than the performance of the proposed hybrid model. These results, thus, indicate that the proposed hybrid model is promising and can be utilized for better understanding and improvement of occupant behavior. The proposed model can be used to discover more efficient building operation and occupant behavior-related strategies under a set of given weather conditions.

83.5 Conclusion

In this paper, the authors proposed a hybrid model, which learns both from simulation-generated data and real data, for predicting cooling energy consumption of an office building. The hybrid model consists of three base models: (1) a machine learning model that learns the impact of outdoor weather conditions from simulation-generated data, (2) a machine learning model that learns the impact of occupant behavior from real data, and (3) an ensembler model that predicts cooling energy consumption based on weather-related and occupant behavior-related factors predicted by the first two models. The model was validated using a testing dataset collected from an office building in PA. The prediction results showed that the proposed model has the potential to be successfully used for better understanding and improvement of occupant behavior.

In future work, the authors will model and simulate a set of new buildings with different geometries and different building properties and retrain the weather-related factor prediction model to learn from this extended set of data. Also, the occupant

Fig. 83.2 Prediction results of the hybrid model



behavior-related factor prediction model will further be improved through including additional types of occupant behaviors. Currently the authors are conducting a set of empirical energy studies in residential and office buildings to collect such real data, which include energy consumption, indoor environmental conditions, outdoor weather conditions, and occupant behavior data.

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References

1. Zhao, Z., Amasyali, K., Chamoun, R., El-Gohary, N.: Occupants' Perceptions about Indoor Environment Comfort and Energy Related Values in Commercial and Residential Buildings. Procedia Environ. Sci. **34**, 631–640 (2016). https://doi.org/10.1016/J.PROENV.2016.04.055
2. Klein, L., Kwak, J., Kavulya, G., Jazizadeh, F., Becerik-Gerber, B., Varakantham, P., Tambe, M.: Coordinating occupant behavior for building energy and comfort management using multi-agent systems. Autom. Constr. **22**, 525–536 (2012). https://doi.org/10.1016/j.autcon.2011.11.012
3. Clevenger, C.M., Haymaker, J.R., Jalili, M.: Demonstrating the impact of the occupant on building performance. J. Comput. Civ. Eng. **28**, 99–102 (2014). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000323
4. Azar, E., Menassa, C.C.: A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. Energy Build. **55**, 841–853 (2012). https://doi.org/10.1016/j.enbuild.2012.10.002
5. Petersen, J.E., Shunturov, V., Janda, K., Platt, G., Weinberger, K.: Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. Int. J. Sustain. High. Educ. **8**, 16–33 (2007). https://doi.org/10.1108/14676370710717562
6. Delmas, M.A., Fischlein, M., Asensio, O.I.: Information strategies and energy conservation behavior: a meta-analysis of experimental studies from 1975 to 2012. Energy Policy. **61**, 729–739 (2013). https://doi.org/10.1016/j.enpol.2013.05.109
7. Jain, R.K., Taylor, J.E., Culligan, P.J.: Investigating the impact eco-feedback information representation has on building occupant energy consumption behavior and savings. Energy Build. **64**, 408–414 (2013). https://doi.org/10.1016/j.enbuild.2013.05.011
8. Li, Z., Huang, G.: Re-evaluation of building cooling load prediction models for use in humid subtropical area. Energy Build. **62**, 442–449 (2013). https://doi.org/10.1016/j.enbuild.2013.03.035
9. Wang, Z., Wang, Y., Zeng, R., Srinivasan, R.S., Ahrentzen, S.: Random forest based hourly building energy prediction. Energy Build. (2018). https://doi.org/10.1016/j.enbuild.2018.04.008
10. O'Brien, W., Gunay, H.B.: Mitigating office performance uncertainty of occupant use of window blinds and lighting using robust design. Build. Simul. **8**, 621–636 (2015). https://doi.org/10.1007/s12273-015-0239-2
11. Yousefi, F., Gholipour, Y., Yan, W.: A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data. Energy Build. **148**, 182–198 (2017). https://doi.org/10.1016/j.enbuild.2017.04.085
12. CBEI: Consortium for Building Energy Innovation, http://cbei.psu.edu/. Accessed 26 Apr 2018
13. Pennsylvania State Climatologist: Pennsylvania State Climatologist, http://climate.psu.edu/. Accessed 26 Apr 2018
14. Abraham, Y., Zhao, Z., Anumba, C., Asadi, S.: Implementation of a preference monitoring application for office building occupants. In: Lean and Computing in Construction Congress—Volume 1: Proceedings of the Joint Conference on Computing in Construction, pp. 793–801. Heriot-Watt University, Heraklion (2017)

Part VI

Computing and Innovations for Design Sustainable Buildings and Infrastructure

Thermal Performance Assessment of Curtain Walls of Fully Operational Buildings Using Infrared Thermography and Unmanned Aerial Vehicles

84

Ivan Mutis and Albert Ficapal Romero

Abstract

Architecture's race skyward has brought with it a variety of functional innovations, one such being glass curtain wall systems. During such building's operating life, failures of insulation systems create areas of reduced resistance to heat transfer, or thermal bridges. These failures enable energy flows that trigger unanticipated temperature changes and increased energy consumption and ultimately, damage the façade structure and cause problems to occupants. Discussion includes design and test method for rapidly identifying thermal bridges in façade systems, with minimum or no-disturbance of occupants. Research focus is set in determining if the damages are just local failures or if they are related to a poor systematic construction assembly. A non-traditional approach is adopted to survey an entire fully operational building using infrared thermography and an Unmanned Aerial Vehicle (UAV). The system is comprised of a non-contact infrared camera mounted on and operated from the UAV. It enables the registration of the emissivity of the façade materials and calculation of the thermal radiation and equivalent factors to estimate localized temperatures. The registration process yields thermal imaging results of the actual state whose temperature will be analyzed quantitatively using graphs and compared with the ASHRAE standards, retrieving the perfect state using THERM software. After evaluation of the results a statistical analysis will be performed, to inform the Architecture, Engineering, and Construction (AEC) community about the areas of most common failures for existing structures. It is expected that the results will also identify improvements for construction methods by projecting better and more efficient processes.

Keywords

Curtain wall system • Building thermal performance • Thermal bridge • Infrared thermography
Unmanned Aerial Vehicle (UAV)

84.1 Introduction

The curtain wall system is an enclosure technique for buildings. It is comprised of several crystal panels assembled to bear its own weight and resist exterior loads such as wind or rain [24]. Most commonly, curtain wall panels are aluminum, span one floor, and support the main structure [18]. Thermal bridges are discontinuities in the curtain wall's thermal barrier, which is the building enclosure that provides an interior insulated environment for HVAC systems, control of vapor transfer, and thermal efficiency. Thermal negative effect is increased in the presence of a highly conductive material, like metal-exterior curtain walls [23]. The metal-exterior curtain wall is formed by vertical and horizontal exterior structures, crystal panels, and sealant finishing. Thermal bridges are most usually located on the interphase between the glass and metal panels or between different crystal panels where the sealant is placed [20]. A highly conductive material (e.g., aluminum) needs sealant as

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thermal breaks made from a non-conductive material (e.g., plastic or rubber) to prevent heat transfer and to provide resistance to condensation.

Several components of the curtain walls could perform poorly producing a thermal bridge. A common cause of problems is the failure of the gaskets and sealings [22]. Gaskets are strips of synthetic rubber or plastic, which also damper the glass when the structure suffers movement. Sealant is a flexible element but the glass is fragile and stiff so a small displacement is allowed by the structure. With age, gaskets dry out, shrink, and the elasticity degrades. Air spaces are created which admit air and moisture inside, leading to condensation, drafts, and leaks. This infiltration of condensation may point to failure, compromising thermal performance and visibility. As the gaskets further disintegrate, they may detach and pull away from the frame. Without the support, the glass loses stability and may shatter or blow out. As an extreme example, if the sealing requirements specified by the architect are not followed in the construction phase, the thermal isolation systemically fails, which means that apart from water leakage, there is air leakage, comprising even more the building envelope. The corrective action includes repairing all the seals at the curtain wall [15].

84.2 Related Work

There are several types of frame and fastening for curtain wall glazing systems [13]. Composed of steel, aluminum, multi-laminate glass, or other resilient materials, the frame is the support grid that holds the glass in place and must be studied separately to determine the possible causes of failure [5, 11, 17, 19].

Mechanically fixed system. A mechanical fastening for the insulating glass is provided. The exterior mechanical restraint is thermally isolated from the interior frame. It may pose some issues, because when aging it is assumed to allow additional exterior air infiltration due to gasket shrinkage, especially if they are assembled onsite because the quality depends highly of the skills of the personnel. There are multiple arrangements described below:

Stick system. It is a structure of extruded horizontal and vertical metallic frame members (sticks) whose mullions are long elements generally made of aluminum or cold rolled steel with coating paint. The materials are cut in the factory and assembled onsite. Elastic gaskets are used under pressure plates. This method results in poor-quality control, given that it is built onsite, and depends heavily on the equipment and personnel involved in its construction.

Unitized. It is the most used type of curtain wall for high-quality finishing. Consisting of a bunch of preassembled glazing panels that are manufactured in controlled factory conditions, the metallic frame is directly attached to the different glass layers. The whole façade is sealed by means of elastic gaskets. It is more expensive than the stick system, but faster and easier to install, with fewer onsite operations. This process is more cost effective and provides a better performance and quality control.

Panelized. It is similar to the unitized system and consists of prefabricated panels. However, the panels are larger and generally have a store span height and a bay span width. This method seeks to avoid mid-span supports to avoid the problems of deflection.

Spandrel panel ribbon glazing. Long continuous glazed panels are fixed between spandrel panels connected to the building's floor slab. They are made of prefabricated metallic, composite panels, or precast concrete units. The glazed panels may be assembled onsite with horizontal transoms fixed to spandrel panels. Vertical mullions may be arranged for an easier construction method. The glazed parts may be of preassembled units that will be fixed on bottom and top to the spandrel panels and on the sides to one another. The level of prefabrication and repetitive assembly lets the performance be quite high and a demanding quality control.

Structural sealant glazing. Using silicone in sealings for a structure made essentially of crystal panels, it is possible to cover almost the total external façade with glazing panels. They can be preassembled, installed on the building's structure, and fastened together like the unitized system or a system of panels with a border frame bolted or fastened to an onsite assembled structure of mullions and transoms like the stick system.

Structural glazing. This system provides the most luminous space given that the glass area is practically the entire façade, being support systems minimized. It is achieved by means of assembling the panels with special brackets. Generally, the panels are fixed to the substructure at the corners with brackets providing support for four panels. The gaps between the panels are weather sealed onsite using wet-applied sealant. There are two types of assemblies: bolted and patched (suspended). However, the differences between the two are the fixtures of the panels to the attachment brackets.

To evaluate the existence of thermal bridges for all these structural systems, nondestructive analysis, in the form of infrared radiation measurement, is proposed. Infrared thermography (IRT) is a science dedicated to the acquisition and processing of thermal information from non-contact measurement devices [14]. The infrared radiation is an electromagnetic radiation with longer wavelengths than those of visible light [16]. Because the human eye is only capable of observing a quite tight range of radiation, the visible spectrum [3], the use of special cameras is required to measure such radiation. This radiation is mainly a function of their temperature and all objects that are not at absolute zero emit infrared radiation [21]. An x-ray test could be carried out. Though the test is usually effective, it costs more to conduct the test than the wall is worth. On the other hand, infrared thermography provides the solution for accurate, inexpensive, non-destructive, non-labor, and intensive results. It can cover a wide range, depending on the lens, and small areas can be tested by using the cameras which are fairly portable. Buildings are typically large constructions. Therefore a smarter way to perform thermal imaging inspections is the use of remotely operated Unmanned Aerial Vehicles (UAVs) equipped with IR cameras. Inspections can be easily carried out on roofs or tall constructions without an operator [12]. IR with UAV inspections of building can be used to detect heat losses, missing or damaged thermal insulation, and especially thermal bridges, air leakage, and moisture intrusions [2]. Advantages to these types of inspections are that repairs specific to the necessary areas will reduce costs while simultaneously saving on the heating and cooling costs that are cut when such defects are repaired.

84.3 Methodology

The framework of evaluation of a curtain wall is divided into different sections as described in the Fig. 84.1. It evaluates the elements conforming the frame and the structure to determine the existence of a thermal bridge and ultimately diagnose the structure and solve the possible defects.

84.3.1 Formulation

To evaluate the thermal performance, the thermal flux must be measured [4]. The overall heat transfer coefficient ($U = [W/m^2\,°C]$) represents the ability of an assembled curtain wall to resist heat transfer. It is a property inherent to the material or assembly [20]. Indeed, all the properties of the glazing materials and sealants must be known to calculate the net radiation of the window. Therefore, the materials and their disposition must be specified. Specifically, heat transfer is the movement of energy due to a temperature difference. It is formulated as a function if the heat transfer rate ($Q = [W]$), the area of the window ($A = [m^2]$), and the difference of temperature ($\Delta T = [°C]$) [3]:

$$U = \frac{Q_{net}}{A(T_{out} - T_{in})} \tag{84.1}$$

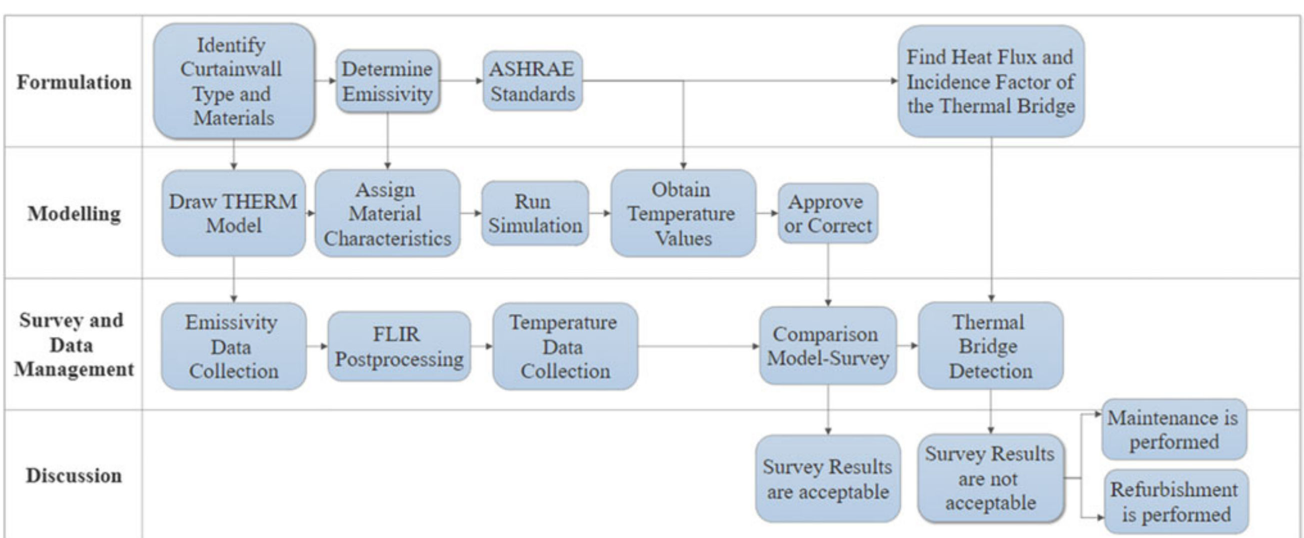

Fig. 84.1 Framework for the detection, diagnosis, and evaluation of thermal bridges

There are three physical mechanisms of heat transfer: conduction, convection, and radiation. To calculate the energy flux for crystal assemblies which have more than one layer, the following expression is used for the infrared energy flux leaving the kth surface as Q_k^r, where the superscript r stands for radiation. Then, it is defined for the nth layer whose boundaries are surfaces 2n and 2n–1 [7]:

$$\begin{aligned} Q_{2n}^r &= S_{2n}^r + R_{2n} Q_{2n+1}^r + T_n Q_{2n-2}^r \\ Q_{2n-1}^r &= S_{2n-1}^r + R_{2n-1} Q_{2n-1}^r + T_n Q_{2n+2}^r \end{aligned} \tag{84.2}$$

Being R_k the infrared reflectance of the layer measured from the kth surface and T_n the transmittance for the nth layer. In addition, transmittance multiplied by the flux gives the transmissivity. The same happens for the reflexivity. The emitted energy flux from the kth surface, S_k is defined:

$$S_k = \varepsilon_k \sigma \theta_n^4 \tag{84.3}$$

where ε_k is the emissivity of the kth surface, θ_n is the temperature of the layer n. The emissivity is the ratio of the radiation emitted compared to that emitted by a black body which absorbs all radiation. Emissivity has a range of values between 0 and 1. The emissivity is the key value for the infrared measurement because it is the value detected by the IR camera. However, there must be a correction to avoid the interference of other radiation like conduction, convection, and solar radiation. At this stage, the intention is to formulate, quantitatively, the possible presence and how to evaluate thermal bridges. The thermograph (thermal image) yields information in every pixel about the radiation emitted by the object of study [1]. Using the methodology proposed, the thermal transmittance can be estimated with a confidence level of 95% given IR tests. It is possible via a reverse analysis of the linear thermal bridge equation [10]:

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j * l_j \tag{84.4}$$

Being $\Psi = [\mathrm{W}/(\mathrm{m}\,^\circ\mathrm{C})]$ the linear thermal transmittance, L_{2D} is the thermal coupling coefficient for a 2D space, U_j is the linear perpendicular thermal transmittance for the element separating the two environments, and $l_j = [\mathrm{m}]$ is the length of the element, which leads to the determination of a parameter that notices the presence of a thermal bridge using only the thermograph itself. It is then defined, the incidence factor of the thermal bridge I_{tb} as the ratio between the actual heat flowing in and the theoretical heat flowing in [1]:

$$I_{tb} = \frac{Q_{tb}}{Q_0} = \frac{h_{tb} A_p \sum_{p=1}^{n} \left(T_{ext} - T_p\right)}{h_i A (T_{ext} - T_{1D})} = \frac{\sum_{p=1}^{n} \left(T_{ext} - T_p\right)}{N(T_{ext} - T_{1D})} = \frac{\mathrm{U_{tb}}}{\mathrm{U_{1D}}} \tag{84.5}$$

where Q_{tb} is the heat flux through a thermal bridge, Q_0 is the theoretical heat flow that there should be through this precise element, h_{tb} is the laminar coefficient of the thermal bridge, h_i is the internal laminar coefficient, the temperatures T_{ext} and T_p respectively represent the external air and the temperature of the thermograph pixel, and T1D is the unaltered temperature. A_p is the area of a pixel and A is N times A_p the total number of pixels. When considering that in the limited domain of the image area, the laminar coefficient is constant $h_{tb} = h_i$, and so it results the equation in Formula (84.5) being U is the thermal transmittance.

To set logical boundaries to the temperatures formulation, ASHRAE standards are followed, specifically the Energy Standard for Buildings manual guides. In ASHRAE/IESNA Standard 90.1-2007 a range is provided according to the purpose of the building and the type of frame.

84.3.2 Modelling

The purpose of modelling is to have a deeper understanding of the different layers' U-factor and obtain the temperatures in the perfect scenario, as well as to have some reference to compare the values obtained in the tests. Under ASHRAE standards, the boundary conditions for temperature and materials are defined as well as the drawing the geometry.

84.3.3 Survey and Data Management

Emissivity is to be measured under the test, however it is not the only existing radiation. The incident solar radiation, transmittance, and air leakage rating could influence the variation of the temperature increasing the effect of the thermal bridge, and not being registered in terms of emissivity [6]. However, the detection of the thermal bridge is just a matter of detecting an anomaly in the emissivity values.

On the other hand, there might be some elements that produce a radiant barrier [8]. Elements like some type of aluminum alloy could produce a low emissivity response in the infrared register. Emissivity stands for the grade up to which a material emits energy as thermal radiation. However, thermal radiation can be present in the form of conduction or convection. Therefore, special attention needs to be paid with such elements. For most non-metallic materials, the value is usually above 0.80. However, for metallic surfaces, especially when polished, the emissivity values drop down between 0.05 and 0.2. Therefore there is the need to adopt corrective measures to determine the exact temperature. For such metals, the values specified in emissivity tables must not strictly be considered because the surface conditions can influence the measurements more than materials themselves [9].

For this test, the practice under ASTM E1933 – 14 is followed under the Contact Thermometer Method conditions to correct the emissivity to perform the tests. Although they may not be applicable for IR measurements under UAV conditions, the adjustments have been followed under these conditions. Therefore, the test is carried out for the IR camera, model Flir Vue Pro R, on the UAV on the adequate location pointing at the targeted element whose emissivity is to be corrected, in this case to correct the emissivity of the surface of polished metals. For that purpose, the function to measure and compensate is used for the high reflected temperature upon the specimen. Therefore, the contact thermometer is used to measure and correct the actual temperature. Focusing the imager on the same spot, adjust its emissivity control until the it indicates the same temperature recorded by the contact thermometer. The indicated emissivity value is the measured emissivity of the specimen at this temperature and spectral waveband. This procedure is repeated a minimum of three times and the emissivity values averaged to obtain an approximate actual emissivity.

On the other hand, there may be other environmental factors that may generate some error or noise in the measurement [2], such as large particles present in the atmosphere, like water vapor or gas molecules. Those interferences will alter the measurement, as well as the ambient air temperature and the distance or angle of incidence from the sample. For that reason, the recommendation is to take measurements as close as possible to be accurate and to let the camera get warm to acclimatize. The sample should be at a temperature that is at least 10 °C warmer or cooler than the ambient temperature so the measurement yields little error on the emissivity results.

Winds may also disturb the results. Therefore, for winds exceeding 5 m/s it is recommended to perform an accurate correction because there may be a difference in temperature of 3 °C or more depending on the humidity or atmospheric conditions [1].

At night, heat energy is dissipated from the external surface. If the façade is being investigated it is possible to observe different behaviors during winter, for example. Then, the external surface will have a lower surface temperature. To avoid the confusion of temperature, increased for the solar radiation, IR measurements should be performed at night or on a cloudy day, with low wind speeds to minimize convective heat losses. Moisture may induce some measurement problems because a wet mass retains the absorbed heat more time than a dry mass. That is how moisture problems are identified.

Going into detail, the emissivity of a specimen is strictly related to a determined combination of temperature and the spectral waveband of the radiometer used to make the measurement. The emissivity is inversely proportional to the reflectivity. For that reason, measurements should be taken from different angles to avoid the reflection from other objects which may interfere in the measurements [21]. When measuring, special attention must be paid when determining the reflected temperature. For materials with emissivity less than 0.5, radiometric temperature measurements and emissivity measurements may have higher errors.

84.3.4 Discussion

Based on the ASHRAE guidelines for interior temperatures, a quantitative analysis will be provided in terms of the materials' quality and desired insulation. Therefore, a desired U-factor is obtained so the actual works aim to emulate that performance and perspective. Throughout time, the assembly should not degrade as much and have a worse performance.

84.4 Case Example

Because the tests are performed from the exterior, only the exterior façade surface is surveyed. For reference, a chart is drawn according to the actual temperatures to detect thermal bridges in specific layers. If the most problematic area is the interphase, a line throughout the exterior surface is plotted following the line between the support, considering the interphase as the origin and ending in the crystal as shown in Fig. 84.2. The intention is to cover from the problematic area until areas where temperatures are not altered by the effect of the thermal bridge, or the undisturbed zone.

THERM results are observed. Focusing on the interphase, there are little hints of an energy flux through the sealant and in the interphase. To quantify these measurements, a graph is plotted that records the variation of temperature along the length of the window so the simulation can be observed and compared with the test results in Fig. 84.3a.

The thermal image is filtered using the Flir software, assuming a straight line from the interphase until the undisturbed zone, to obtain a plot as shown in Fig. 84.3b.

Comparing objectively the results, the shape of the curve is similar which means that the simulation matches the actual performance in terms of general capture. Apparently, both graphs help notice that there is a leak in the interphase which must be quantified obtaining the incidence factor of the hypothetical thermal bridge. In this example, it is $I_{tb} = 0.992$, which is not enough to consider it a thermal bridge. Indeed, it yields some conclusions, as it is a recently assembled façade, the degradation is low and it has been properly assembled to ensure thermal insulation. On the other hand, there is a slight difference in the increment of temperature registered on both plots, for the simulation $\Delta T = 0.5\,°C$, meanwhile it has been measured a temperature with $\Delta T = 0.06\,°C$. The reason is the simulation gets the most accurate results and a perfect estimation of the temperature. Meanwhile, the thermal imaging camera is not that accurate and levels the temperature to an average, possibly by means of the reflected radiation of the exterior or coming from the particles beside. However, this is not a concern because the aim of the project is thermal bridge detection in a macro scale.

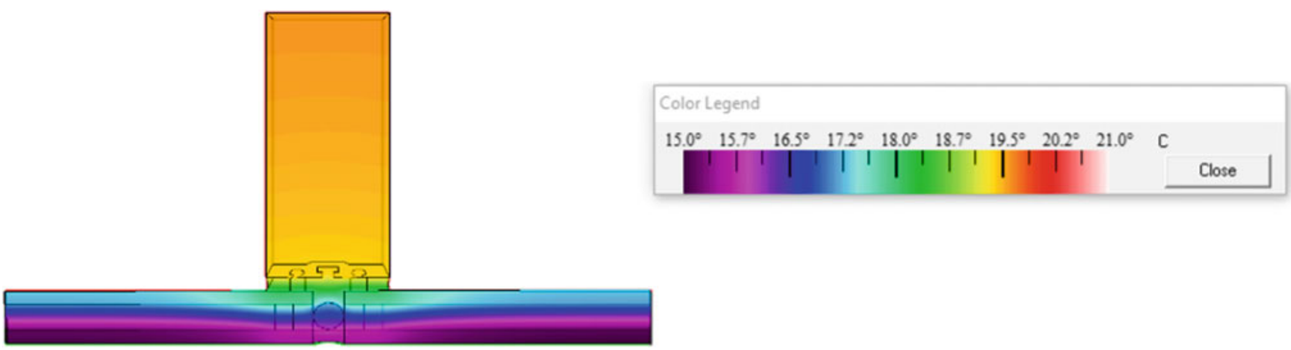

Fig. 84.2 Temperature distribution along the Façade surface of the mullion and the shadow box of the curtain wall

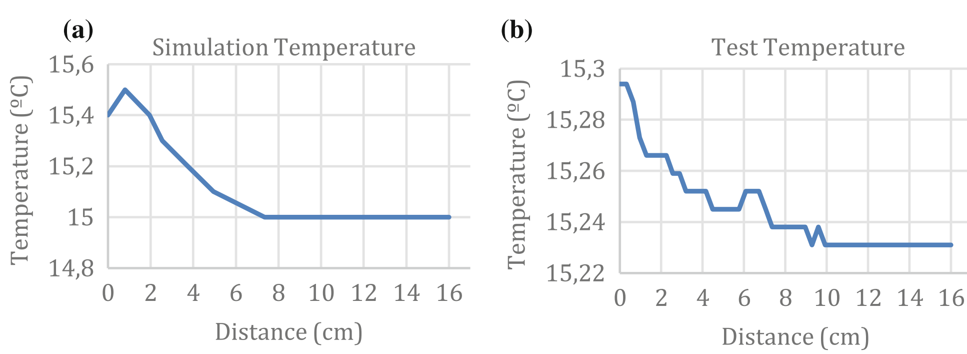

Fig. 84.3 **a** and **b** Temperature measurements of the Façade simulation and thermal imaging

84.5 Conclusion

The objective is to identify, according to the incidence factor, the existence of a thermal bridge and quantify the magnitude of it. According to the regulations for the tolerable temperatures in interior spaces, thresholds will be provided for the incidence factor to diagnose the actual building. An evaluation can be performed from a single window to the general performance of the building to tell the actual state of deterioration, obsolescence, energy consumption, and functionality. Based on these premises, different retrofitting actions will be adopted and the corresponding costs to make the best use of the existing structure will be determined. As an ultimate conclusion, determine the possible scenarios:

- The current state of the building or curtain wall is acceptable.
- The current state is not acceptable and maintenance is to be performed.
- The current state is not acceptable and refurbishment is to be performed.

References

1. Asdrubali, F., Baldinelli, G., Bianchi, F.: A quantitative methodology to evaluate thermal bridges in buildings. Appl. Energy **97**, 365–373 (2012)
2. Balaras, C.A., Argiriou, A.A.: Infrared thermography for building diagnostics. Energy Build. **34**(2), 171–183 (2002)
3. Beard, J.: Introduction to Infrared Thermography. Lecture presented at IT 570 in Tennessee, Knoxville. University of Tennessee (2018)
4. Bergman, T.L., Incropera, F.P., Lavine, A.S., DeWitt, D.P.: Introduction to Heat Transfer. Wiley (2011)
5. Centre for Window and Cladding Technology (CWCT), D. o. t. E., Transport and the Regions. CWCT Curtain Wall Installation Handbook. University of Bath, Claverton Down, Bath (2001)
6. Council, N.F.R.: Independent energy ratings. Informed purchase decisions (2017)
7. De La Perrelle, E.T., Moss, T.S., Herbert, H.: The measurements of absorptivity and reflectivity. Infrared Phys. **3**(1), 35–43 (1963)
8. DOE Consumer Energy Information, U. o. K. D. o. B. a. A. E. (2010). Radiant Barriers Lexington, KE, University of Kentucky: 1–2
9. Gruner, K.D.: Principles of non-contact temperature measurement. Raytek Company (2003)
10. ISO.: Thermal Bridges in Building Construction—Heat Flows and Surface Temperatures—Detailed Calculations. ISO 10211:2017(en) (2017)
11. Khoraskani, R.A.: Advanced Connection Systems for Architectural Glazing, pp. 11–17. Springer (2015)
12. Krawczyk, J.M., Mazur, A.M., Sasin, T., Stokłosa, A.W.: Infrared building inspection with unmanned aerial vehicles. Prace Instytutu Lotnictwa (2015)
13. Lawrence D. Carbary, A. I. S. F. A., Application Engineer/Technical Service, Dow Corning (2007). A Thermal Modeling Comparison of Typical Curtain wall Glazing Systems. Energy Performance in Buildings Glass Performance Days 2007
14. Maldague, X.: Theory and Practice of Infrared Technology for Nondestructive Testing. Wiley (2001)
15. McCowan, D., Kivela, J.: Lessons learned from Curtain Wall Failure Investigations. Interface (2011)
16. Modest, M.F.: Radiative Heat Transfer. Academic Press, Waltham, MA (2013)
17. Muhammad, L.B.: Systematic Evaluation of Curtain Wall Types Doctoral dissertation, Eastern Mediterranean University (EMU) (2010)
18. Murray, S.: The Curtain Wall in Architectural Education: Technology, History and Design, ACSA (2009)
19. Patterson, M.R.: Structural glass Façades: a Unique building technology. Faculty of the School of Architecture, University of Southern California. Master of Building Science (2008)
20. Song, J.H., Lim, J.H., Kim, Y.I., Song, S.Y.: Thermal insulation performance of metal-exterior curtain wall panel systems with thermal bridges in winter. Procedia Eng. **146**, 8–16 (2016)
21. Stockton, G.R., Allen, L.R.: Using infrared thermography to determine the presence and correct placement of grouted cells in single-width concrete masonry unit (CMU) walls. In Thermosense XXI (Vol. 3700, pp. 483–494). International Society for Optics and Photonics (1999, March)
22. Tooley, F.V.N.: The Handbook of Glass Manufacture: A Book of Reference for the Plant Executive, Technologist, and Engineer, Books for the Glass Industry Division, Ashlee Publishing Company (1984)
23. Totten, P.E., O'Brien, S.M., Pazera, M.: The effects of thermal bridging at interface conditions. Building Enclosure Science & Technology, **1** (2008)
24. Yeomans, D.: The pre-history of the curtain wall. Constr. Hist. **14**, 59–81 (1998)

BIM and Lean-Business Process Reengineering for Energy Management Optimization of Existing Building Stock

Athanasios Chassiakos, Stylianos Karatzas, and Panagiotis Farmakis

Abstract

Global warming and energy shortage has drastically increased the necessity to reduce energy use in buildings. Improving the energy efficiency of buildings is a key step-in achieving the energy and CO_2 emission targets globally. In this effort, in the presented paper, advanced modeling methods like BIM and energy simulations are conjoined with lean waste elimination concepts into a building process-centric model. Integrating building systems, processes and energy data supports decision making for retrofitting and process reengineering actions within budget constraints. The proposed approach combines existing BIM-based energy performance tools with the development of a Business Process Reengineering architecture to develop an energy efficiency optimization model. In the first direction, BIM-based energy analysis is performed to automatically assess energy performance under varying building conditions. The Lean Business Process Reengineering (LBPR) architecture describes the fundamental layers needed to achieve more energy efficient organizational environments. These layers refer to "Definition", "Data Information", "Analysis" and "Therapy". As Process Performance Indicators are also augmented to the process model, the impacts of modifications through generating different process views can be compared. An optimization model employing genetic algorithms is developed in which, considering the potential budget shortage for building asset interventions, preselected lean business process scenarios feed the optimization model to investigate the optimum solutions. A pilot case that shows the practicability of the proposed methodology is presented.

Keywords

BIM • Lean • Process • Energy • Optimization

85.1 Introduction

Energy Efficiency is a key component of the European energy policy underlying the fundamental objectives of the European Union's (EU) 2020 strategy. Buildings are a major constituent of the urban ecosystem accounting for almost 40% of the overall energy demand in Europe [1]. Several studies on energy efficiency in buildings indicate that appropriate design improvements, supported by building energy performance simulation software, could reduce energy use in both existing and in new building envelopes [2, 3]. Building energy performance can be more accurately analyzed by taking into account both descriptive data of the building (structural characteristics, equipment) and information related to building user operation. Focusing on both, design and retrofitting phase, this paper presents a framework that captures the organizational processes

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underlying the building operations, attempting to deliver a holistic building performance simulation framework. The proposed framework can be considered as a further extension of BIM utilization in the domain of commercial premises, towards incorporating business process modeling (BPM) elements regarding organizational structure and respective business processes performed by its occupants. Alternative energy efficient building designs are extracted based on optimization and balancing of typically conflicting building performance aspects, namely energy efficiency and business performance taking into account the information from the real building usage by the occupants.

85.2 Related Work

Significant research efforts focus on BIM-based assessment of building energy performance at earlier stages of building projects but only a few papers report on research using BIM for energy efficient building operation. Costa et al. [4] consider BIM as a structure for visualizing measurements and building performance datasets. In Wong and Zhou [5], the authors review a number of studies addressing "environmental sustainability over building life cycles through green BIM" and identify that BIM used in operation and maintenance (OM) should provide efficiency, improve the quality of service to customers, reduce emergencies in OM, improve safety, and reduce resource waste. Gokce et al. [6] develop a continuous assessment process by combining the data from different sources and phases in a single data repository centered on building BIM spaces. However, Reeves et al. [7] highlight a limitation in using BIM (associated with the building energy model (BEM)) for monitoring the building performance in operation which is its "inability to simulate building performance under realistic conditions".

Recently, there is an increasing emphasis on delivering simulation tools and methods that improve the prediction of the building energy use by analyzing also the performance in connection with the building space utilization by its occupants [8]. A comprehensive occupancy model was proposed by Zimmerman [9] for the aim of improving the building control system (lighting, heating and cooling system), which investigated the modeling of user activities over time considering user groups, their roles in functional units and the tasks that they may perform. In another study, Tabak [10] categorized activities in three different ways depending on (i) the nature of the activity (social, physiological or business related); (ii) the number of occupants involved resulting in solo or group activities, and (iii) the type of the activity, such as planned or unplanned.

In this paper, two main contributions are provided: ((i) a BIM-oriented methodology is presented for supporting building energy optimization, based on which directions with regards to lean business process reengineering and to the aim of minimizing process energy wastage are identified, and (ii) an application use case to demonstrate the feasibility of the proposed framework is provided.

85.3 Methodology

The proposed approach combines existing BIM-based energy performance tools with the development of a Lean Business Process Reengineering architecture to develop an energy management optimization model.

85.3.1 BIM Energy Analysis

In the first direction, BIM-based energy performance analysis of buildings is performed employing advanced and interoperable (gbXML files) simulation techniques. Energy simulation involves cloud-based tools to automatically assess energy requirements and performance under varying building conditions. Building element characteristics are then altered to obtain instant feedback on performance impacts. This task is aimed at defining asset retrofitting actions that can potentially be executed to improve the global performance of the buildings. Retrofit actions may refer to construction or mechanical systems, building heating or cooling equipment, appliance replacement, and lighting fixtures.

85.3.2 Lean Business Process Reengineering for Energy Efficiency

The Lean Business Process Reengineering (LBPR) architecture describes the fundamental layers needed to achieve energy efficient organizational environments. These layers include the "Definition", "Data Information", "Analysis" and "Therapy" ones.

Definition Layer: The first layer "Definition" is used to identify and define appropriate KEIs (Key Energy Indicators) [11] which reflect measurable attributes that characterize the building energy performance with respect to its demand for power and electricity consumed (heating, cooling and lighting) and PPI (Process Performance Indicators) describing Business Performance aspects, e.g. total execution time of a business process, total activity time per room, etc.

Data Information layer: In this layer, the measurement of KEIs is performed and linked to the corresponding activities and processes. For the calculation of energy consumption referring to the whole business process, we need to collect the necessary data of each process activity. This layer is responsible for collecting energy use data from WSN devices. This data stream is captured automatically, appropriately processed and analyzed, addressing specific types of loads/sensors including:

(a) ubiquitous loads, like HVAC and lighting, triggered by business processes,
(b) office equipment loads directly linked and supporting the execution of everyday business activities, and
(c) environmental sensors, which capture context conditions (luminance, temperature & humidity) within premises.

Analysis layer: For the "Analysis" layer, 'process views' [12] that enable a proper visualization of the process model are developed with the use of BPMN 2.0 software. By means of augmenting the process model with energy information from the previous layer, virtual views of a process are built and the KEIs of the complete process or specific activities of interest are identified and visualized. This enables analyzing the current energy impact of a process model by identifying the main cause of KEI deviations. Based on the 'process views', Lean metrics are combined with the energy data to determine non-adding value activities of the process in order to reduce or eliminate such activities in favor of adding value activities for minimizing energy wastage. As PPIs are also augmented to the process model, the impacts of modifications through generating different process views can be compared [13]. A first step when detecting a KEI violation is that the given process model needs to be augmented with related data (Fig. SM1 in supplementary material, left). The augmented process model now contains all relevant information about the PPIs and KEIs to proceed with the next step, in which activities with the highest amount of energy are reengineered. First, we use a visual transformation that omits all activities where the augmented energy consumption is below their dedicated threshold Xn. As a next step, we additionally omit all activities that cannot be changed and alter the color and/or the size of the process view depending on their augmented energy consumption data (Fig. SM1 in supplementary material, right).

Therapy layer: Several Business Process Reengineering techniques are feasible to improve the KEIs of the observed process. These include but are not limited to: (1) New binding of services implementing a process activity, (2) changing the underlying infrastructure which better adapts the process characteristics, (3) changing the flows of a process model, (4) rearranging activities, i.e., add, remove or modify (groups of) activities, or (5) introducing dynamic provisioning of activities. Utilizing these techniques provides a wealth of opportunities for making a business process more sustainable and can therefore be fully applied to our approach.

85.3.3 Building Information Model and Business Process Model Alignment

In BIM model, the hierarchical structure is presented, starting from the building to floor and further space level, in which the association of devices with specific spaces is presented. Following to the BIM related parameters, business processes, associated to specific devices and spaces accordingly (and further to specific users) are presented, within the context of the LBPR model. The overall model is a synthesis of energy uses, business process modeling, and building information modeling, associated with the corresponding KEIs and PPIs (Fig. 85.1).

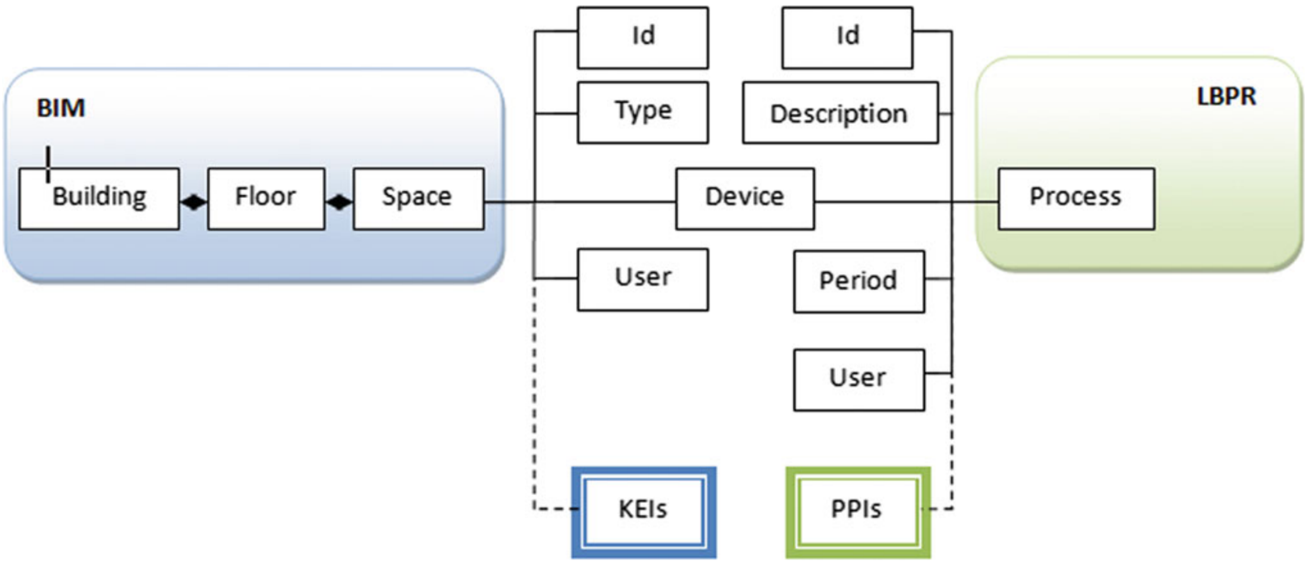

Fig. 85.1 BIM to BPM representation

85.4 Case Study

To illustrate our proposed methodology, we use a motivating example in which a part of the Transportation Lab in Civil Engineering Department, University of Patras, has been selected as the pilot site. More specifically, the place includes the Director office, Researcher office I, Researcher office II, and Meeting room, as shown in the plan view (Fig. SM2 in supplementary material). Six staff persons regularly work in these rooms. A list of pilot specific requirements has been defined to set constraints on the proposed framework.

85.4.1 Building Requirements

The pilot site limitations, either topology limitations or organization limitations, which set the list of requirements for the case study development, are described in Table 85.1. Based on observation of the activities taking place in the building units, there is a potential in managing the plug-in loads in premises but the highest potential is in reengineering activities towards reducing the heat and cooling consumption of ACs. In general, the observation has come up with the following conclusions:

C.1 Continuous usage of lighting devices, is observed leading to high consumption during the day.
C.2 Typical office activities are performed in office premises (typical usage of PCs, printers) with a potential of promptly managing loads during idle mode.
C.3 A/Cs are managed independently by the users.
C.4 Considering thermal and visual preferences, there are no significant complaints from occupants.
C.5 High potential for eliminating vampire loads.
C.6 Highest potential for managing heating/cooling devices in a more efficient way.

85.5 Framework Application

BIM Energy Analysis: The specific building characteristics have been used to develop the BIM model using the Autodesk Revit platform. Based on this model, the Insight software has been used to run energy simulation and calculate current building energy performance (Fig. SM3 in supplementary material).

Table 85.1 Building technical requirements and limitations

Building units	Occupants	Size (m^2)	Facilities	Working hours	Heating/cooling (power cons.)	Lamp power cons. (w/h)	Computers power cons. (w/h)
Director's office	2	18	1 Heating/Cooling AC (12000 btu) 2 windows 6 fluorescent lamps 2 computers 1 Heating/Cooling AC (9000 btu)	Director Tue–Thur: 9:00–12:00 & 15:00–18:00 Finance Manager Mon–Fri:9:00–18:00	A/C 12000 BTUs: 1.333 w/h	58	280
Researcher 1 office	2	12	1 window 2 fluorescent lamps 2 computers 1 Heating/Cooling AC (9000 btu)	Mon–Fri: 9:00–18:00	A/C 9000 BTUs: 900 w/h	58	280
Researcher 2 office	2	18	1 window 3 fluorescent lamps 2 comp ut ers 1 Heating/Cooling AC (24000 btu)	Mon–Fri: 9:00–18:00	A/C 9000 BTUs: 900 w/h	58	280
Meeting room	6	25	2 windows 8 fluorescent lamps	Wedn: 9:00–15:00	A/C 24000 BTUs: 2.800 w/h	58	Laptop–60

Definition Layer: Easily quantified and measured PPIs are selected to give an indication of the building business process performance with respect to energy consumption [14]. The following types of PPIs are taken in consideration in the case study:

Energy Consumption per m2 (EC_A)—this measures building energy consumption (for a specific reporting period, e.g. annual, hourly) related to the total floor space.

Energy Consumption per Business Process (EC_BP)—by addressing also the BPM elements as part of the BIM model, a detailed alignment of energy consumption with main business processes is revealed. Therefore, this indicator defines the cost of energy per business process in premises (measured in kWh).

Business Process Cycle Time (BPCT)—is related to the time period needed to perform a specific process. This indicator is not directly aligned to energy measurement data, but it is linked to the typical time period needed for a process and therefore affects the usage of specific devices within this timeframe (measured in hours).

Data Information Layer: Within this task, a small number of representative low-cost sensors will be deployed in the lab environment and will have connection to a single master, namely gateway, which is the end connection to the proposed system. Information about the activation and use of loads will be captured for remote observation of the on-going activities and under certain conditions.

As this is a step forward to the research, for the purposes of the example, energy capacity metrics of resources used in a business process and affecting the energy consumption will be used.

Analysis layer: The information previously collected provides the basis for analyzing and managing the existing organizational processes by facilitating the identification and localization of vital KEI violations. In order to localize and finally visualize the cause of a KEI violation, we use the concept of process view to reengineer two common energy consuming processes.

Business Process Reengineering 1: 'Weekly Progress Meeting', as it is identified as one of the most energy consuming process of the department. At the initial process condition, this is conducted in the meeting room every Wednesday for a fixed 6 h period time. The lab director and finance manager provide feedback to the researchers for several subjects in a parallel way. This is changed to a sequential communication process, based on themes, where the involved researchers participate and the maximum time period for each one is set to be 0, 5 h/theme (usually between 4 and 6 different themes discussed). Aris Business Process Modeling platform is used to visualize the initial and transformed process (Fig. 85.2a and b respectively).

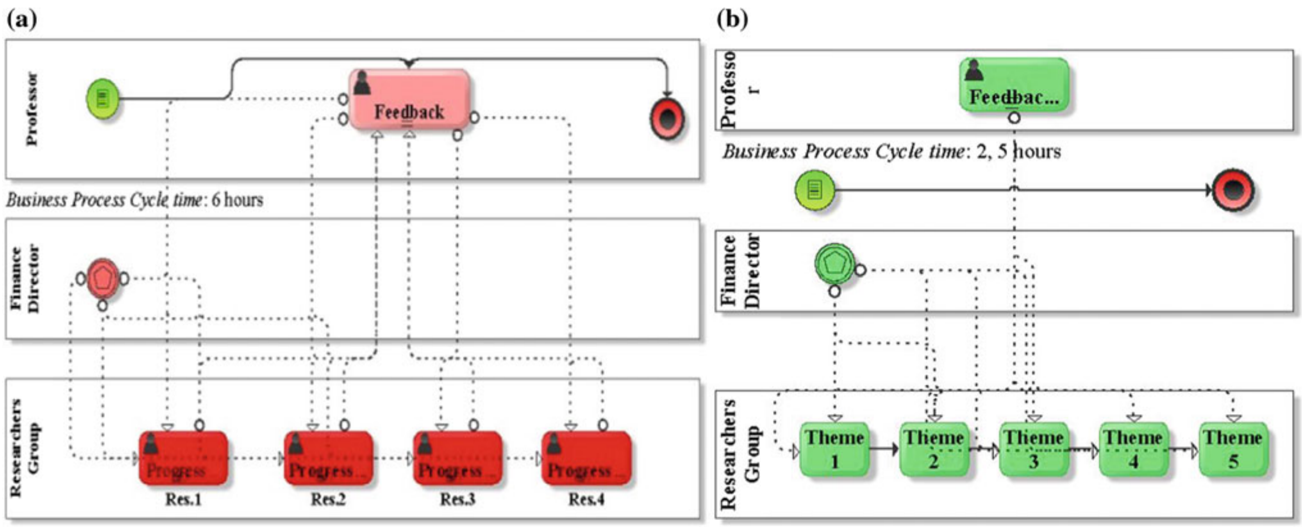

Fig. 85.2 **a** Initial process **b** Transformed process

According to this transformation,

$$\begin{aligned} \text{ECBP1i} &= \text{ Energy Consumption } * \text{BP1 CTi} \\ &= (\text{HVAC cons.} + \text{Lighting cons.} + \text{Computer cons.}) * \text{BP1 CTi} \end{aligned}$$

From Table 85.1, the cost savings (from energy savings) for process 1 is:

$$\text{CS1} = 7{,}856\text{kw/h} * (\text{BP1 CTi} - \text{BP1 CTr})\ \text{h} * 0{,}1437\ \text{USD/kwh} \quad (85.1)$$

$$\text{with constraints, BP1 CTi} = 6 \text{ hours } 2\text{hours} < \text{BP1 CTr} < 3\text{hours} \quad (85.2)$$

Business Process Reengineering 2: Every researcher has to give course instructions to undergraduate students. This process currently is conducted in the meeting room by spending every day about 1 h, depending on the number of students asking for instructions. This process is reengineered and the researchers are available to give the instructions every Friday morning through skype from 2 to 3 h.

Accordingly,

$$\text{CS2} = 7{,}856\text{kw/h} * (\text{BP2 CTi - BP2 CTr})\ \text{h} * 0{,}1437\ \text{USD/kwh} \quad (85.3)$$

$$\text{BP2 CTi} = 20 \text{ hours } 8 \text{ hours} < \text{BP2 CTr} < 12\text{hours} \quad (85.4)$$

Therapy layer: At this point, in order to find building renovation scenarios, an evolutionary optimization algorithm is developed. Genetic algorithms, via Palisade Evolver software is implemented for the optimization process due to their robustness in providing efficient and feasible solutions in reasonable computational time. The objective function which evaluates the quality of chromosomes—potential solutions refers to energy cost savings and additional constraints have been set for non-overlapping (choosing between alternative activities) and non- exceeding the available budget. Based on the BIM model, Insight Energy simulation software is used for the development of a set of 25 scenarios that include interventions regarding:

- window glasses (single, double and triple glass) for each window of the different building orientation,
- shading interventions (4 different interventions with different shade sizes),
- lighting (2 scenarios with lamps of lower energy consumption).

The scenario parameters and Eqs. (85.1), (85.2), (85.3) and (85.4) are set as inputs to the optimization model, for the extraction of several retrofitting cases with optimum cost savings. Case examples are described below

Table 85.2 Case 4 results

Asset Interventions	Energy Cost Savings (USD)	**Processes**	Energy Cost Savings (USD)
Window Glass		Business Pr.Reeng. 1	1174,06
Scenario 1-(G)S-Trp.	653,73	Business Pr.Reeng. 2	3522,19
Scenario 4-(G) E-Trp.	526,85	**Cost Saving**	**4696,25**
Shading		Budget=2000USD	
Scenario 15-(Sh) E-1/3H	294,7	Time Period=5 years	
Scenario 20-(Sh) S-1/6H	500,29	BP1 CTr=2 hours	
Lighting		BP2 CTr=8 hours	
Scenario 25-Lighting 2	1332,69		
Cost Saving	**3308,28/2000**	**Total Cost Savings**	8004,54

Case 1. With an insufficient budget, no asset intervention is qualified and only savings from process reengineering are gained. For maximum BPCT decrease for 3 year period time, the total cost saving is estimated at 2818 USD.

Case 2. With a budget of 1000 USD and the maximum BPCT decrease for 3 years, an average shading and the maximum lighting performance change are qualified, with a total cost saving of 3918 USD.

Case 3. With 2000 USD budget and the maximum BPCT decrease for 3 years, two high window glass changes, a high and a medium shading and a high lighting performance change are qualified, with a total cost saving of 4803 USD.

Case 4. With 2000 USD budget and the maximum BPCT decrease for 5 years, two high window glass changes, a high and a medium shading and a high lighting performance change are qualified, with a total cost saving of 8005 USD (Table 85.2).

Case 5. With unlimited budget in a 5 year period time, without process reengineering, all asset high performance changes are qualified with a total cost saving of 4247 USD.

85.6 Setting Up Future Research

The agenda is organized based on the technical needs of BIM in energy retrofitting projects. The technical needs in the pre-energy analysis phase depend on the availability of a BIM model. If a model is available, it can be used for energy simulations after the necessary updates. If there is no available BIM for the existing building, BIM modelers and architects can build one from scratch which requires a significant data collection effort. Research is already directed to automate the process of capturing as-built information, integrating it into BIM databases, with the use of laser scanners and photogrammetry technologies.

In the energy analysis phase, the interface between BIM platforms and energy simulation software is still complex because of incompatibility in information exchange protocols. Future research may focus on ensuring a smooth information flow from BIM to the selected energy simulation software by creating algorithms to automate rules for the exchange protocols.

The technical needs extend to the retrofitting options phase, where modelers face challenges in choosing the optimal retrofitting scenario, because of uncertainty or volatility in the data. Integrating, for example, energy price variation in the proposed method, it provides a more solid decision making platform for an energy-driven retrofit project. The retrofitting option will be based on these factors as they affect energy costs.

85.7 Conclusions

In this paper, an approach is presented for supporting the energy-aware adaptation and energy waste elimination of business processes in office buildings with energy management being driven by a retrofitting optimization process that takes into account both infrastructure and process activity parameters. The research proposes a four phase conceptual framework (‘Analyze’, ‘Design’, ‘Implement’ and ‘Monitor & Control’) based on Business Process Management and supported by BIM based-energy analysis. It involves several tools (such as Revit, Insight energy simulation, Aris Business Process Modeling platform, Evolver optimization software) adapted to the building energy efficiency analysis and working together as a holistic solution. The paper has also presented a case study to exemplify the use of the conceptual framework, developing a model for office energy consumption of a real building case. The case study results constitute a proof of the proposed framework practicability.

This approach is currently based on the assumption that sensoring and monitored data are available and that the necessary pieces of information regarding the essential metric values are all included in this knowledge base. Taking the research a step further, the sensing and monitoring layer will be developed in the case study area. The model will be enriched with additional Process Performance Indicators while extra infrastructural intervention scenarios will be included in the optimization model. Finally, as thermal comfort of building occupants is a major criterion in evaluating their operation performance and optimizing their energy usage, the research aims to extend its scope towards studying the feasibility of using wearable devices to collect data including location, air temperature, relative humidity, skin temperature, heart rate, and perspiration rate, integrating these metrics into the proposed framework.

References

1. European Commission, Energy Efficiency Plan 2011, https://ec.europa.eu/clima/sites/clima/files/strategies/2050/docs/efficiency_plan_en.pdf. Assessed 21 June 2018
2. Clarke, J.A.: Energy simulation in building design. In: Boonstra, C., Rovers, R., Pauwels S. (eds.) International Conference Sustainable Building 2000. Vol. 2003. Butterworth-Heinemann (2001)
3. Kim, H., Stumpf, A., Kim, A.: Analysis of an energy efficient building design through data mining approach. Autom. Constr. **20**(1), 37–43 (2011)
4. Costa, A., Keane, M.M., Torrens, J.I., Corry, E.: Building operation and energy performance: monitoring, analysis and optimisation toolkit. Appl. Energy **101**, 310–316 (2013)
5. Wong, J.K.W., Zhou, J.: Enhancing environmental sustainability over building life cycles through green BIM: a review. Autom. Constr. **57**, 156–165 (2015)
6. Ufuk Gökçe, H., Umut Gökçe, K.: Integrated system platform for energy efficient building operations. J. Comput. Civil Eng. **28**(6), 05014005 (2014)
7. Reeves, T., Olbina, S., Issa, R.R.: Guidelines for using building information modeling for energy analysis of buildings. Buildings **5**, 1361–1388 (2015)
8. Goldstein, R., Tessier, A., Khan, A.: Space layout in occupant behavior simulation. Conference Proceedings: IBPSA-AIRAH Building Simulation Conference, 1073–1080 (2011)
9. Zimmerman, G.: Modeling and simulation of individual user behavior for building performance predictions. In: Proceedings of the Summer Computer Simulation Conference, San Diego, USA, (2007)
10. Tabak, V.: User simulation of space utilisation: system for office building usage simulation. Ph.D. dissertation, Eindhoven University of Technology, Netherlands (2008)
11. Buildings Performance Institute Europe (BPIE): Energy performance certificates across the EU—a mapping of national approaches (2014)
12. Schumm, D., Leymann, F., Streule, A.: Process viewing patterns. In: Proceedings of the 14th IEEE Intl. EDOC Conference, 89–98, IEEE Computer Society, Los Alamitos (2010)
13. Nowak, A., Leymann, F., Schumm, D., Wetzstein, B.: An architecture and methodology for a four-phased approach to green business process reengineering. In: Proceedings of the First International Conference on Information and Communication Technology for the Fight Against Global Warming (ICT-GLOW2011), Toulouse, France (2011)
14. Lewry, A.J., Ortiz, J., Nabil, A., Schofield, N., Vaid, R., Hussain, S., Davidson, P.: Bridging the gap between operational and asset ratings - the UK experience and the green deal tool. Sustainable Energy Team, Building Research Establishment Ltd, UK. https://www.bre.co.uk/filelibrary/pdf/other_pdfs/KN5477_Energy_Paper_v1.pdf. Assessed 21 June 2018

Geographic Information Systems (GIS) Based Visual Analytics Framework for Highway Project Performance Evaluation

86

Chau Le, Tuyen Le, and H. David Jeong

Abstract

Advances in data and information technologies have resulted in the availability of different types of useful data and easy accessibility. However, much of the data is not fully leveraged to gain insights for decision making due to the labor-intensive and time-consuming process of data collection and the unstructured format of data, which imposes challenges for data analytics. This paper discusses a Geographic Information Systems (GIS) based visual analytics framework for highway project performance evaluation in terms of cost and productivity. The study employs web data extraction techniques and database technologies to automatically extract data of interest from different web data sources to develop databases that contain structured data for data analytics. To merge the data from distinct sources, natural language processing techniques are also used to deal with the inconsistency of data terminology and word choices. In addition, the use of GIS technologies allows for the visualization and analysis of data collected from different locations. A case study was undertaken, which implemented part of the framework for unit price visualization, estimation, and evaluation of highway projects.

Keywords

Visual data analytics • Web data extraction • Database • Natural language processing
Geographic information systems • Unit price predictions and visualizations

86.1 Introduction

Advances in data and information technologies have resulted in the availability of different types of useful data and easy accessibility. However, much of the data is not fully leveraged to gain insights for decision making due to the labor-intensive and time-consuming process of data collection and the unstructured format of data. In the highway sector, State Departments of Transportations (DOTs) have been collecting data about highway projects and publishing the data on their websites for public view. The data includes a variety of information for each project such as project plans, location, schedule, scopes of work, and estimated costs; but most of them are in unstructured formats (e.g., PDF files). There is a need for an efficient way that can extract useful information from DOT's websites and integrate different types of information for data analytics to gain understanding of highway projects.

This paper discusses a Geographic Information Systems (GIS) based visual analytics framework for highway project performance evaluation regarding cost and productivity. The study employs web data extraction techniques and database

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technologies to automatically extract data of interest from different web data sources to develop databases that contain structured data for data analytics. To merge the data from distinct sources, natural language processing techniques are used to deal with the inconsistency of data terminology and word choices. Also, the use of GIS technologies allows for the visualization and analysis of data collected from different locations. A case study was undertaken, which implemented part of the framework for unit price visualization, estimation, and evaluation of highway projects.

86.2 Background

86.2.1 Web Data Extraction Techniques

The internet contains a massive amount of data from various sources and in different formats. Extracting data from web pages and transforming it into structured forms are necessary for data analysis to explore useful information and gain understanding about phenomena of interest [4, 11]. Web data extraction techniques come from a variety of areas and disciplines, such as natural language processing, machine learning, databases, and ontologies [21]. The techniques can be divided into two main approaches: tree matching and machine learning [11, 31]. The former is based on the semi-structured format of the HTML web pages to identify the location of the required information. The latter learns from examples labeled by domain experts to extract data from similar unseen websites by using machine learning algorithms such as convolutional neural networks [12, 31].

86.2.2 Natural Language Processing

Natural Language Processing (NLP) is an area of artificial intelligence which includes a collection of techniques that can process, analyze, and manipulate human language data such as text and speech. Some of the techniques are tokenization [29, 32], Part-of-Speech tagging [7, 27], and Named Entity Recognition [1]. NLP research has been around since the 1950s and has been applied in various tasks, for example in translation, information extraction, information retrieval, and topic modeling [3]. These applications are being supported by the availability of highly accurate NLP packages and libraries such as NLTK and Gensim.

Information Extraction. Information extraction is the process of extracting desired structured information from text documents. It includes two major tasks name entity recognition (NER) and relation extraction (RE) [19]. NER aims to find names of entities such as organizations (e.g., “Iowa State University”), persons (e.g., “Joanna Shaffer”), places (e.g., “Ames, Iowa”), time (e.g., “April, 2018”), and numbers (e.g., “11”). RE refers to finding relationships between entities, for example: “Iowa State University” is located in “Ames, Iowa” [26]. Two main approaches for NER are the rule-based approach and the statistical learning approach. Rule-based methods use a set of predefined rules to find matches in text documents. Those rules can be manually developed by domain experts or automatically identified through applications of machine learning to NLP [18, 24]. The statistical learning approach treats the text as a sequence of words with labels, and each one depends on the others in the series [19].

Semantic Measures. One of the main NLP related research topics is semantic measurement, which aims to evaluate the similarity or relatedness between semantic units (words, phrases, sentences, concepts, etc.) [15]. Semantic similarity indicates the likeness in the meaning of different semantic units; for instance, the words “road” and “highway” are semantically similar even though they do not share the same string representations. The two primary approaches for semantic measures are (1) knowledge-based method and (2) corpus-based method [15]. The former builds upon ontologies or digital dictionaries, which are lexical networks of terms and their semantic relations such as synonym and hypernym. The relatedness of the two words is measured by a similarity measure such as the distance between them in the network. However, ontologies and digital dictionaries are not available to many domains. The latter method relies on corpora of text and distributional models from those corpora. A distributional model stands on the distributional hypothesis: two words that occur in the same contexts have similar meanings [16]. Therefore, distributional models represent a word through its surrounding words observed from a given corpus [10]. The outcome of this approach is a Vector Space Model (VSM), where each word is represented by a point in a high-dimensional space. Two words with similar contexts are close to each other in the vector space.

A considerable amount of literature has been published on learning vector representations of words by using neural networks [23, 25, 28]. For example [23] proposed two neural network models (also known as word2vec): continuous bag-of-word model (CBOW) and skip-gram model. For the CBOW model, the target word is at the output layer, and context words (surrounding words) are at the input layer. Conversely, for the skip-gram model, the target word is at the input layer, and the context words are at the output layer. Also, several attempts have been made to learn distributed representations of phrases, sentences, paragraphs, and documents by extending word representations in vector space [13, 22]. Paragraph vector (also known as doc2vec) was proposed by Le and Mikolov [22] is an extension of word2vec, which is capable of constructing vector representations of word sequences of various length (sentences, paragraphs, and documents).

86.2.3 Geographic Information System and Spatial Interpolation Methods

GIS technologies have been increasingly used to handle spatial data in various application areas, such as urban planning, transportation planning, and environmental management. It allows for positioning real properties or objects on a local map based on their geographical coordinates [8]. GIS represents some aspect of the real world through spatial models using simplified spatial entities like points, lines, and areas [17]. Each entity is associated with one or more attributes that give additional information about that entity [17]. By organizing, integrating, analyzing different types of data, GIS can handle complex spatial data and create new information to support decision making [6, 17].

Interpolation techniques is an essential component of GIS [9]. Spatial interpolation, as defined by Burrough et al. [2], is the prediction of the value of a variable at unknown locations within the area surrounded by known data points. Spatial interpolation techniques can be considered to consist of two categories: deterministic ones (e.g., inverse distance weighted and global polynomial) and geo-statistical ones (e.g., ordinary kriging, simple kriging, and cokriging) [5, 20]. Deterministic interpolation depends on the values of measured points or mathematical calculations from them while geostatistical methods rely on statistics (e.g., spatial autocorrelation among the measured locations). Some popular interpolation techniques are supported by GIS platforms. One of the most popular ones is ArcGIS which support spatial data analysis to create continuous surfaces or maps from measured data, along with errors of the predicted surfaces [20].

86.3 GIS-Based Visual Analytics Framework for Highway Project Performance Evaluation

This paper proposes a GIS-based visual analytics framework for highway project performance evaluation. The idea arises from applications of GIS in other research areas such as analysis of heavy metal sources in soil [14] or analysis of groundwater level in a specific region [30]. In this proposed framework, each highway project can be modeled as a spatial entity such as a point or a line on a map. In case that the purpose of a study is to make comparisons among many projects in a large area, point entities can be used to present highway projects. Each point can be associated with different types of data: spatial data (e.g., latitudes and longitudes), temporal data (e.g., recorded date of the data), and other un-spatial data that contain specific information about the project. Each project has its characteristics, and many of them are influenced by project locations, such as weather, topographical conditions, and geotechnical conditions. By integrating different types of data, researchers not only can implement standard analyses for un-spatial data but also explore relationships among variables or influences of time and location on other characteristics of highway projects. Thanks to GIS, spatial questions relating to highway projects can be answered to support decision-making processes. For example, developing a unit price map of a work item over several states can help contractors see some overall patterns or variations of unit prices in different states, from which they can have appropriate bidding strategies for each state. By such comparisons, performances of a project can be evaluated through cost, productivity, and performance indexes when those of other similar projects are known and shown on the same map.

A next question that needs to be addressed is how to obtain those kinds of data of highway projects for data analysis. Ideally, data of interest can be provided by data creators such as DOTs. Those ideal situations are not common and the corresponding processes still heavily rely on human interactions. There is, however, another option. With the availability of data in DOTs' websites, the desired information can be automatically harvested using web data extraction and NLP information extraction techniques. For example, an algorithm can be developed to obtain bid tabulations from DOTs' websites and then extract desired information (e.g., bid item code, item description, unit, unit price, and location) through NER tasks. To evaluate the accuracy of the algorithm, a testing dataset, which is developed by domain experts, is needed to compare the output of the algorithm with the one identified by the experts. In addition, outlier analysis may be employed to exclude information that is extracted by errors. After that, data is ready for analysis of projects within the same state. For comparisons across different states, the issue of inconsistencies in data terminology and word choices also needs to be dealt

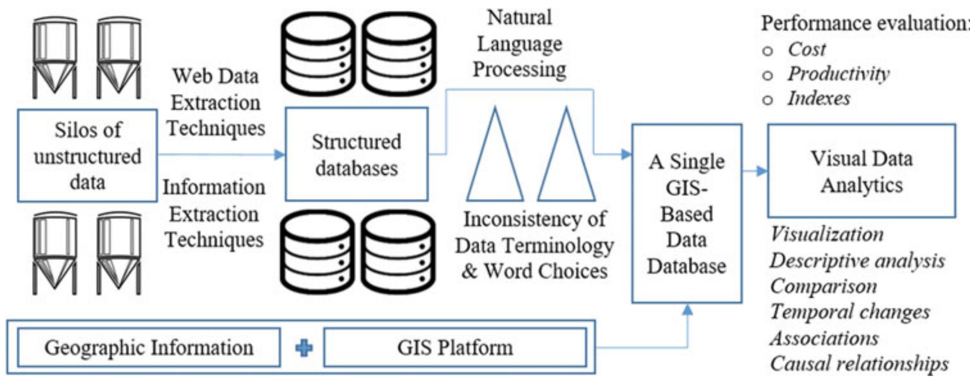

Fig. 86.1 A GIS-based visual analytics framework

with because each DOT has their own specifications, standards, and work breakdown structures. To overcome this barrier, manual matching of variable descriptions by experts is possible, but time-consuming and labor intensive. To save time and reduce human involvement in the process, NLP techniques can be utilized to automatically measure semantic similarity between word units. The results from automatic matching should then be evaluated by domain experts to ensure the reliability of the combined data.

The above discussions are organized and summarized to form a GIS-based visual analytics framework as Fig. 86.1.

The following is a case study which partially implemented the proposed framework. The authors collected bid data for the year 2013 from Iowa DOT and Montana DOT. The bid items selected for illustration were “Asphalt binder, PG 64-28” (Iowa DOT, item code “2303-0246428”) and “Asphalt cement, PG 64-28” (Montana DOT, item code “402020092”). With the assumption that the two bid items represent the same work, unit prices of 17 projects in Iowa and 26 projects in Montana were used for comparisons. By using an interpolation method available in ArcGIS, inverse distance weighting, unit price maps for each entire state were developed as Fig. 86.2. The maps were color-coded with increasing unit prices when colors changed from blue to red. The maps can visually show that Montana had higher unit prices of the work item than Iowa in 2013.

The above statement was further checked by statistical analysis. The average unit price of the projects in Iowa was $643.11 per ton, while the average in Montana was $688.44 per ton. Since some tests of normality (i.e., normal Q-Q plot, Kolmogorov-Smirnov, and Shapiro-Wilk) proved that two samples of unit prices were not normally distributed, a non-parametric test was used to determine whether two sets of data are significantly different. The Mann-Whitney U test rejected the hypothesis that the two distributions are the same with the significance level of 0.05, which was consistent with the results from the maps.

86.4 Conclusion

This study presents a GIS-based visual analytics framework for highway projects by applying technologies and techniques from web data extraction, information extraction, databases, semantic similarity, and GIS. Depending on the availability of data and scale of research, part of or entire framework can be utilized for visual analytics. The framework allows for not only typical data analyses of un-spatial data (e.g., frequencies, average values, and mean differences) but also spatial analysis (e.g., variations of unit prices over an area). Applying the entire framework can enable a large-scale study of highway projects for several DOTs, a region, or even the whole nation. Our goals are to evaluate project performances regarding cost and productivity, quantify the effects of location and time on the performances, and visualize the results through interactive maps.

The case study in this paper is just limited in comparison of a work item from two DOTs using the inverse distance weighting interpolation method. In future research, it can be expanded to a regional level such as for Midwest region including twelve states. Major bid items in highway projects, which account for the majority of the total cost, will be identified and then matched across DOTs for comparisons. Different kinds of interpolation methods will be utilized and evaluated to find the one that can produce unit price maps with smallest errors. The variances of unit prices across states will

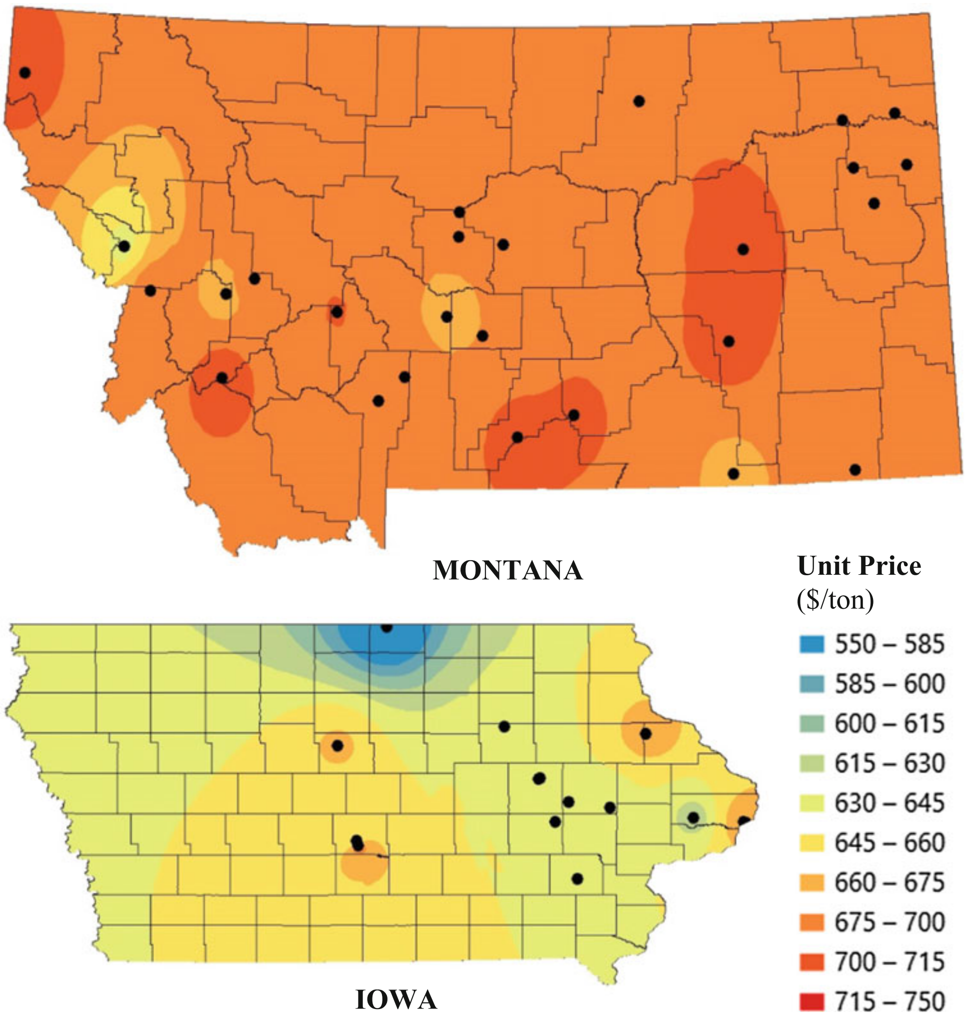

Fig. 86.2 Unit price maps of asphalt binder/cement PG 64-28, 2013

be visualized to support decision-making processes such as unit price estimations. Further interviews with practitioners from DOTs could be implemented to explain any differences between DOTs.

References

1. Aggarwal, C., Zhai, C.: Mining Text Data. Springer Science & Business Media (2012)
2. Burrough, P.A., McDonnell, R.A., Lloyd, C.D.: Principles of Geographical Information Systems. Oxford University Press (2015)
3. Cambria, E., White, B.: Jumping NLP curves: a review of natural language processing research [review article]. IEEE Comput. Intell. Mag. **9** (2), 48–57 (2014). https://doi.org/10.1109/MCI.2014.2307227
4. Chia-Hui, C., Kayed, M., Girgis, M.R., Shaalan, K.F.: A survey of web information extraction systems. IEEE Trans. Knowl. Data Eng. **18** (10), 1411–1428 (2006). https://doi.org/10.1109/TKDE.2006.152
5. Childs, C.: Interpolating surfaces in ArcGIS spatial analyst. ArcUser, July-September, 3235, 569 (2004)
6. Clementini, E., Di Felice, P.: A comparison of methods for representing topological relationships. Inf. Sci. Appli. **3**(3), 149–178 (1995)
7. Cunningham, H., Maynard, D., Bontcheva, K., Tablan, V. GATE: an architecture for development of robust HLT applications. Paper presented at the Proceedings of the 40th annual meeting on association for computational linguistics, Philadelphia, Pennsylvania, 2002
8. Din, A., Hoesli, M., Bender, A.: Environmental variables and real estate prices. Urban stud. **38**(11), 1989–2000 (2001)
9. Eberly, S., Swall, J., Holland, D., Cox, B., Baldridge, E.: Developing spatially interpolated surfaces and estimating uncertainty. U. S. Environ. Prot. Agency (2004)
10. Erk, K.: Vector space models of word meaning and phrase meaning: a survey. Lang. Linguist. Compass **6**(10), 635–653 (2012). https://doi.org/10.1002/lnco.362

11. Ferrara, E., De Meo, P., Fiumara, G., Baumgartner, R.: Web data extraction, applications and techniques: a survey. Knowl.-Based Syst. **70**, 301–323 (2014). https://doi.org/10.1016/j.knosys.2014.07.007
12. Gogar, T., Hubacek, O., Sedivy, J.: Deep Neural Networks for Web Page Information Extraction. Cham (2016)
13. Grefenstette, E., Dinu, G., Zhang, Y.-Z., Sadrzadeh, M., Baroni, M.: Multi-step regression learning for compositional distributional semantics. arXiv preprint arXiv:1301.6939 (2013)
14. Ha, H., Olson, J.R., Bian, L., Rogerson, P.A.: Analysis of heavy metal sources in soil using kriging interpolation on principal components. Environ. Sci. Technol. **48**(9), 4999–5007 (2014)
15. Harispe, S., Ranwez, S., Janaqi, S., Montmain, J.: Semantic similarity from natural language and ontology analysis. Synth. Lect. Hum. Lang. Technol. **8**(1), 1–254 (2015). https://doi.org/10.2200/S00639ED1V01Y201504HLT027
16. Harris, Z.S.: Distributional structure. Word, 10 (2–3): 146–162. Reprinted in Fodor, J.A, Katz, J.J. (eds.), Readings in the Philosophy of Language. Prentice-Hall, Englewood Cliffs, NJ (1954)
17. Ian, H., Sarah, C., Steve, C.: An Introduction to Geographical Information Systems. Pearson Education India (2010)
18. Iorio, A.D., Peroni, S., Poggi, F., Vitali, F., Shotton, D.: Recognising document components in XML-based academic articles. Paper presented at the Proceedings of the 2013 ACM symposium on document engineering, Florence, Italy, 2013
19. Jiang, J.: Information extraction from text. In: Aggarwal, C.C., Zhai, C. (eds.) Mining Text Data, pp. 11–41. Springer and Boston, MA, US (2012)
20. Johnston, K., Ver Hoef, J.M., Krivoruchko, K., Lucas, N.: Using ArcGIS geostatistical analyst (Vol. 380): Esri Redlands (2001)
21. Laender, A.H.F., Ribeiro-Neto, B.A., da Silva, A.S., Teixeira, J.S.: A brief survey of web data extraction tools. SIGMOD Rec. **31**(2), 84–93 (2002). https://doi.org/10.1145/565117.565137
22. Le, Q., Mikolov, T.: Distributed representations of sentences and documents. Paper presented at the international conference on machine learning, 2014
23. Mikolov, T., Chen, K., Corrado, G., Dean, J.: Efficient estimation of word representations in vector space. arXiv preprint arXiv:1301.3781 (2013)
24. Mooney, R.: Relational learning of pattern-match rules for information extraction. Paper presented at the Proceedings of the sixteenth national conference on artificial intelligence, 1999
25. Pennington, J., Socher, R., Manning, C.: Glove: Global vectors for word representation. Paper presented at the Proceedings of the 2014 conference on empirical methods in natural language processing (EMNLP), 2014
26. Piskorski, J., Yangarber, R.: Information extraction: past, present and future. In: Poibeau, T., Saggion, H., Piskorski, J., Yangarber, R. (eds.) Multi-source, Multilingual Information Extraction and Summarization, pp. 23–49. Springer, Berlin, Heidelberg (2013)
27. Toutanova, K., Klein, D., Manning, C.D., Singer, Y.: Feature-rich part-of-speech tagging with a cyclic dependency network. Paper presented at the Proceedings of the 2003 Conference of the North American chapter of the association for computational linguistics on human language technology—Volume 1, Edmonton, Canada, 2003
28. Turian, J., Ratinov, L., Bengio, Y.: Word representations: a simple and general method for semi-supervised learning. Paper presented at the Proceedings of the 48th annual meeting of the association for computational linguistics, Uppsala, Sweden, 2010
29. Webster, J.J., Kit, C.: Tokenization as the initial phase in NLP. Paper presented at the Proceedings of the 14th conference on computational linguistics—Volume 4, Nantes, France, 1992
30. Xiao, Y., Gu, X., Yin, S., Shao, J., Cui, Y., Zhang, Q., Niu, Y.: Geostatistical interpolation model selection based on ArcGIS and spatio-temporal variability analysis of groundwater level in piedmont plains, northwest China. SpringerPlus **5**(1), 425 (2016)
31. Zhai, Y., Liu, B.: Web data extraction based on partial tree alignment. Paper presented at the Proceedings of the 14th international conference on World Wide Web, Chiba, Japan, 2005
32. Zhao, H., Kit, C.: Integrating unsupervised and supervised word segmentation: the role of goodness measures. Inf. Sci. **181**(1), 163–183 (2011). https://doi.org/10.1016/j.ins.2010.09.008

87 Usage of Interface Management in Adaptive Reuse of Buildings

Ekin Eray, Benjamin Sanchez, Seokyoung Kang, and Carl Haas

Abstract

Adaptive reuse of buildings is considered a superior alternative for new construction in terms of sustainability and Circular Economy (CE). Adaptive reuse takes existing buildings that are reaching the end of their lifespan, restores them, and in some cases, changes their use. The conceptualization and execution phases of adaptive reuse projects involve the integration of emergent complex processes. In comparison to green-field construction projects, adaptive reuse projects require distinct stages, definition of interfaces, decision gates, and planning methods. Therefore, there is a need for defining better ways to identify, record, monitor, and track the project interfaces required for adaptive reuse of buildings. Interface Management (IM) systems are a potential solution for managing the project complexities in these types of projects. Using IM in adaptive reuse projects has the potential of bringing cost and time benefits during project's execution. The present study proposes a framework for a IM in adaptive reuse projects. First, the concept of adaptive reuse and IM will be explained. Then, an ontology of interfaces for this class of projects will be defined. Finally, a discussion of how IM could be a part of a solution for adaptive reuse projects problems will be presented with a case study.

Keywords

Adaptive reuse • Interface management • Circular economy

87.1 Introduction

Due to environmental concerns, the global trend of trading in the construction industry is shifting from a resource-based economy to a Circular Economy. Adaptive reuse of buildings plays a key role in this transformation. It takes existing buildings that are obsolete, restores them, and in some cases, changes their use [1]. Adaptive reuse is considered superior to new construction in terms of sustainability [2]. However, the current implementations of adaptive reuse rely on descriptive approaches, with little objective measurement, that depend on the intuition and experience of practitioners. Intuitive planning and execution procedures are easy to apply but often lead to suboptimal results. Therefore, there is a need to define better ways to identify, record, monitor, and track the project interfaces required for adaptive reuse of buildings. The conceptualization and execution phases of adaptive reuse projects involve the integration of emergent complex processes, such as supply chain management and logistics, and require numerous work packages distributed across multiple contractors. These emergent processes follow the transformation of the construction industry towards more sustainable development through the implementation of circular building principles, such as product recovery management, Life Cycle Assessment (LCA), design for disassembly, adaptability, deconstruction, closed material loops, and dematerialization. Interface Management Systems (IMS), which focus on managing the communications, relationships, and deliverables between project stakeholders, are a potential solution for managing the complexities of adaptive reuse projects, through defining better ways to identify,

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record, monitor, and track the project interfaces. In general, IM is used in complex projects executed by a large number of stakeholders who have different specializations, with many overlapping activities; so adaptive reuse projects are a good class for IM system implementation.

87.2 Background

87.2.1 The Role of Adaptive Reuse in a Circular Economy

Due to the growing concern for the environment, design for sustainability and Circular Economy (CE) have become a requirement rather than merely a desirable characteristic for products and services in the construction industry [3, 4]. To remedy this situation, the construction industry is implementing designs and systems with improved long-term life-cycle performance. The main objective is to consider closed-loop circular design principles. Closed-loop material cycle (CLMC) in construction can be defined as recovering construction materials and building elements from old buildings and infinitely recycling them through natural or industrial processes [5]. Several studies have recognized the opportunity to minimize the negative environmental impacts in the of the End of Life (EoL) stage of buildings through Product Recovery Management (PRM) [3, 5, 6]. The main goal of PRM is to recover as much of the economic and ecological value of a product and its components as possible [6]. Additionally, several studies have demonstrated that the application of green design methods in the building industry, such as design for disassembly, design for deconstruction, planning for disassembly, and Life Cycle Assessment (LCA), presents a way to fully exploit the lifecycle expectancy of buildings and their materials/components [7–10].

The processes associated with the project management of an adaptive reuse project are diverse and dynamic. The difficulty lies in all the different aspects that have to be taken into account, such as the physical integrity of the building, economic issues, functionality, technological retrofits, social impact, and legal and political challenges [11]. The transition from the current linear economic model towards a circular one, implies a radical rearrangement of: (1) the value chain of the built environment [12, 13], (2) the ownership models for buildings [4], (3) the business models for profitability in the construction industry [14, 15], (4) the engagement of stakeholders in all the levels of society, e.g. government, suppliers, builders, and owners [16], and (5) the technical protocols and the methodologies utilized for sustainable construction [17]. For these reasons, little research has been done regarding the establishment of feasible systems for the planning [1], assessment [17, 18], and management [19] of adaptive reuse projects. Some authors stress that intuition and experience are the only guides in making decisions about adaptive reuse [20]. However, there is enough evidence to suggest that the shortcomings of adaptive reuse will be addressed in the coming years to move towards more sustainable development in the construction industry.

87.2.2 The Concept of Interface Management

There are several definitions and classifications for “interfaces” in the literature. According to the CII’s Interface Management Guideline, “interface” is defined as “a soft and/or hard contact point between two interdependent interface stakeholders”, and “interface management” is defined as “the management of communications, relationships, and deliverables among two or more interface stakeholders” [21].

When a project is divided into several sub-projects undertaken by different organizations, many interfaces occur between these organizations [22–24]. There are several different interface classifications in the literature. In this research paper, interfaces in the adaptive reuse projects will be studied under three main categories: physical, organizational, and contractual interfaces. Physical interfaces are the physical connections between two or more elements or components in a project. These are generally the easiest interfaces to notice in a project. Contractual interfaces can be defined as connections between interface stakeholders through contractual agreement. These type of interfaces can also be related with a physical interface. Organizational interfaces are the interactions between several interface stakeholders that are involved in the project. These interfaces include all the relationships and connections between any individual and any parties involved in the project throughout the project lifecycle [24, 25]. Other classifications for interfaces including soft and hard interfaces, time interface, geographical interface, and technical interface can be also found in literature [22].

A typical Interface Management System (IMS) would consist four main components: Interface Stakeholders, Interface Points (IP), Interface Agreements (IA), and Interface Agreement Deliverables (IAD). Basically, IAs are the documents that present communications and agreements between two interfaces stakeholders over an IP, and IADs are combination of the documents that are required to fulfıl related IA such as documents that show the tasks and activities completed. Generally, an IMS may include many IPs, and each IP can include many IAs, and each IA can include many IADs. Therefore, there could be numerous IADs in a system [24].

87.3 Research Methodology

This research paper is being carried out according to the following methodology steps:

1. Conduct an extensive literature review on adaptive reuse projects and define a list of barriers in these projects,
2. Conduct an extensive literature review on interface problems in construction projects and compare these interface problems to the barriers on adaptive reuse projects,
3. Pair interface problems with similar adaptive reuse barriers defined in the literature and explain them in a case study,
4. Discuss how these problems can be solved and how interface management system usage presents a solution for improving the performance of adaptive reuse projects.

87.4 Barriers in Adaptive Reuse Projects

Although adaptive reuse has many economic, social, and environmental benefits, these projects face many challenges and barriers during the project lifecycle, especially the project involves heritage buildings. Hein and Houck [26] conducted research regarding construction challenges in adaptive reuse of historical buildings in Europe, where adaptive reuse is widely practiced to preserve these historical buildings [26]. The main construction challenges explained with examples from four significant European adaptive reuse projects are: compliance with building codes and preserving laws, temporary structural support of preserved components, expectations of modern tenants such as new electrical, plumbing, HVAC systems etc., toxin removal, modification on structural integrity of the building such as modification of the structural skeleton, foundation system, or roof system, and site access problems [26].

In 2016, Conejos et al. identified fourteen barriers that occur in building type adaptive reuse projects: building codes and regulations/legal constraints, physical restrictions, high remediation costs and construction delays, complexity and technical difficulties, inaccuracy of information and drawings, maintenance, availability of materials and lack of skilled tradesmen, limited response to sustainability agenda, inertia of production and development criteria, classification change, economic considerations, social considerations, commercial risk and uncertainty, and financial and technical perceptions [27]. In this research, these barriers defined by Conejos et al. will be used as base point for defining adaptive reuse project problems. In addition to that barriers, "Management problems" is added to this list as 15th barrier.

More than half of the barriers defined by Conejos et al. [27] are due to physical interfaces between project participants such as compliance with building codes, physical constraints, complexity and technical difficulties [27]. These barriers are also a subject of interface problems in any construction projects and they can be managed by creating interface points and interface agreements between project participants in the early phases of the projects, such as the conceptual design and detailed design phases. In the case study presented in this paper, the concept and how IM system can be a solution to some of these problems is explained.

87.5 Common Interface Problems in Construction Projects

In literature, interface problems in construction projects are studied mainly under varying constraints for example limiting the study to only two parties involved to the project, or limiting the project type to a specific construction category, to a specific phase in the project lifecycle, to a country/region, or to a specific interface type, etc. In order to define the connections between common interface problems and adaptive reuse barriers, different types of articles addressing interface problems in construction projects were studied.

Interface problems between two main parties in construction projects such as interface problems between owners and contractors, designers and contractors, contractors and subcontractors, owners and maintenance contractors, owners and

Table 87.1 Comparison of adaptive reuse barriers to common interface problems

No	Type	Adaptive reuse challenges	Paper-1	Paper-2	Paper-3
1	P, C	Building codes and regulations/legal constraints	x	x	x
2	P	Physical restrictions	–	x	x
3	P	High remediation costs and construction delays	x	–	–
4	P	Complexity and technical difficulties	x	x	x
5	P, C	Inaccuracy of information and drawings	x	x	x
6	P	Maintenance	–	–	–
7	O	Availability of materials and lack of skilled tradesmen	x	x	x
8	O	Limited response to sustainability agenda	–	–	–
9	O	Inertia of production and development criteria	–	–	–
10	C	Classification change	x	x	x
11	S	Economic considerations	x	x	–
12	S	Social considerations	–	x	–
13	S	Commercial risk and uncertainty	–	x	–
14	S	Financial and technical perceptions	x	x	–
15	P, O, C	Management problems	x	x	x

designers, etc. have been studied by various researchers [28–34]. A more general research related to interface problems in construction projects was done by Al-Hammad in 2000 [35]. In the aforementioned research, which will be called as Paper-1 from this point on, nineteen common interface problems between various construction parties were defined.

Investigating interface problems that could happen during either the design phase, construction phase, or during both (aka design-construction interface) has been investigated by several researchers [36–39]. Many lists that contain design-construction interface problems are provided in various articles. For example, Sha'ar et al. [37], in a study which will be called Paper-2 from this point on, defined sixty design-construction interface problems in order to identify the causes of these problems in large building construction projects in Palestine [37]. Also, Al Mousli & El-Sayegeh [38], in a study which will be called Paper-3 from this point on, provided a list of 22 design-interface problems [38].

In order to find connections between adaptive reuse barriers and interface problems in the construction industry, the list explained in Sect. 4 of this paper, was compared with the interface problems provided in Paper-1, Paper-2, and Paper-3 individually. Comparisons are made on the basis of ideas rather than words, which means that "Inaccuracy of information and drawings" and "Mistakes and discrepancies in design documents" are accepted as being the same even though they are explained in different words. The result of these comparisons, is presented on Table 87.1.

Many of these defined barriers in Table 87.1 are related with interface points between project participants. For example, any barrier related with physical restrictions in the project would be related with physical interface points between project participants. For the purpose of this research paper, these defined barriers are also categorized into 4 interface groups which are namely: Physical interface (P), Organizational interface (O), Contractual interface (C), and out of scope group (S). The category of the listed barriers is shown in the second column of the Table 87.1.

87.6 Case Study

The case adaptive reuse project subjected to this research is a mid-20th century building built with a modern architectural style. The project is a four-story structure with a basement and has a shape similar to a boomerang with a footprint area of 1233 and 5341 m^2 gross floor area. The primary structural system of the building is a steel frame. The original building was built in 1964 and was redeveloped using adaptive reuse from 2014 to 2015. According to the heritage report of the case project, the building was classified as non-designated property of cultural heritage value. All of the building's subsystems had modifications which were primarily due to the increment of loads, the complete rearrangement of the floor layouts and the expansion of the gross floor area by 487 m^2. One of the changes included the in-filling of two large double-height rooms. The redeveloped project has been rated as a Leadership in Energy and Environmental Design (LEED) Gold Building.

The aim of this case study is to present IP examples for selected adaptive reuse barriers and interface problems documented during the realization of the case project. In order to define these IPs in the project, first project stakeholders were investigated. According to the project documents, there were seventeen stakeholders namely; Owner (OWN), Architecture (ARC), Structural Consultant (STR), Mechanical Consultant (MEC), Electrical Consultant (ELE), Landscape Consultant (LND), Civil Consultant (CVL), LEED Consultant (SD), Geotechnical Consultant (GEO), Hazardous Material Consultant (HBM), Asbestos Abatement Contractor (AAC), Finishing Hardware Contractor (FHC), General Contractor (GC), Mechanical Contractor (MECC), Electrical Contractor (ELEC), and Roofing Contractor (RC), in this project and each of them were responsible for different parts of the project.

After determining the project stakeholders and their responsibilities, IPs between these stakeholders were investigated. The documentation of the case study showed many critical IPs between the parties: the assurance of the accuracy of the technical information, drawings, and specifications for the adaptive reuse of the building. The main IPs detected were between the consultants and the designer, during the planning stage, as well as between the contractors and the consultors, during the execution of the project.

87.6.1 Physical Interfaces

As it is presented in Table 87.1, four of the physical interface related adaptive reuse barriers, namely, “Building codes and regulations/legal constraints”, “Complexity and technical difficulties”, “Inaccuracy of information and drawings” and “Management problems” are also mentioned as interface problems in the articles studied. When the documentation of the case project was investigated, it was found out that there was a continuous feedback between the consultants and the designer, as well as continuous corrections of the structural, civil, mechanical, and electrical final design through addendums to the original project. The contract specified reiteratively that the contractor should verify all dimensions and existing conditions on site and should report all discrepancies to the consultant before proceeding with the work. Also, the contract emphasized that the drawings (civil, landscape, structural, mechanical, electrical drawings, geotechnical and acoustical reports) should be read in conjunction with one another. All of these documentations are examples of “inaccuracy of information and drawing” related interface agreements.

Additionally, the fulfillment of the legal constraints related to the adaptive reuse of a building is a point of high interaction between different project parties. In these points of interaction, the responsibility of the consultants is to ensure a final design according to the current normativity, and to report any change in the pertinent timing. Because the consultants have to be aware of the existing conditions of the building asset, they have to develop an accurate and detailed inspection of the site, and then develop accurate reports, drawings, and building specifications for the other parties. It is worth to highlight that just for this kind of projects that involves the restoration of a building asset, it is necessary to create these physical interface points during the planning stage. For new construction, it is not necessary because there is not an existing asset to inspect.

Table 87.2 shows seven example interface points than can be created between the consultants and the designer, as well as the normativity established for the case study under analysis. Also, for the construction phase, the interface points presented in the table would be the same, but the communication of them should be between the contractors as interface EPC and the

Table 87.2 Interface point examples related with physical adaptive reuse barriers

Lead party	Interfacing party	IP type	IP title	Interface agreements topics
ARC	GEO	P	Geotechnical investigation	The due date
ARC	HBM	P	Asbestos removal	Construction methodology
ARC	STR	P	Column renovation	Loads that need to be considered
ARC	STC	P	Foundation Footings	Sizes and types of new footings
ARC	MEC	P	Duct design	Sizes of the ducts required,
ARC	ELE	P	Technical room	Electrical plans, voltages
ARC	VT	P	Elevator shaft	Dimensions of the elevator shaft

designer as the lead. Ideally these interface points should be created and managed from the beginning in order to secure the final accuracy, quality, and veracity of the technical information, drawings, and specifications.

87.6.2 Contractual and Organizational Interfaces

In construction projects, contractual and organizational interface points also exist as well as physical interface points. For example; in the contract between an architect and one of the contractors of the case project, it was written that "The Consultant's review of shop drawings does not relieve the Contractor of their responsibility to re-view all information pertaining to: 1. detail design; 2. dimensions; 3. information pertaining to fabrication processes; 4. techniques of construction and installation; 5. coordination of the work of Subcontractors". While this statement allocates responsibilities to the contractor, it also created contractual interface points which are also subject to physical interface points.

The main barrier in the adaptive reuse case project was related with management problems which are classified as physical, contractual, and organizational interfaces in Table 87.1. The case project ended up with cost and time overruns since it had a complex structure of project stakeholders where roles and responsibilities were unclear. The architect was responsible for both design and the management of the project which includes managing different types of consultants and contractors with subcontractors.

These problems can be solved by hiring an interface manager for the project and set-ting an IMS where IPs between project stakeholders can be defined, and IAs and IADs can be tracked more efficiently. Depending on the project size, a shared spreadsheet or a more sophisticated IMS software could be used.

87.7 Conclusion

In conclusion, depending on the project size, either a shared spreadsheet that shows interface points and related agreements between stakeholders, or a more sophisticated IMS software usage is recommended for adaptive reuse projects. The main objective behind establishing an appropriate IMS for adaptive reuse projects is to give more certainty to all the parties regarding their responsibilities in the project. When interface points between stakeholders are defined early in the project, participants can see the work packages, and deliverables can be tracked more efficiently. The workflow can also be streamlined as clear agreements between stakeholders are established. In this way, more and more participants in the construction industry would feel comfortable and secure when they get involved in these kinds of complex projects.

References

1. Langston, C., Wong, F.K.W., Hui, E.C.M., Shen, L.: Strategic assessment of building adaptive reuse opportunities in Hong Kong. Build. Environ. **43**, 1709–1718 (2008)
2. Conejos, S., Langston, C., Smith, J.: Enhancing sustainability through designing for adaptive reuse from the outset: A comparison of adaptstar and adaptive reuse potential (ARP) models. Facilities **33**, 531–552 (2015)
3. Kibert, C.J.: The next generation of sustainable construction. Build. Res. Informat. **35**, 595–601 (2007)
4. Pomponi, F., Moncaster, A.: Circular economy for the built environment: a research framework. J. Clean. Prod. **143**, 710–718 (2017)
5. Sassi, P.: Defining closed-loop material cycle construction. Build. Res. Inf. **36**, 509–519 (2008)
6. Schultmann, F., Sunke, N.: Energy-oriented deconstruction and recovery planning. Build. Res. Informat. **35**, 602–615 (2007)
7. Sanchez, B., Haas, C.: A novel selective disassembly sequence planning method for adaptive reuse of buildings. J. Clean. Prod. **183**, 998–1010 (2018)
8. Gorgolewski, M.: Designing with reused building components: some challenges. Build. Res. Inf. **36**, 175–188 (2008)
9. Yeung, J., Walbridge, S., Haas, C., Saari, R.: Understanding the total life cycle cost implications of reusing structural steel. Environ. Syst. Decisions **37**(1), 101–120 (2017)
10. Volk, R., Luu, T.H., Mueller-Roemer, J.S., Sevilmis, N., Schultmann, F.: Deconstruction project planning of existing buildings based on automated acquisition and reconstruction of building information. Autom. Constr. **91**, 226–245 (2018)
11. Conejos, S., Langston, C., Smith, J.: Designing for better building adaptability: a comparison of adaptSTAR and ARP models. Habitat Int. **41**, 85–91 (2014)
12. Ortlepp, R., Gruhler, K., Schiller, G.: Material stocks in Germany's non-domestic buildings: a new quantification method. Build. Res. Inf. **44**, 840–862 (2016)
13. Stephan, A., Athanassiadis, A.: Quantifying and mapping embodied environmental requirements of urban building stocks. Build. Environ. **114**, 187–202 (2017)
14. Lacy, P., Rutqvist, J.: Waste to Wealth: The Circular Economy Advantage. Palgrave Macmillan, London, UK (2015)

15. Lyngsgaard, S., Guldager Jorgensen, K.: Cradle to Cradle®—in the Built Environment: A Manual for the Danish Building Industry, Vugge Til Vugge Danmark and GXN with support from Realdania, Danmark, 2013
16. Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J.: The circular economy a new sustainability paradigm? J. Clean. Prod. **143**, 757–768 (2017)
17. Sanchez, B., Haas, C.: Capital project planning for a circular economy. Constr. Manage. Econ., 1–10 (2018)
18. Sanchez, B., Haas, C.T.: Methodology for improving the net environmental impacts of new buildings through Product Recovery Management (2017)
19. Nwachukwu, C.V., Udeaja, C., Chileshe, N., Okere, C.E.: The critical success factors for stakeholder management in the restoration of built heritage assets in the UK. Int. J. Build. Pathol Adapt. **35**, 304–331 (2017)
20. Highfield, D., Gorse, C.: Refurbishment and Upgrading of Buildings, 2nd edn. Taylor & Francis Group, New York, USA (2009)
21. CII RESEARCH TEAM 302, 2014: Interface Management Implementation Guide. The University of Texas at Austin, USA: Construction Industry Institute
22. Chua, D.K.H., Godinot, M.: Use of a WBS matrix to improve interface management in projects. J. Constr. Eng. Manage. **132**, 67–79 (2006)
23. Stuckenbruck, L.C.: Integration: The essential function of project management. Project Management Handbook, 2nd edn, pp. 11–21. Wiley, Hoboken, NJ (1997)
24. Shokri, S., Haas, C.T.G., Haas, R.C., Lee, S.H.: Interface-management process for managing risks in complex capital projects. J. Constr. Eng. Manage. **142**(2), 04015069 (2015)
25. Pavitt, T.C., Gibb, A.G.F.: Interface management within construction: In particular, building facade. J. Constr. Eng. Manage. **129**(1), 8–15 (2003)
26. Hein, M.F., Houck, K.D.: Construction Challenges of Adaptive Reuse of Historical Buildings in Europe. Int. J. Constr. Educ. Res. **4**(2), 115–131 (2008)
27. Conejos, S., Langston, C., Chan, E.H.W., Chew, M.Y.L.: Governance of heritage buildings: Australian regulatory barriers to adaptive reuse. Build. Res. Inf. **44**(5–6), 507–519 (2016)
28. Al-Hammad, A.: A study of the interface problems between owners and contractors over the construction of residential houses in Saudi Arabia. Hous. Sci. **14**(4), 245–257 (1990)
29. Al-Hammad, A., Assaf, S.: Design–construction interface problems in Saudi Arabia. Build. Res. Inf. **20**(1), 60–63 (1992)
30. Al-Mansouri, O.: The relationship between the designer and the contractor in Saudi Arabia, Ph.D. thesis, University of Reading, Reading (1988)
31. Al-Hammad, A.: Factors affecting the relationship between contractors and their sub-contractors in Saudi Arabia. J. Perf. Constr. Fac., ASCE, **21**(5), 194–205 (1993)
32. Hinze, J., Andres, T.: The contractor–subcontractor relationship: the subcontractor's view. J. Constr. Eng. Mgmt., ASCE, **120**(2), 274–287 (1994)
33. Al-Hammad, A.: Interface problems between owners and maintenance contractors in Saudi Arabia. J. Perf. Constr. Fac., ASCE, **9**(3), 194–205 (1995)
34. Al-Hammad, A., Al-Hammad, I.: Interface problems between building owners designers. J. Perf. Constr. Fac., ASCE, **10**(3), 123–126 (1996)
35. Al-Hammad, A.: Common interface problems among various construction parties. J. Perform. Constr. Facil. **14**(2), 71–74 (2000)
36. Arain, F., Sui, P., Assaf, S.: Consultant's prospects of the sources of design and construction interface problems in large building projects in Saudi Arabia. Environ. Des. Sci. **5**(2), 15–37 (2007)
37. Sha'ar, K.Z., Assaf, S.A., Bambang, T., Babsail, M., El-Fattah, A.M.A.: Design–construction interface problems in large building construction projects. Int. J. Constr. Manage. **17**(3), 238–250 (2016)
38. Al-Mousli, M.H., El-Sayegh, S.M.: Assessment of the design–construction interface problems in the UAE. Archit. Eng. Des. Manage. **12**(5), 353–366 (2016)
39. Vanegas, J.A., Opdenbosch, A.: Using simulation and visualization technologies to strengthen the design/construction interface, Winter Simulation Conference Proceedings, pp. 1137–1144 (1994)

Semantic Enrichment of As-is BIMs for Building Energy Simulation

88

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Abstract

Recent efforts on automatic 3D modeling of existing buildings often result in semantically poor as-is building information models (BIMs). Such a BIM usually consists of a set of objectified surfaces characterized by the building element types they represent and 3D surface geometries. It cannot be directly used as the geometry input of building energy modeling (BEM) as the key concepts of second-level space boundaries (SBs) are missing. This paper proposes a semantic enrichment approach for automatically adding such semantic concepts inferred from the semantically poor as-is BIM. The output of this approach is a corresponding IFC BIM with second-level SBs, which can be further used by various energy simulation tools. Preliminary experimental results using a building surface model demonstrate the performance of the proposed approach.

Keywords

Semantic enrichment • Second-level space boundary • Building information modeling
Building energy modeling • Existing buildings

88.1 Introduction

Energy retrofits of existing buildings play a significant role in reducing global energy consumption [1, 2]. In an energy retrofit project, building energy modeling (BEM) is commonly used for assessing actual building performance, diagnosing malfunctioning building systems, and prioritizing various retrofit strategies quantitatively [2, 3].

Recent efforts have been conducted in automatic 3D modeling of existing buildings for BEM purpose, due to the inaccuracy and labor inefficiency of current manual BEM input preparation practice [4–8]. In these efforts, state-of-the-art surveying technologies such as laser scanning and photogrammetry are widely used to capture the as-is conditions of buildings. The outputs (as-is BIMs) generally consist of recognized building components with reconstructed 3D geometries of their visual surfaces [5–7, 9]. As summarized in [10], there are two main limitations in these efforts from the view of geometric modeling of existing buildings for BEM purpose. First, existing efforts generally focus on reconstructing building components of specific building parts, such as building facades [5, 7], interior spaces [9], or surrounding shades [6]. Thus, their outputs only support some preliminary energy analysis (e.g. building orientation and shading analysis) and cannot be used for the detailed whole-building energy simulation that requires complete building geometry descriptions. Second, their outputs usually lack semantic information required by BEM, especially the concept of second-level space boundary (SB). In BEM, the building geometry is depicted as a collection of objectified SBs, which specify the topological relationships between spaces and their surrounding building elements, space boundary geometries and other related attributes (see

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Sect. 88.2) [12]. However, the results produced by existing efforts only contain the element type that each reconstructed visual surface represents and the corresponding 3D geometry.

To address these limitations, Ying et al. [10] proposed an image-driven framework for automatically constructing complete BEM geometry models for existing buildings. Specifically, that framework aims at directly generating IDF-based models from images for the dedicated building energy performance (BEPS) tool called EnergyPlus.

This paper refines that framework by redesigning the semantic enrichment module to generate as-is IFC BIMs with second-level SBs. These second-level SBs define building geometry data required by BEM in IFC format, which can be further extracted and directly mapped to internal data models of various BEPS tools. In other words, this improvement enables the access of as-is BEM geometry data by various BEPS tools, as IFC is an open and neutral format to support life-cycle BIM data exchange [12]. The proposed semantic enrichment approach takes semantically poor as-is models of existing buildings as an input. Such a model consists of a set of visual surfaces of the entire building. Each surface only carries the information (i.e. building element type it represents and corresponding 3D surface geometry) that can be obtained by most existing as-is modeling efforts (e.g. [5, 6, 9]). The proposed approach consists of a set of rules and computational geometry algorithms, which are developed to infer the second-level SBs and other semantic requirements based on the inputs.

The rest of the paper is structured as follows: Sect. 88.2 explains the semantic requirements of as-is BIMs for BEM; Sect. 88.3 details the proposed semantic enrichment approach; Sect. 88.4 reports a preliminary experimental validation; and Sect. 88.5 concludes this paper with a discussion on the limitations and future work.

88.2 Semantic Requirements

In most BEPS tools, building geometry is defined as a collection of second-level SBs [11]. In IFC, a SB is defined as an objectified relationship by IfcRelSpaceBoundary. To standardize the definition and processing of SBs, a dedicated model view definition (MVD) based on IFC 2 × 3 specification called Space Boundary Add-on View has been published by buildingSMART [13]. In this paper, IFC4 is used as the base specification, as it introduces a new entity called IfcRelSpaceBoundary2ndLevel [14]. Compared to IfcRelSpaceBoundary, this entity stores two additional types of relationships required by BEM: (1) the relationship between pairwise type 2a SBs; and (2) the relationship between a SB of an opening element and the SB of the wall that hosts the opening.

This study designs a dedicated IFC data structure with specific IFC entities (see Fig. 88.1) to store enriched as-is BIM data. In addition, Fig. 88.1 also lists the attributes of relevant entities (except entities in red dashed box) used for storing necessary information. Two attributes (i.e., GlobalID and ObjectPlacement) are used for the entities in red dashed box. The structure design is based on three principles: (1) storing minimal information required for the definition of SBs; (2) keeping consistent with existing energy analysis-related MVDs; and (3) satisfying syntactic constraints from IFC4 specifications.

Except the computation of second-level SB geometries (see the green dashed box in Fig. 88.1), the semantic information that need to be added can be classified into two groups:

Semantic information required by the definition of second-level SBs. This information is required by the attributes of IfcRelSpaceBoundary2ndLevel, including:

(1) GlobalID: assigning a unique identifier for specifying the SB.
(2) Description: specifying the type of the SB in terms of “2a” or “2b”. The SB is type 2a if there is a space on the other side of the building element providing this SB; type 2b, otherwise [13]. The heat transfer between the space that the SB bounds and the space on the other side can occur in the first case, but not in the second case. Therefore, an input surface may need to be spilt into several pieces, in accordance with these concepts.
(3) RelatingSpace: specifying the space object that this SB bounds. The space object can either be an internal space defined by IfcSpace or the outdoor environment by IfcExternalSpatialElement.
(4) RelatedBuildingElement: specifying the building element that provides this SB.
(5) PhysicalOrVirtualBoundary: specifying whether this SB is physical (i.e. provided by a physical element such as walls and slabs) or virtual (i.e. provided by a virtual element such as virtual space separators).
(6) InternalOrExternalBoundary: specifying whether this SB is external (i.e. provided by an external element) or internal (i.e. provided by an internal element).
(7) ParentBoundary: for a SB of an opening (i.e. window or door), specifying the parent SB (usually a SB of a wall) that hosts this SB; for a SB of a shading device, specifying the parent SB that this SB is attached to.

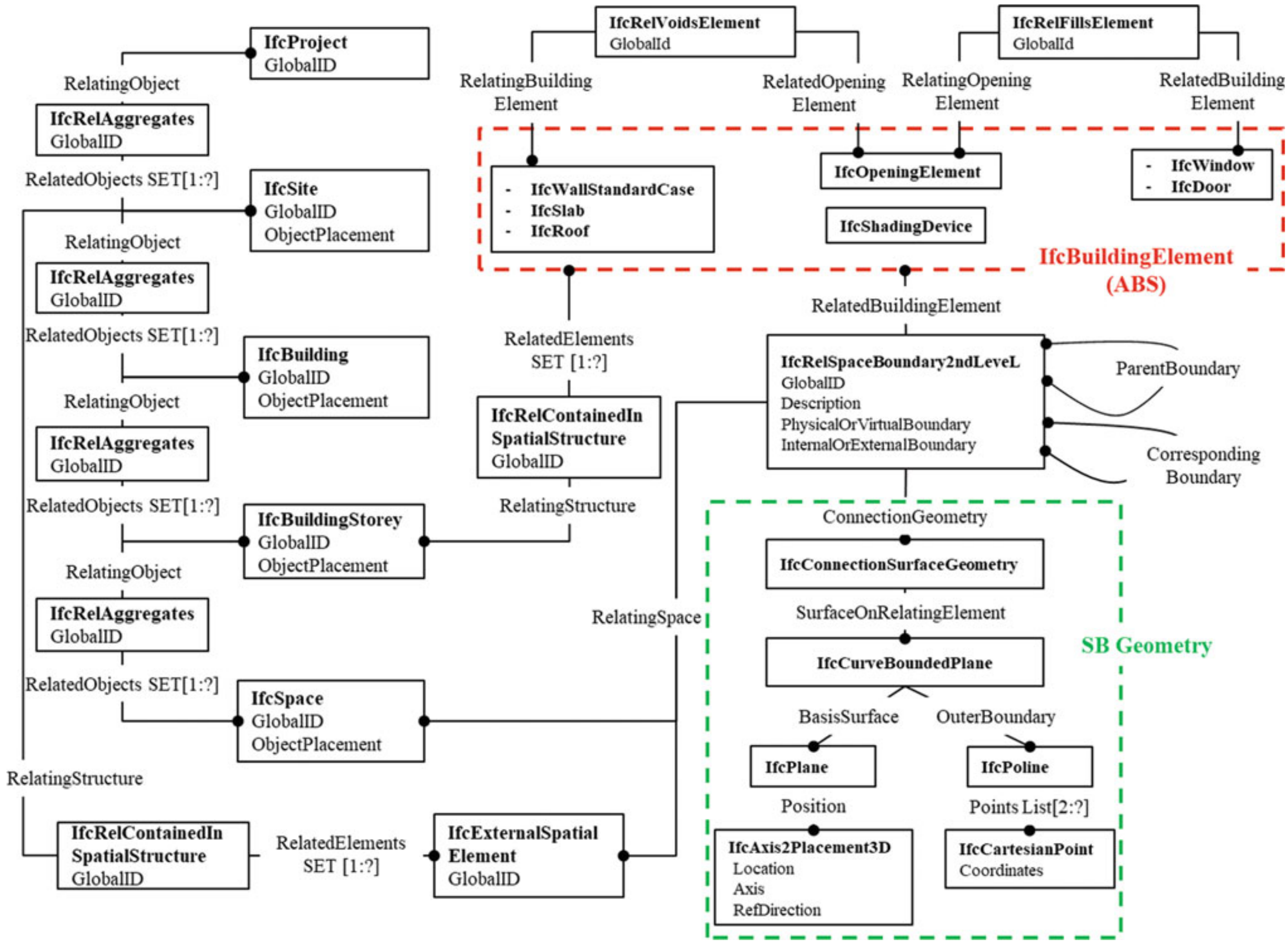

Fig. 88.1 The IFC data structure to store semantically enriched as-is BIM data *Note* Beams, columns and curtain walls are not considered yet in this paper

(8) CorrespondingBoundary: only for a type 2a SB, specifying the symmetrical SB on the other side of the building element providing this SB.

Semantic information required by syntactic constraints of IFC4 specifications.

(1) IFC Root and spatial objects: Entities required to maintain the hierarchical structure, including IfcProject, IfcSite, IfcBuilding, and IfcBuildingStorey.
(2) Aggregation relationships: the one-to-many aggregation relationships including IfcProject-IfcSite, IfcSite-IfcBuilding, IfcBuilding-IfcBuildingStorey and IfcBuildingStorey-IfcSpace should be correctly defined by IfcRelAggregates.
(3) Containment relationships: the one-to-many containment relationships including IfcBuildingStorey-IfcBuildingElement and IfcSite-IfcExternalSpatialElement should be correctly defined by IfcRelContainedInSpatialStructure.
(4) Topological relationships: the topological relationships between physical elements and their hosting opening elements should be correctly defined via IfcRelVoidsElement and IfcRelFillsElement.

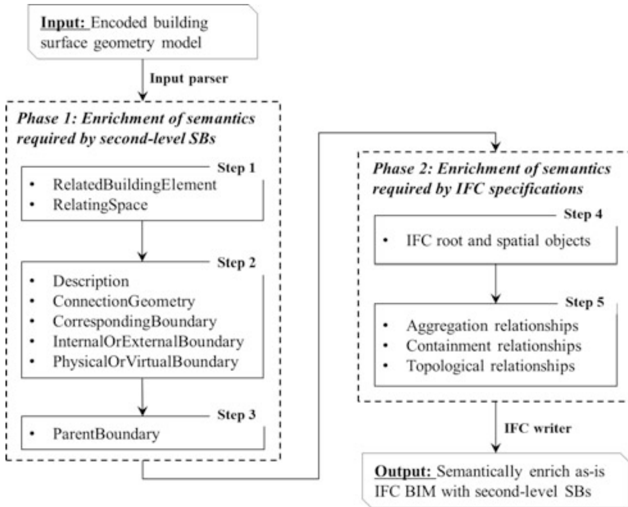

Fig. 88.2 Proposed semantic enrichment approach for as-is BIM

88.3 Semantic Enrichment Approach

The proposed approach for automatically enriching semantically poor as-is models includes two primary phases (see Fig. 88.2): enrichment of semantics required by second-level SBs (see Sect. 3.2) and enrichment of semantics require by IFC specifications (see Sect. 3.3).

The semantic enrichment process is progressive as some semantic information triggers other semantics. Specifically, the geometries of surfaces in the input model are defined by the following rules to ensure a correct surface normal, which is essential to the process: polygon vertices of an exterior surface follow a clockwise order (viewed from outdoor); while, polygon vertices of interior surfaces follow a counter-clockwise order (viewed from interior spaces).

88.3.1 Enrichment of Semantics Required by Second-Level SBs

Step 1: Add semantics of "RelatingSpace" and "RelatedBuildingElement". The core of this step is to recognize the space that an input surface bounds and the building element that provides it. The recognized space and element are then added to the objectified surface and can be directly inherited by corresponding SBs split from this surface in the next step.

Space recognition. The input surface sets are firstly classified into three groups: surfaces of building exterior, surfaces of interior non-opening elements, and surfaces of interior openings. For the first group of surfaces, an outdoor space object is logically created and then attached to all surfaces via a new attribute "RelatingSpace".

For surfaces in the second group, a Monte Carlo-based ray tracing algorithm is developed to infer spaces that they bound. The basic idea of the algorithm is described as follows. First, for a surface, a set of rays emitted from the back side (i.e. the side viewed from reverse surface normal direction) of the surface are generated by using Monte Carlo technique. Second, all the surfaces that these rays first hit are detected and reserved after removing the duplicates. Third, for each detected surface, a recursive function consisting of previous two steps is conducted. The recursive operations end when no new surfaces are found. So far, all surfaces bounding the same space with the selected surface are found. Then a corresponding space object is logically created and assigned to these surfaces. The next step is to update the original group by removing the grouped surfaces and start new iterations to cluster all remaining surfaces in spaces.

After processing the second group, all space objects in building interior are recognized. The space object bounded by an opening surface in the third group is identical to the space bounded by the non-opening element surface hosting the opening surface. The exact non-opening element surface can be detected by the following computational method: first, filtering out the surfaces in the second group that are not coplanar with the opening surface; second, examining whether each surface remained in the second group contains the opening surface geometrically.

Building element recognition. Although the element type of each surface is known (given in the input), its corresponding building element remains unknown. Rather than re-constructing the solid geometry, building element recognition, in this paper, aims to group the surfaces belonging to a comment element logically. In order to achieve this objective, this study developed a set of rule-based algorithms. Specifically, rule sets are established respectively for the recognition of different types of building elements (e.g., walls, roofs, slabs, windows, doors, and shading devices). As an example, for an opening surface S_O, another corresponding surface are recognized by checking whether the following rules are satisfied: SameSurfaceTypeWith (S_O), ParallelWith(S_O), DistanceWith(S_O) < *dist* (a constant slightly larger than the thickness of openings), and AfterProjectionOverlapWith (S_O). After all surfaces are grouped, corresponding building elements can be logically created and assigned to relevant surfaces via "RelatedBuildingElement".

Step 2: Add semantics of "Description", "ConnectionGeometry", "CorrespondingBoundary", "InternalOrExternal", and "PhysicalOrVirtual". This step is to compute second-level SBs including geometries and all the remaining semantics except ParentBoundary. The SBs are created at the building element level, more specifically, by processing surfaces belonging to a common building element.

For surfaces of opening elements, the SBs are directly inferred as each surface corresponds to a SB. The rules for defining a SB of an opening are detailed as follows:

- "Description": "2a";
- "ConnectionGeometry": the geometry of the corresponding surface;
- "CorrespondingBoundary": another SB provided by the same element;
- "PhysicalOrVirtual": "Physical";
- "InternalOrExternal": if the surface comes from the building interior, then the value is "Internal"; otherwise, "External".

The concept of second-level SBs is extended for shading elements. Input surfaces of shading elements are directly defined as corresponding SBs by the following rules:

- "Description": "ShadingDevice";
- "ConnectionGeometry": the geometry of the corresponding surface;
- "CorrespondingBoundary": Null;
- "PhysicalOrVirtual": "Physical";
- "InternalOrExternal": "External".

A computational geometry approach is developed to compute relevant SBs for surfaces of other building elements (i.e. walls, slabs, roofs). The basic idea of this approach is described as follows. First, a surface (*S*) from the set of surfaces (*Ss*) of a common building element is selected. Second, all the remaining surfaces are projected on the plane of *S*. Third, the intersection parts and difference parts between *S* and all other projected surfaces are computed. Fourth, SBs ("Description" and "ConnectionGeometry") from *S* are defined by using the following rule: each intersection part refers to a "2a" SB and each difference part a "2b" SB. Fifth, the previous four steps for all other surfaces in *Ss* are repeated to split all these surfaces into corresponding SBs. Finally, the following semantics are added to each SB:

- "CorrespondingBoundary": for a "2b" SB, the value is null; for a "2a" SB, the corresponding SB is another "2a" SB of the related element, which fully overlaps this SB on the plane perpendicular to the surface normal;
- "PhysicalOrVirtual": if the related element is a virtual element, then the value is "Virtual"; otherwise, "Physical".
- "InternalOrExternal": if the original surface comes from building exterior, the value is "External"; otherwise "Internal".

To ensure the correct geometric definition of these SBs, two additional operations are performed. First, the geometry of a SB should be a simple polygon without holes. In this paper, the SBs with holes generated from the above algorithms are further triangulated to remove those holes. Second, a SB should be defined with an outward surface normal. If not, the order of the vertices of corresponding polygon will be reversed.

Step 3: Add semantic of "ParentBoundary". This step is to add the semantic information required by ParentBoundary to each SB output from Step 2. This attribute is only needed for SBs of opening elements and shading devices. The parent boundary (*PSB*) of an opening SB (*OSB*) refers to the SB of a wall that hosts the particular SB. Geometrically, *OSB* is fully contained in *PSB*. A two-step method is developed to assist the detection of *PSB* for *OSB*: first, find out SBs (*CandinateSBs*) that are coplanar with *OSB*; second, examine each SB in *CandinateSBs* until the SB that geometrically contains *OSB* is found. The *PSB* of a SB of an attached shading element refers to the SB of a wall that the element is attached to. It can be detected by checking whether a SB of a wall geometrically contains an edge of this SB.

88.3.2 Enrichment of Semantics Required by IFC Specifications

Step 4: Create IFC root and spatial objects. This step aims to create objects required by IFC specifications for maintaining the IFC hierarchical structure. These objects include IFC root object (Project) and spatial objects (i.e., Site, Building, Building Storey). Objects including Project, Site, and Building can be directly created by using IfcProject, IfcSite, and IfcBuilding entities respectively. Note that a Project may contain more than one Site, which also may contain more than one Building. For the sake of simplicity, this paper assumes that there is one Building and one Site. The building stories are inferred by the gaps between the boundary geometries (i.e. geometries of the surfaces bounding the spaces) of spaces in the vertical direction.

Step 5: Create aggregation, containment and topological relationships. In this step, three types of relationships are created to link generated IFC objects. The aggregation relationships of IfcProject—IfcSite, IfcSite—IfcBuilding, and IfcBuilding—IfcBuildingStorey are defined using the entity IfcRelAggregates. The aggregation relationship between a building storey object and all the space objects in this storey are also defined by IfcRelAggregates. The one-to-many containment relationship between a building storey and all the building elements in this storey is defined by IfcRelContainedInSpatialStructure. This relationship is computed based on relevant SBs and the aggregation relationships between building stories and space objects. SBs provide linkages between a building element and spaces that the building element bounds. The building storey that the building element stands in can thus be determined through the aggregation relationships of building storey—spaces. The topological relationships between opening elements and non-opening elements that host them need to be explicitly reserved. Procedures for computing this type of relationships are as follows. First, all SBs (i.e., *BSBs*) provided by the building element are found via the attribute RelatedBuildingElement of SBs. Second, all SBs (i.e., *OSBs*) of opening elements are found. Third, for each SB in *OSBs*, a check whether its parent boundary matches any SB in *BSBs* is implemented. If so, it means that the opening element is hosted by the building element.

88.3.3 Enriched IFC Model Generation

All the objects, attributes and relationships created so far are ready to be defined with corresponding IFC entities and output as an IFC instance file. The hierarchical coordinate systems of an IFC model are defined through the attribute ObjectPlacemnt of IfcSite, IfcBuilding, IfcBuildingStorey, and IfcSpace. To simplify this process, all these coordinate systems are set to be same with the coordinate system of the input surface geometry model. In this way, there is no need to compute transformation relationships between two linked coordinate systems. It is important to note that a SB needs to be defined in a specific coordinate system, which is relative to the coordinate system of the space that the SB bounds.

88.4 Approach Implementation and Validation

To prove the feasibility of the proposed approach, a prototype application was implemented in C# programing language. The IFC Engine DLL [15] was used as the IFC writer to save the output in IFC. A building surface model was manually prepared for an experimental test from a two-story building (see Fig. 88.3a). This model consists of 65 surfaces covering all the types of building elements targeted in this paper. All these surfaces were coded by the schema “SurfacePosition(Interior/Exterior) SurfaceType SurfaceGeomerty” and saved in a txt file, as shown in Fig. 88.3b.

The prototype application parsed and processed the test model and generated a corresponding IFC file with second-level SBs. In the IFC file, a total of 201 second-level SBs including 78 “2a” SBs, 121 “2b” SBs (including 112 triangulated “2b” SBs), and 2 “ShadingDevice” SBs were saved. 6 spaces that these SBs bound, 8 walls, 2 slabs, 5 doors, 6 windows, 2 shading elements and 1 roof that provides these SBs are identified. Furthermore, other objects (i.e. IfcProject, IfcSite, IfcBuillding, and IfcBuildingStorey) and their relationships (i.e. the aggregation, containment and topological relationships specified in Sect. 2) are also correctly defined in the IFC file, as shown in Fig. 88.4a. Figure 88.4b, c display the geometries of the second-level SBs of building exteriors and interiors respectively.

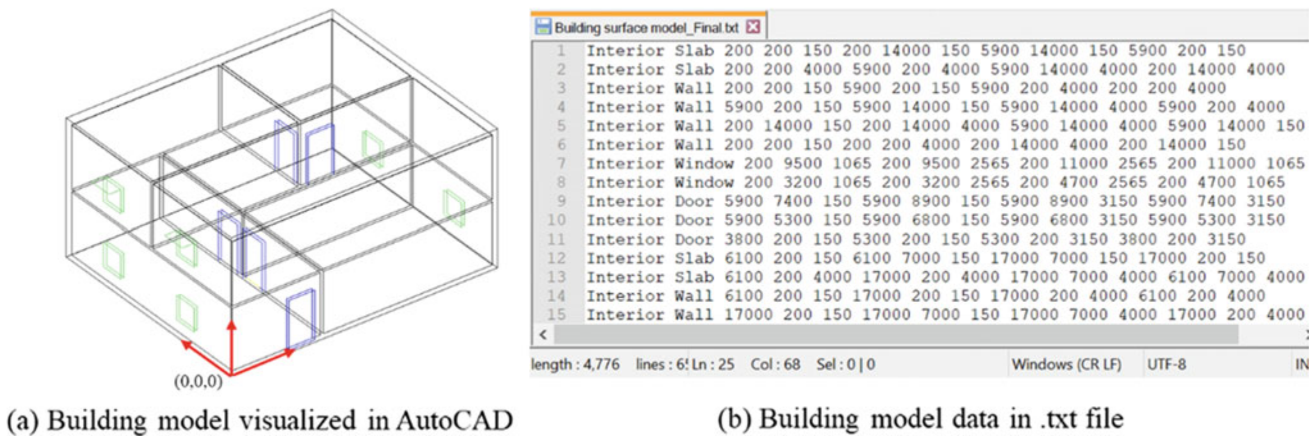

Fig. 88.3 The test model and its input data

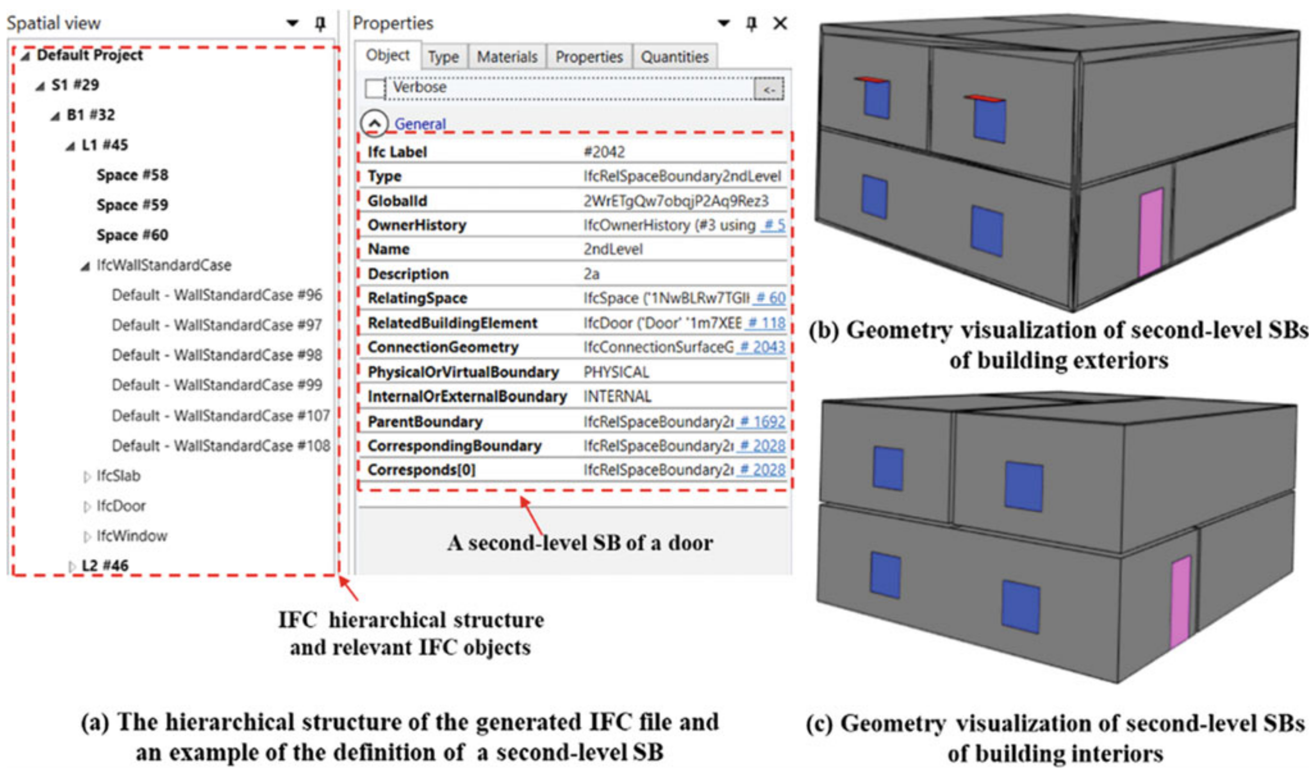

Fig. 88.4 The output IFC BIM *Note* in **b** and **c** SBs are colored based on the building element types (window-blue; door-pink; shading element-red; others-gray)

88.5 Conclusions and Future Work

Recent efforts on using state-of-the-art surveying technologies to construct as-is BIMs of existing buildings often result in semantically poor surface geometry models. However, such surface models cannot be directly used as the geometry input for building energy simulations, since the key concept of second-level SBs has not been established. This paper proposed a progressive approach for automatically computing such semantic concepts based on those surface models. The proposed approach provides procedures for constructing semantic as-is IFC BIMs from surface representations of existing buildings.

In addition, the developed processes and methods for inferring spatial objects, building elements, aggregation relationships, containment relationships and topological relationships are applicable to the generation of IFC-based BIMs from scratch. A prototype application was developed and preliminary experimental results using a building surface model demonstrate the feasibility of the approach.

This approach has some limitations to be addressed in future. First, this approach requires that the surface geometries should be appropriately defined to satisfy specific requirements on surface normal. However, this may not be assured by the input models. An automatic pre-checking and correction method is suggested. Second, this approach is limited to processing polygonal surfaces. Curved surfaces need to be manually segmented. Third, the approach considers the building elements essential to BEM only. Some interior elements like ceilings that are usually found in existing buildings have not been considered. Finally, some algorithms in this approach need to be improved to address various cases in real-word buildings. For example, the algorithm for clustering surfaces of slabs assumes that there is only one slab in a building story, which is not always common in the practice.

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References

1. Sustainable Buildings and Construction Programme. http://web.unep.org/10yfp/programmes/sustainable-buildings-and-construction-programme. Accessed 16 Apr 2018
2. Ma, Z., Cooper, P., Daly, D., et al.: Existing building retrofits: methodology and state-of-the-art. Energy Build. **55**, 889–902 (2012)
3. Sanhudo, L., Ramos, N.M., Martins, J.P., et al.: Building information modeling for energy retrofitting-a review. Renew. Sustain. Energy Rev. **89**, 249–260 (2018)
4. Cho, Y.K., Ham, Y., Golpavar-Fard, M.: 3D as-is building energy modeling and diagnostics: a review of the state-of-the-art. Adv. Eng. Inform. **29**(2), 184–195 (2015)
5. Wang, C., Cho, Y.K., Kim, C.: Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. Autom. Constr. **56**, 1–13 (2015)
6. Díaz-Vilariño, L., Lagüela, S., Armesto, J., Arias, P.: Semantic as-built 3D models including shades for the evaluation of solar influence on buildings. Sol. Energy **92**, 269–279 (2013)
7. Cao, J., Metzmacher, H., O'Donnell, J., et al.: Facade geometry generation from low-resolution aerial photographs for building energy modeling. Build. Environ. **123**, 601–624 (2017)
8. Ham, Y., Golparvar-Fard, M.: Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. Autom. Constr. **49**, 214–224 (2015)
9. Xiong, X., Adan, A., Akinci, B., Huber, D.: Automatic creation of semantically rich 3D building models from laser scanner data. Autom. Constr. **31**, 325–337 (2013)
10. Ying, H., Lu, Q., Zhou, H., Lee, S.: A framework for constructing semantic as-is building energy models (BEMs) for existing buildings using digital images. In: ISARC, Berlin, Germany (2018)
11. Bazjanac, V.: Space boundary requirements for modeling of building geometry for energy and other performance simulation. In: 27th International Conference on CIB W78, Cairo, Egypt (2010)
12. International Organization for Standardization, ISO 10303-11: Industrial automation systems and integration—Product data representation and exchange—Part 11: Description methods: The EXPRESS language reference manual (2004). https://www.iso.org/standard/38047.html. Accessed 16 Mar 2018
13. Häfele, K.H., Liebich, T.: IFC2x3 space boundary implementation guide summary (2010)
14. BuildingSMART, IfcRelSpaceBoundary2ndLevel. http://www.buildingsmart-tech.org/ifc/IFC2x4/rc2/html/schema/ifcproductextension/lexical/ifcrelspaceboundary2ndlevel.htm. Accessed 14 Mar 2018
15. RDF, IFC Engine DLL. http://rdf.bg/ifc-engine-dll.php. Accessed 01 Dec 2017

Proof of Concept for a BIM-Based Material Passport

89

Iva Kovacic, Meliha Honic, and Helmut Rechberger

Abstract

Building stocks and infrastructures are representing the largest material stock of industrial economies. In order to minimize the use of primary resources and the dependency on imports, "Urban Mining" strategy aims to recycle these urban stocks. For enabling of higher recycling rates detailed knowledge about the composition of building stocks in needed. Recyclability is also determined through design and is depending on constructive criteria defining accessibility and separability of building components, whereby the early design-stage plays an important role. In order to optimize the recycling potential and material composition of buildings, new design-centric tools and methods are required. The so called Material Passports represent such tools, which next to the design optimization would enable circular economy in the building industry. In this paper we will present the results of funded research project BIMaterial: Process design for BIM-based, Material passport. The main aim of this research is to create a BIM-based Material Passport for the optimization of the building design regarding resources use and documentation of materials, thereby using Building Information Modelling as knowledge base for geometry and material properties and coupling to further databases for assessment of ecologic footprint and recycling potentials. Thereby a framework for modelling and methodology for semi-automated Material Passport assessment will be proposed. As the methods and structured data that would allow an automated creation of a Material Passport are still lacking, therefore the current research has an innovative character and closes a research gap in this field.

Keywords

Circular economy • Digital tools • Resources efficiency

89.1 Introduction

Global material resources consumption is increasingly rising as well as the world's population; thereby the future challenge will be to provide sufficient land, material and natural resources; as well as to deal with upcoming waste.

Building stocks and infrastructures are the largest material stock of industrial economies. It is of long-term importance to maintain or frequently recycle these urban stocks, and in consequence to minimize the use of primary resources and thus the dependency on imports—a strategy labelled as "Urban Mining". The increased application of construction materials with some delay triggers the equivalent increase in solid waste generation. Considering the average lifetime for construction products to be 40–50 years, a significant increase in solid waste generation is to be expected within the next decades. The only response to the challenge of landfill shortages can be the consequent increase of recycling and re-use rates. For higher

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recycling rates, it is vital to have detailed knowledge about the composition of both building stocks and construction wastes. Recyclability changes over time, as it is a function of technological development and resource markets. Building design has also a strong impact on recyclability, which depends on constructive criteria defining accessibility and separability of building elements (or its parts). Currently we lack knowledge on exact composition and construction of building stocks, representing a major obstacle for optimization of recyclability of build-in materials and thereby increase of recycling rates.

Powerful computational technologies and tools such as Building Information Modeling (BIM) and Geographical Information Systems (GIS) offer large potentials for modeling and analysis of both new construction and building stocks in terms of material composition, and creation of so called material cadaster, for which a Material Passport (MP), as documentation of material composition of a single building builds a fundament.

The main research question is how to efficiently model, analyze, and optimize predict the material flows within a building, particularly with regard to the assessment of material masses and the reduction of landfill waste in order to increase re-use and recyclability?

In this paper we will present the results of funded research project BIMaterial: Process design for BIM-based MP. The main aim of this research is to create a BIM-based MP for the optimization of the building design regarding resources use and documentation of materials, using BIM as knowledge base for geometry and material properties and coupling to further databases for assessment of eco-indicators and recycling potentials. Thereby a modelling methodology and workflow for semi-automated MP assessment will be proposed.

89.2 Literature Review

Life Cycle Analysis (LCA) and analysis of resources and material-composition of buildings stand in close relationship. The LCA is a general assessment of environmental impacts of buildings along the life-cycle and considers the environmental impacts of production process, transport, renewal, and finally recyclability or waste management of materials in terms of indicators such as global warming potential, primary energy consumption and further. The most common LCA-method is the process analysis method, whereby the direct and indirect energy inputs in each product process are evaluated. The LCA method is determined by the International Organization for Standardization (ISO) Standard 14040:2006, which describes the principles, the framework and temporal and spatial system limits of the LCA. Further, the main phases of LCA are explained, which imply the goal and scope definition, the inventory analysis, the impact assessment and the interpretation phase.

BIM-use for life cycle analysis in the design stage has been of increasing interest in the research community. BIM as emerging tool bears large potentials in terms of process-automation. Azhar et al. [3] carried out a thorough analysis of BIM-fitness for sustainability assessment using Leadership in Energy and Environmental Design (LEED) rating analysis. Thereby they established a procedural framework for the environmental analysis that can be conducted using a BIM-model, and LEED credit requirements. However, an automated work-flow is not possible, due to lack of LEED features integrated in the software.

Geyer and Buchholz [9] developed an innovative urban system model frame-work that follows a holistic approach, whereby both, energy and resources, are evaluated. This approach is described as Parametric Systems Modelling (PSM) and is based on the System Modeling Language (SysML). SysML is a design-oriented modelling approach, which supports geometry-based CAD. SysML considers multidisciplinary information and parametric interdependence. The results are displayed as flow chart, where energy, water and CO_2 emissions and dependencies are shown. However, the resulting system-model is a non-geometric model and the process is not automated.

Accomplishing a LCA is a challenging task, since information about the material composition of buildings and the production process of the materials is lacking. Apart from that, the manual input of life cycle inventory data for every material is an obstacle [6], for which the integration of BIM and LCA software might represent a solution, since it is possible to integrate material specifications and conduct quantity take-offs in BIM [1]. However, there still exists lack of data interoperability between BIM and LCA-tools as well as the problematic of inaccessibility and complexity of LCA inventories and tools [13]. LCA tools have to be built into BIM-software to get standardized implementation of LCA and improve data exchange [8]. Coupling LCA databases to the BIM-tools could also overcome the obstacles.

BIM as information rich model of a building shows large potentials for the automated generation for both LCA and MP. Prins et al. [18] described and evaluated in a research several Circular Economy cases in the Netherlands. One use case was an educational building, which required a renovation. Therefore a resource passport has been created in form of a digital BIM.

BIM has also been identified as tool for minimizing the amount of Construction and Demolition waste (C&D waste) [21]. As C&D waste is growing continuously, it receives big attention from practitioners and researchers around the world [14]. BIM shows big potential for reducing design errors, rework, and unexpected changes.

However, automated generation of MP as well as automated LCA from BIM are still facing numerous challenges. Major challenges are LCA-data accessibility and automated coupling of BIM-models (and object libraries) with LCA inventories. Further on, current LCA inventories are including eco-indicators regulated by ISO. These inventories are generally lacking information on recyclability or separability of materials within building elements or between elements, which is a crucial information for the MP. Although BIM shows large potentials as optimization and documentation tool of material composition of a building as well as for an automated creation of LCA, a method for an automated creation of a MP is still lacking, therefore the current research addresses innovative approach in this field.

89.3 Methodology

Based on our previous research [22] through testing of software for semi-automated BIM supported LCA on a case study, we have decided for generation of semi-automated MP through coupling of BIM with the data management and analysis tool BuildingOne (BO). We are using the data management approach of linking the model with the external eco-databases through BO, instead of integrating the data in the model itself.

For the compilation of a MP numerous databases provide data for the composition of construction elements, their recycling potential and eco-indicators. The main obstacle when using data from different databases is the inconsistent naming and structuring of products and materials, which leads to incoherencies in data transfer. In order to guarantee for consistency of data regarding eco-indicators as well as indicators of recyclability and separability, we use only data provided by Austrian Institute for Building (IBO), and their corresponding databases baubook or tools such as eco2soft [10].

In the first step the scope of necessary information was defined, which on the one included expert—interviews (demolition companies, material recycling union, material industry) and on the other was based on the knowledge generated in the project "Christian Doppler Lab". As MP will be compiled at the conceptual-structural level, and is regarding short-term as well as long-term benefits, where as raw material extraction and upcoming of waste should be minimized. The MP should address resources and material efficiency along the life cycle of a building, and will thereby be developed for four stages:

MPa is addressing conceptual design phase. This stage has the largest impact on life-cycle performance regarding re-usability of the building elements and materials as well as on upcoming waste. Thereby the optimization potential is the largest at this stage, as is the importance of MP a as design-optimization tool.

MPb is addressing the preliminary design phase, as planning-optimization tool and support for design for deconstruction, as well as to compile a deconstruction concept.

MPc is completed in tendering stage in order to assess the exact material composition.

MPd is representing a final document on material inventory of a building and is delivered at the handover to the operation.

A methodology for modeling is proposed upon national BIM-standard (Austrian BIM-standards ÖNORM 6241-1 and 6241-2), defining Level of Development (LOD) and Level of Detail (LoD) of a BIM-model. The proposed framework defines the necessary LOD along various design stages. Thereby the material matching and coupling with state-of-the art LCA-data inventories is carried out according to the granulation of LOD.

For the compilation of MP a LCA methodology is applied. LCA focuses on evaluating the total environmental impacts of buildings over their entire life cycles. The environmental impacts occur throughout several life cycle stages—production, transport, operation and end-of-life scenarios. The LCA assessment as proposed by building certificates or IBO assesses the three most important indicators as environmental impacts: Global Warming Potential (GWP)—CO_2 equivalent, Acidification Potential (AP) and Primary Energy Intensity (PEI), consisting of Non-Renewable and Renewable parts. For the compilation of MP additional indicators have to be assessed such as reusability, recyclability and separability; which are also proposed by IBO.

BO was chosen as powerful database and management tool, enabling bi-directional data exchange with BIM-model, thus all of the geometry or material changes can be carried out either in the model or in the database; as a tool for material-inventory and LCA assessment; and was tested for such use for the first time; as originally the software tool is developed for asset management. Further on BO enables the creation of Rule Sets for the assessment of quantities and LCA, thus supporting automated compilation of MP, once Rule Sets have been created and materials matched. Thereby the properties needed for LCA were generated in the BO tool. The results of the conducted test studies show that the data exchange between the BIM-software and the tool works properly [23]. Based on the insights of the study, requirements for generating a BIM-based MP and a proper workflow were developed. A workflow description will be presented in detail in Chap. 4.

89.4 Workflow Design

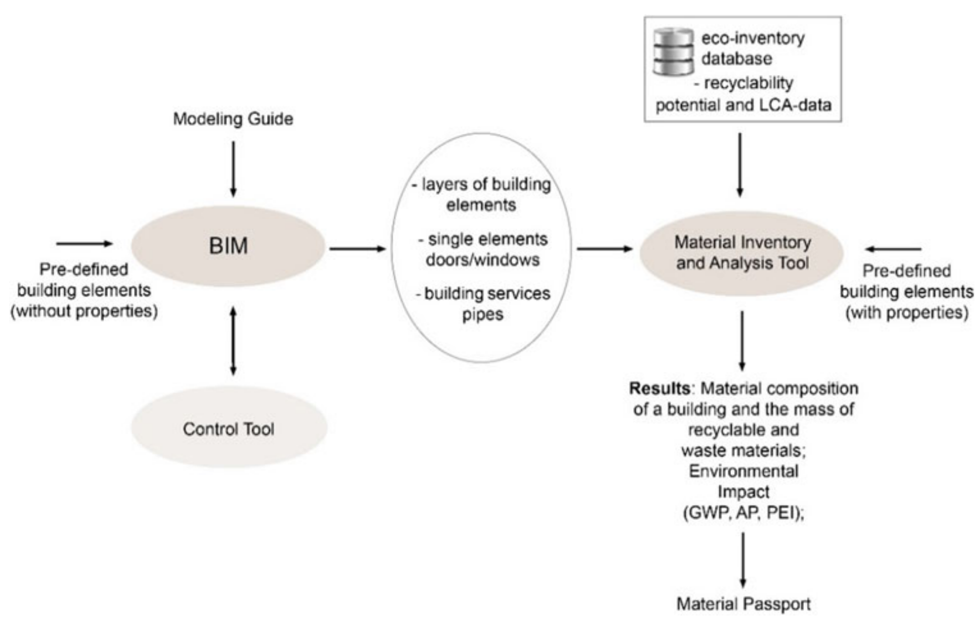
For the generation of MP, we propose coupling of BIM-model with the material inventory and analysis tool BO. BIM-software is used for modeling and BO for matching of eco-indicators to materials and LCA/MP assessment. The workflow is tested with two BIM-software Tools (ArchiCAD and Revit). The material inventory and assessment tool BO offers a bi-directional data exchange to BIM-software and an automated synchronization of data. Figure 89.1 illustrates the developed workflow for the compilation of a MP.

BIM-software is used for generating a detailed model, whereby a modeling-guide is taken into consideration, which defines the requirements for a MP-Model, e.g. that all building elements should be multi-layered (in design stage MP b). A control tool (Solibri Model Checker) is used to ensure that the BIM-model is error-free. In a further step all the required information about building components is exported to the assessment tool (BO), where the materials used in BIM-software have to be matched with the materials existing in the eco-inventory-database in order to conduct the LCA and assess environmental life-cycle impact expressed through indicators such as e.g. the GWP. Therefore, the eco-database requires coupling with the tool (Fig. 89.2). In the assessment-tool, the building components are also parametrized through values for the recyclability and separability in order to assess the total mass of recyclable and waste materials. Due to the direct connection with the BIM-model, all model changes are synchronized automatically and queries are recalculated. Final result is a MP consisting of the information about all materials and their recycling potential existing in the building.

For the compilation of an automated **MPa** “component catalogue”, where elements are pre-defined has to be used. The “component catalogue” is outlined in an Excel-file, whereby each layer of an element is attributed with properties like e.g. separability and recycling potential, data that originates from eco2soft database. In a further step, the developed elements are modeled in BIM-software (ArchiCAD or Revit), which are provided as a template. In BO these elements are enriched with further information (property/m^2) and summed up in categories such as GWP, AP etc. On material-level, all materials have a characteristic value, which is also summed up on the element-level. Modeling in hybrid-modeling-methodology and mono-layered-modeling-methodology (each layer as wall) is not permitted (assessment for elements would not be possible).

In conceptual design stage (**MPa**), the BIM is modelled with mono-layered elements, which are then in a further step matched with pre-defined elements in BO. In this stage, variant studies can be carried out; as for example a variant in timber compared to a variant out of concrete; thereby MP a serving as an important decision-support tool.

Fig. 89.1 Workflow



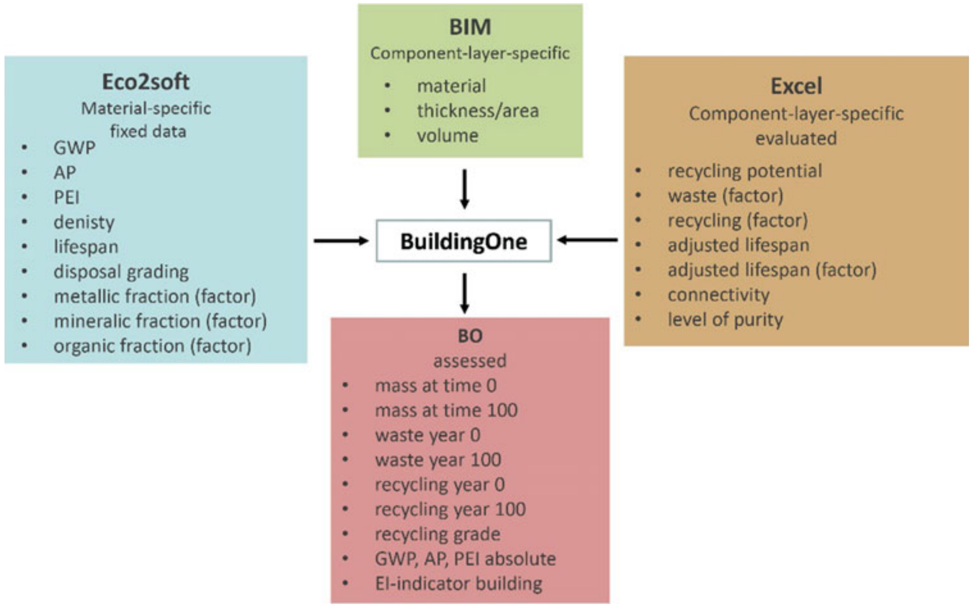


Fig. 89.2 Data for assessment

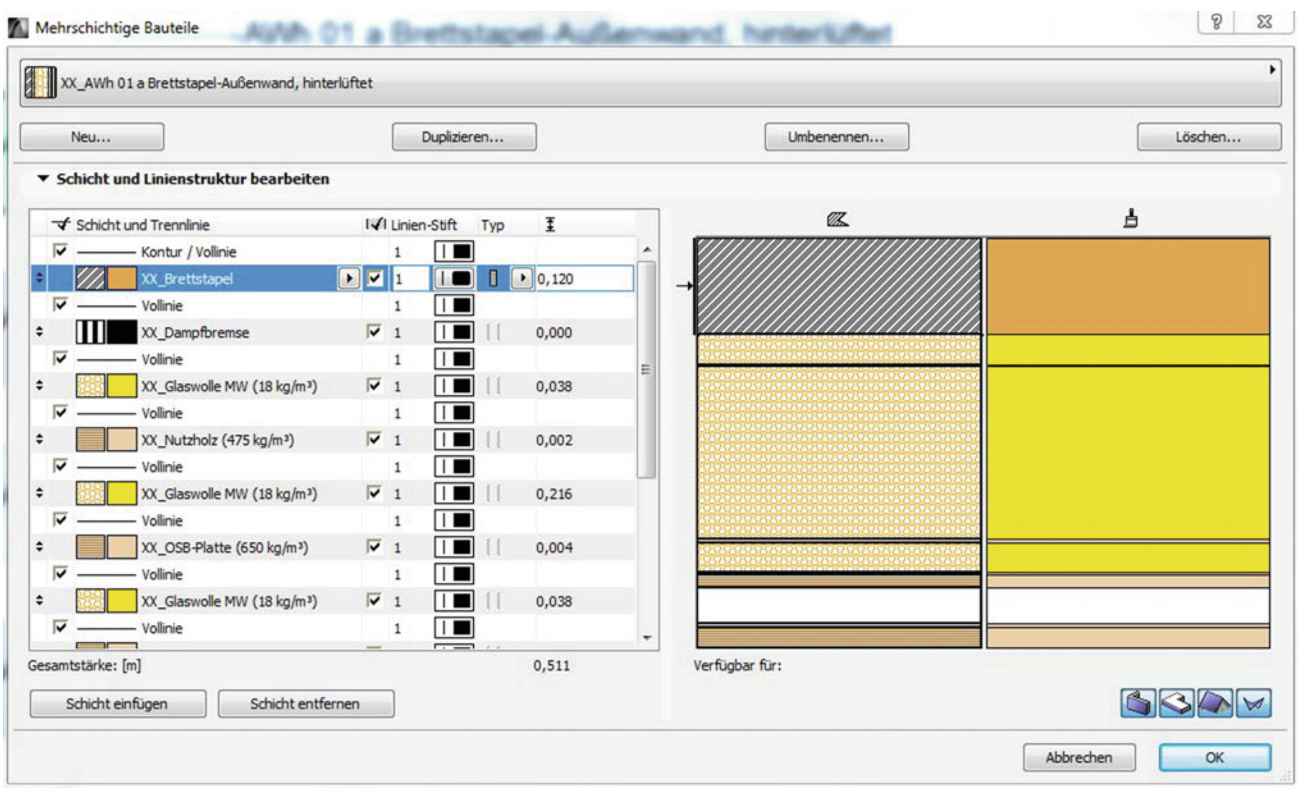


Fig. 89.3 Pre-defined exterior wall in ArchiCAD, MPb

In the design stage, the model is already created with multi-layered elements, which only have information about the thickness, materials and volume/area. In this stage, it is important to use the elements provided in the template, in order to make matching with the elements in BO possible, as these elements have the same designation (Fig. 89.3). In the design stage small changes as for example, optimizing the thicknesses of layers is possible. The **MPb** serves mainly as an optimization tool.

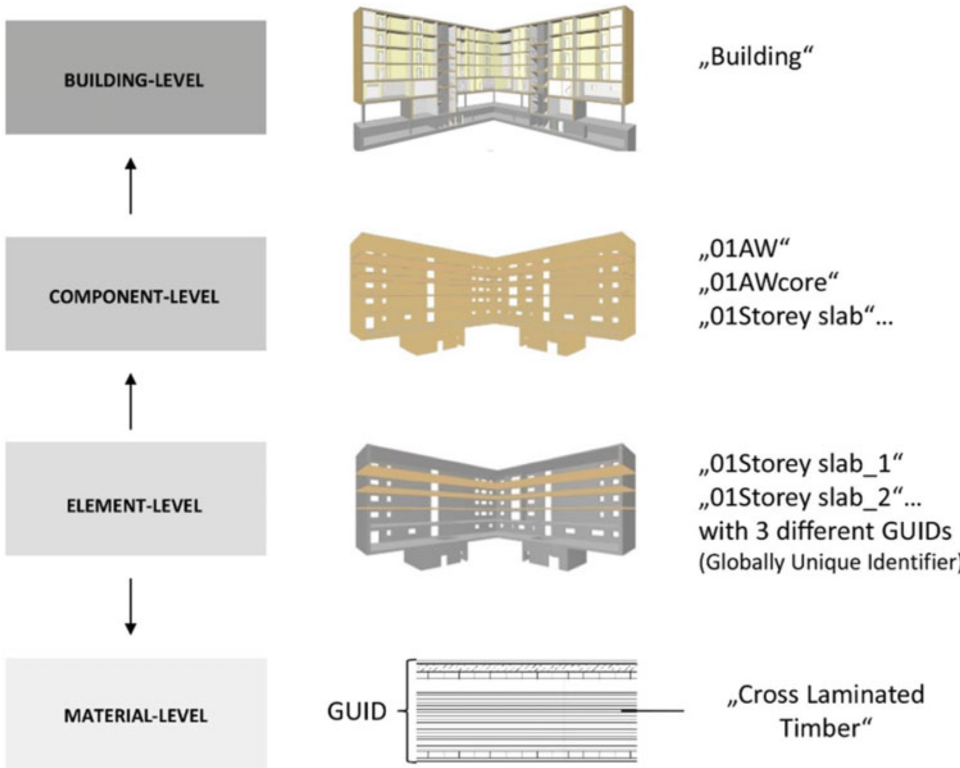


Fig. 89.4 Scheme for the MP

For the compilation of the Material Passport a scheme was developed (Fig. 89.3), incorporating top-down and bottom-up approach.

Thereby the building is divided in four levels: the Building-Level, which consists of the mass and the share of all materials in the whole building; the Component-Level, which is the sum of all materials existing in a particular component (e.g. slabs); the Element-Level, which represents all materials of one particular element (e.g. slab "01") and the Material-level, whereby the mass, type of connection with the enclosed materials and the recycling potential is described for one specific layer/material. The scheme is based on a prior research from Markova and Rechberger [15] whereby a mixture of the bottom-up and top-down approach is tested by starting with the Element-Level in this case.

With up-and downscaling we obtain the sum of recyclable and waste material in tones and as a share in % for each material, element, component and building, underlining the weak points regarding recyclability.

The Globally Unique Identifier (GUID) is automatically generated for each building element by BIM-software, thus allowing identification and allocation of every element within "higher" system e.g. building model (Fig. 89.4). In this way accessibility can be parametrised. Accessibility is expressed as sub-indicator of recycling potential indicator.

Finally, the data-transfer and analysis of BIM-model in BO allows extensive assessment and analysis of material composition of a building, such as assessment of all material-quantities, of percentage of mineralic, metallic or organic materials, of recyclable and waste materials over buildings' life cycle etc.

89.5 Conclusion

In this paper, we presented a proof of concept for compilation of BIM supported material passport as multifold instrument along building's lifecycle—as design-optimization tool, material-inventory and as a document on material assets of real estates or building stocks, and finally enabling successful implementation of Urban Mining strategies.

The problems encountered through conducted research primarily address the processual issues such as lack of standards and structures for material properties in data repositories. Further on, as the LOD of BIM-models in the early design stages is still very vague, exact allocation and attributing of materials is very difficult for the planners. The early design stages are characterized by high level of implicitness, aggregated indicators for building elements of different typologies instead for each material layer, would be therefore necessary. In latter planning stages, high level of expertise regarding materials and sustainability is required by designers in order to be able to conduct material assessment, which often is not the case, therefore an auditor or additional competencies would be necessary to compile MP. The identified limitations of BIM—data handling and allocation in BIM models and lack of standardized object properties regarding material characteristics create a handicap for the implementation of the proposed “passport”, therefore further actions towards synchronization of data dictionaries and eco-data repositories are needed for problem-solution.

The future research should address development of an integrated set of methods and tools (BIM to GIS) to establish a material cadaster for a city as well as modelling and prediction of future resources flows.

MPs should hence become a standard procedure for certified structures and buildings, and contribute to the implementation of circular economy principle along value chain within AEC (Architecture, Engineering and Construction).

References

1. Ajayi, S.O., Oyedele, L.O., Ceranic, B., Gallanagh, M., Kadiri, K.O.: Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment. Int. J. Sustain. Build. Technol. Urban Dev. **6**(1), 14–24 (2015)
2. ArchiCAD Homepage. https://www.graphisoft.at/archicad
3. Azhar, S., Carlton, W.A., Olsen, D., Ahmad, I.: Building information modeling for sustainable design and LEED® rating analysis. Autom. Constr. **20**(2), 217–224 (2011)
4. Baubook Homepage. https://www.baubook.info
5. BuildingOne Homepage. http://www.onetools.de/de/buildingone
6. Eastman, C.M., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Wiley, New Jersey (2011)
7. Eco2soft Homepage. https://www.baubook.info/eco2soft
8. Fischer, M., Hartmann, T., Neuberg, F., Rank, E.: Combining different project modeling approaches for effective support of multi-disciplinary engineering tasks. In: World IT in Construction Conference 2004 (INCITE), Malaysia (2004)
9. Geyer, P., Buchholz, M.: Parametric systems modeling for sustainable energy and resource flows in buildings and their urban environment. Autom. Constr. **22**, 70–80 (2012)
10. IBO—Austrian Institute for Building Biology, OI3-Berechnungsleitfaden (2013). http://www.ibo.at/de/documents/20131016_OI3_Berechnungsleitfaden_V3.pdf
11. ISO 14040: Environmental management—Life cycle assessment—Principles and framework. International Organization for Standardization (2006)
12. LEED Homepage. https://new.usgbc.org/leed
13. Loh, E., Dawood, N., Dean, J.: Integration of 3D tool with environmental impact assessment (3D EIA). In: Em‘body’ing Virtual Architecture: The Third International Conference of the Arab Society for Computer Aided Architectural Design (ASCAAD 2007), Egypt, pp. 51–66 (2007)
14. Lu, W., Yuan, H.: A framework for understanding waste management studies in construction. Waste Manag **31**(6), 1252–1260 (2011)
15. Markova, S., Rechberger, H.: Entwicklung eines Konzepts zur Förderung der Kreislaufwirtschaft im Bauwesen: Materieller Gebäudepass und Design for Recycling für das Bauwesen. Technische Universität Wien, Wien (2011)
16. ÖNORM A 6241-1: Digitale Bauwerksdokumentation - Teil 1: CAD-Datenstrukturen und Building Information Modeling (BIM)—Level 2. Austrian Standards International (2015)
17. ÖNORM A 6241-2: Digitale Bauwerksdokumentation - Teil 2: Building Information Modeling (BIM)—Level 3-iBIM. Austrian Standards International (2015)
18. Prins, M., Mohammadi, S., Slob, N.: Radical circular economy. In: Proceedings of the CIB Joint International Symposium—Going North for Sustainability: Leveraging Knowledge and Innovation for Sustainable Construction and Development. IBEA Publications Ltd., UK (2015)
19. REVIT Homepage. https://www.autodesk.com/products/revit/overview
20. Solibri Model Checker Homepage. https://www.solibri.com/de
21. Won, J., Cheng, J.C., Lee, G.: Quantification of construction waste prevented by BIM-based design validation: case studies in South Korea. Waste Manag. **49**, 170–180 (2016)
22. Kovacic, I., Honic, M.: BIM–supported Life–cycle analysis in the early design stages. In: Proceedings of the CIB world building congress 2016-Understanding impacts and functioning of different solutions (2016)
23. Kovacic, I., Honic, M., Rechberger, H.: BIM-based material passport. In: Conference proceedings of the 13th OTMC conference (2017)

90 Learning from Class-Imbalanced Bridge and Weather Data for Supporting Bridge Deterioration Prediction

Kaijian Liu and Nora El-Gohary

Abstract

Evaluating the impact of learning from weather data, in addition to bridge data, on the performance of bridge deterioration prediction is critical for identifying the right data needed for better prediction for enhanced bridge maintenance decision making. However, the majority of the studies in the bridge domain did not consider such evaluation. For those that conducted the evaluation, their evaluation results usually varied. There is, thus, a need for re-evaluating whether the use of weather data could improve the prediction performance. However, conducting the evaluation is challenging because of class imbalance problems in the bridge domain. Therefore, prior to the evaluation, conducting data sampling to alleviate/eliminate such problems is necessary. To address these needs, this paper offers a pilot evaluation study for better evaluating the impact of learning from weather data on bridge deterioration prediction. To conduct the evaluation, a sampling method was used to deal with the data imbalance problems, and a deep neural network model was developed to predict the condition ratings of decks, superstructures, and substructures. A number of alternative sampling methods were tested and the prediction performances—with and without weather data—were compared. The preliminary experimental results indicated that: (1) the random over-sampling method outperformed the other alternatives; and (2) the change in the prediction performance after further learning from the weather data was only marginal.

Keywords

Weather and bridge data • Bridge deterioration prediction • Data imbalance problems • Deep neural networks

90.1 Introduction

Bridge deterioration prediction is an indispensable component of bridge maintenance decision making. Recent studies (e.g., [1–3]) have emphasized the need for taking a data-driven approach for better predicting bridge deterioration. The increasing availability of heterogeneous bridge data from different sources opens unprecedented opportunities to data analytics for better predicting deterioration and for learning how to better maintain bridges. Such data include National Bridge Inventory (NBI) and National Bridge Elements (NBE) data, traffic and weather data, unstructured sensory data from various types of sensors, and unstructured textual data from bridge inspection reports.

To capitalize on the wealth of these data, in their previous work [4–6], the authors proposed a big bridge data analytics framework. It includes three main components: (1) semantic information and relation extraction for extracting information about bridge conditions and maintenance actions from unstructured textual bridge inspection reports, and representing the extracted information in a structured way [4], (2) semantic data linking and fusion for integrating data from multiple sources into a unified representation [5], and (3) semantic data analytics for predicting bridge deterioration and learning bridge

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maintenance strategies [6]. One of the most important research tasks in the data analytics component is to evaluate the impact of learning from weather data on the performance of data-driven, machine learning (ML)-based bridge deterioration prediction. This is because of two main reasons. First, such an evaluation can help identify the right data needed for better predicting bridge deterioration. Second, as further analyzed in Sect. 2.2, the impacts of learning from weather data concluded by previous studies varied or even disagreed.

There is, thus, a need for re-evaluating whether learning from weather data, in addition to bridge data, could improve the prediction performance. However, conducting such an evaluation is challenging because of the class imbalance problems. The numbers of bridges in different condition rating categories are naturally imbalanced. Such imbalance negatively affects the prediction performance. Further incorporating weather data as features for evaluating its impact on bridge deterioration prediction increases the data dimensionality. This changes the levels of the impacts caused by the imbalance [7] and thus makes the prediction performances across the datasets incomparable. Previous studies are rather limited in considering the varied impacts of the imbalance, which could be the key contributing factor that led to the conflicting evaluation results. Therefore, prior to the evaluation, conducting data sampling to alleviate/eliminate such varied impacts across the datasets is necessary. To address these needs, this paper offers a pilot evaluation study for better evaluating the impact of learning from weather data—in addition to bridge data—on the performance of bridge deterioration prediction. This paper focuses on presenting the evaluation method and the preliminary experimental results.

90.2 Background

90.2.1 State of the Art in Bridge Deterioration Prediction

Many research efforts have been undertaken towards developing data-driven bridge deterioration prediction methods/models. The majority of them focused on using bridge characteristic data for developing bridge deterioration prediction models, and did not consider weather data or sufficiently evaluate their impacts on the prediction. For example, Huang [8] developed an artificial neural network model for predicting the condition ratings of bridge decks. The model mainly learns from data about bridge characteristics, such as design load, deck length, and number of spans. Li et al. [9] developed a Markov-Chain-based bridge deterioration model to capture the transition probabilities of bridge condition ratings for predicting urban bridge deterioration at the network level.

On the other hand, there are several studies (e.g., [10, 11]) that evaluated the impact of using weather data on the performance of bridge deterioration prediction. However, their evaluation results varied largely. For example, Chang et al. [10] concluded that weather data were found not important. However, Qiao et al. [11] concluded that the region variable (a proxy for climate/weather) is generally influential, and the number of cold days is among the most significant factors. In addition to these studies, there are studies (e.g., [12, 13]) that tried to identify the critical sources/factors of bridge deterioration. For example, Kim and Yoon [12] identified the following factors as the most significant contributors to bridge deterioration: year built, structural characteristics, and traffic volume. Weather data, such as precipitation, snow fall, and average temperature, were not among these most-contributing factors [12]. But, Huang et al. [13] found that factors related to weather were rather significant in bridge deterioration.

90.2.2 Knowledge Gaps

Despite the importance of the existing research efforts, two main knowledge gaps are identified. First, the majority of the existing studies did not evaluate the impact of using weather data on the performance of data-driven bridge deterioration prediction. Such evaluation is, however, very important for identifying the right source of data to be used in data-driven bridge deterioration prediction. Using the right data without abundancy is key for improving the prediction performance and reducing the computational needs. Second, although there are several studies that attempted to evaluate the impact of using weather data on the performance of data-driven bridge deterioration prediction, they are rather limited in considering the varied impacts across datasets caused by the imbalance. As discussed, the numbers of bridges in different condition rating categories are naturally imbalanced. Further incorporating weather data as features for evaluating its impact increases the data dimensionality. This changes the levels of the negative impacts caused by the imbalance and thus makes the prediction performances across the datasets incomparable. The existing studies, mostly, did not consider the varied impacts of the imbalance, which could be the key contributing factor that led to the conflicting evaluation results.

90.3 Evaluation Method

To address the above-mentioned knowledge gaps, this paper offers a pilot evaluation study for better evaluating the impact of learning from weather data, in addition to bridge data, on the performance of data-driven, ML-based bridge deterioration prediction. To conduct the evaluation, a sampling method was used to deal with the data imbalance problems, and a deep neural network (DNN) model was developed to predict the condition ratings of decks, superstructures, and substructures. The prediction performances—with and without weather data—were evaluated. The evaluation study, thus, included five main steps: (1) data collection, (2) data preprocessing, (3) data sampling, (4) DNN modeling, and (5) performance evaluation.

90.3.1 Data Collection

Two main types of data were collected for this pilot study: data about bridge characteristics and data about weather characteristics. The bridge data included features about bridge location, geometric characteristics (e.g., bridge length, deck width, number of spans, etc.), structural characteristics (e.g., functional classification, design load, wearing surface type, etc.), construction characteristics (e.g., year built and type of construction), and traffic volumes (e.g., average daily traffic and percent of truck traffic). These data were collected from the National Bridge Inventory of the Federal Highway Administration. The weather data included features about cooling degree days, heating degree days, diurnal temperature range, precipitation totals, snowfall totals, and temperature. Table 90.1 provides a brief description for the main weather features. These data were collected from the National Oceanic and Atmospheric Administration (NOAA). As a pilot study, this work focused on the bridge and weather data collected from nine U.S. states: Illinois (IL), Michigan (MI), Delaware (DE), Idaho (ID), Arkansas (AR), South Carolina (SC), Utah (UT), Nevada (NV), and Wyoming (WY). These states were selected because each of them belongs to one of the climatically consistent regions that were defined by the NOAA. By capturing different weather and bridge deterioration patterns, the collected data would, thus, help better evaluate the impact of learning from weather data.

As a result, a total of 1078 data instances were included in this study. Three different datasets were then generated. Dataset #1 only included the data about bridge characteristics. Dataset #2 included the bridge data as well as partial weather data (i.e., only the weather features about the normal were included). For example, for the cooling degree days, only the feature about the cooling degree day normal, which is computed with a base of 65 °F, was included. Dataset #3 included both the bridge data and the full weather data (i.e., all the weather features were included).

Table 90.1 A brief description of the main features of the weather data

Feature	Brief description
Cooling degree days	The cooling degree day normal is computed with a base of 65 °F. The other bases include 45, 50, 55, 57, 60, 70, and 72 °F
Diurnal temperature range	The diurnal temperature range is the difference between the F maximum and minimum temperature over a day
Heating degree days	The heating degree day normal is computed with a base of 65 °F. The other bases follow those used in cooling degree days
Precipitation totals	The annual precipitation totals. The other features about the precipitation include the number of days whose precipitation is greater than 0.01, 0.10, 0.50, and 1.00 inches
Snowfall totals	The annual snowfall totals. Similarly, the other features include the number of days whose snowfall is greater than 0.1, 1.0, 3.0, 5.0, and 10.0 inches
Average temperature	The annual average temperature
Maximum temperature	The annual maximum temperature. The other features include the number of days whose maximum temperature is greater than 32, 40, 50, 60, 70, 80, 90, and 100 °F
Minimum temperature	The annual minimum temperature. Similarly, the other features include the number of days whose minimum temperature is less than 32, 40, 50, 60, and 70 °F

90.3.2 Data Preprocessing

Four main steps were conducted to process the weather and bridge data. First, the missing data values in the data were imputed. For each feature type, the mean of the data values that are available was calculated and then used for imputing the missing ones. Second, the data values of the numerical features (e.g., bridge length and average temperature) were normalized. Both the original and imputed values of the same feature type were translated into the same range between 0 and 1, using the min-max normalization method. Third, the data values of the categorical features (e.g., wearing surface type) were converted into numerical values, using one-hot feature representation. Finally, the bridge data were mapped to the weather data. In conducting the mappings, for each weather station, its distances to all the bridges were calculated. The station was mapped to the bridge that is spatially closest. For calculating the distance, the latitudes and longitudes of the bridges and the weather stations were used.

90.3.3 Data Sampling

Data sampling aimed to balance the training dataset for addressing the negative, yet varied, impacts caused by the imbalance. Table 90.2 summarizes the imbalance characteristics of the data. The numbers of bridges in different condition rating categories (the ratings are the target classes for the bridge deterioration prediction) are naturally imbalanced. For example, there are around 30.5 and 8.0% of the bridges whose deck condition ratings are 7 and 5, respectively. Two main sampling approaches are commonly used for addressing data imbalance problems: over-sampling and under-sampling. The over-sampling approach [e.g., the random over-sampling technique and the synthetic minority over-sampling technique (SMOTE)] adds data instances to the minority classes to create a balanced dataset [14]. The under-sampling approach (e.g., the random under-sampling and the cluster centroid-based techniques) removes a subset of the data from the majority classes for balancing the dataset [14]. For this pilot study, several commonly-used sampling methods were tested and compared. These methods were selected based on the state-of-the-art literature review studies [14, 15] in the area of imbalanced learning. Table 90.3 provides a summary of the selected sampling methods/techniques.

90.3.4 Deep Neural Network Modeling

A deep neural network (DNN) model was developed for learning from the sampled data instances for predicting the condition ratings of the decks, superstructures, and substructures. This deep learning approach was selected mainly because it is the current state-of-the-art ML approach and has been applied for bridge deterioration prediction (e.g., [8]) and many other ML applications (e.g., [16]). In this paper, the DNN model was developed with a feed-forward architecture that

Table 90.2 Imbalance characteristics of the dataset

Condition rating[a]	Percentage of bridge elements in different condition rating categories		
	Deck (%)	Superstructure (%)	Substructure (%)
N	22.6	21.6	21.6
0	0.2	0.1	0.1
1	0.0	0.0	0.0
2	0.1	0.1	0.1
3	0.6	0.9	0.6
4	1.9	2.0	2.2
5	8.0	9.2	8.4
6	24.5	21.1	22.2
7	30.5	27.8	31.2
8	10.2	15.4	11.8
9	1.6	1.8	1.8

[a]Condition rating of "0" stands for "failed condition"; condition rating of "9" stands for "excellent condition"; condition rating of "N" stands for "not applicable"

Table 90.3 Commonly-used candidate sampling methods

No.	Method	Description[a]
SM #1	Random over-sampling	Randomly select samples from the minority classes, and augment the dataset by replicating the selected samples and adding the replicates to the dataset
SM #2	Synthetic minority over-sampling technique (SMOTE) 1	For a sample from the minority classes, its nearest neighbors are defined based on the Euclidian distance. The sample that has half of its neighbors belong to a different class will be used for the sampling. A new synthetic sample will be generated by interpolating between the original sample and one of its neighbors who has a different class
SM #3	SMOTE 2	Similar to SMOTE 1. But, a new synthetic sample will be generated by interpolating between the original sample and any one of its neighbors
SM #4	Random under-sampling	Randomly select samples from the majority classes, and remove the samples from the dataset
SM #5	Cluster centroids	A number of clusters are generated based on the samples in each of the majority classes. The number is defined based on the smallest number of samples in the minority cluster. The centroids of the clusters are used as samples for representing the majority classes
SM #6	Near miss	Select the samples from the majority classes, and use a subset of the samples whose average distance to the furthest samples of the minority classes is the smallest

[a]SM = sampling method. The description is based on literature review studies [14] and [15]

contains an input layer, several hidden layers, and a softmax output layer. Different numbers of hidden layers and activation functions were tested through model parameter tuning. As a result, the DNN model with five hidden layers and the rectified linear unit activation function was developed.

90.3.5 Performance Evaluation

Two performance evaluation cases were developed. The first case aimed to compare the performances of the selected sampling methods. The second one aimed to evaluate the impact of learning from the weather data, in addition to the bridge data, on the performance of bridge deterioration prediction—predicting the condition ratings of the decks, superstructures, and substructures. Accuracy was selected as the evaluation metric for benchmarking the prediction performance. Accuracy, here, is the percentage of the number of correctly-predicted condition ratings out of the total number of the predicted ratings. In order to examine the robustness of the results, for each experimental run, a 10-fold cross validation was conducted. For each validation iteration, the data instances in the training folds were sampled by the tested sampling method, and the resulting dataset was used for training a DNN model. The performance of the sampling method and the impact of learning from the weather data were tested using the instances in the testing fold. The average accuracy over the ten folds was reported.

90.4 Preliminary Experimental Results and Discussion

90.4.1 Performances of Data Sampling Methods

As mentioned in Sect. 3.2, a total of six commonly-used data sampling methods for dealing with the class imbalance problems were tested. Table 90.4 summarizes their performances for the three datasets. Three main observations are drawn from the experimental results. First, the over-sampling approach (SMs #1, #2, and #3 as per Table 90.4) performed better than the under-sampling approach (SMs #4, #5, and #6). On average, compared to the baseline where no sampling method was used, the over-sampling approach improved the accuracy by over 30.0%. The under-sampling approach only improved the accuracy by around 14.0%. This is mainly because the under-sampling methods decreased the size of the dataset. For

Table 90.4 The performances of the data sampling methods

Method[a]	Dataset #1 (%)	Dataset #2 (%)	Dataset #3 (%)	Average (%)
Baseline	52.1	51.6	53.2	52.3
Baseline + SM #1	+36.9[b]	+37.7	+34.7	+36.4
Baseline + SM #2	+32.8	+33.0	+30.9	+32.2
Baseline + SM #3	+30.6	+31.2	+29.0	+30.3
Baseline + SM #4	+14.5	+14.3	+14.3	+14.4
Baseline + SM #5	+14.1	+14.7	+13.9	+14.3
Baseline + SM #6	+13.2	+15.6	+14.6	+14.5

[a]The baseline was developed without using any sampling method. The index for the sampling methods follows that defined as per Table 90.3 (SM = sampling method)
[b]The average prediction accuracy improvement compared to the baseline

example, the random under-sampling method randomly dumped the data instances of the majority classes to make the numbers of the instances in both majority and minority classes equal. The decrease in the data size prevented the DNN model to sufficiently capture the different deterioration patterns represented by the dumped instances. Conversely, the over-sampling approach boosted the dataset by adding more instances to the minority classes, which preserved all the patterns represented by the data, and, at the same time, addressed the imbalance problems.

Second, the random over-sampling method outperformed the other over-sampling methods. On average, it improved the prediction accuracy by 36.4%, which is 4.2 and 6.1% higher compared to SMs #2 and #3, respectively. This indicates that: (1) sampling the data by interpolation, as used in SMs #2 and #3, created synthetic data that cannot fully represent the real-world deterioration cases/patterns; and (2) the interpolation generated some data instances that are close to the decision boundaries for separating different condition ratings. This made the classifiers somewhat confused and thus resulted in less-improved performance. Third, although the under-sampling approach reduced the data size, it still performed better than the baseline. This shows that, compared to the reduced data size, the imbalance is more significant in negatively affecting the performance of the bridge deterioration prediction.

90.4.2 Impact of Weather Data on Bridge Deterioration Prediction

The impact of learning from the weather data, in addition to the bridge data, on the performance of the bridge deterioration prediction was evaluated. The evaluation was conducted by comparing the prediction accuracies of the three datasets. The evaluation results are summarized in Table 90.5.

The evaluation results indicate that the impact of using the weather data on the prediction performance is marginal. Using the bridge data alone (i.e., dataset #1) an average prediction accuracy of 89.1% was achieved. Compared to this accuracy, adding the partial weather data (i.e., dataset #2) only improved the accuracy by 0.2% (i.e., an accuracy of 89.3%). Further adding all the weather data (i.e., dataset #3), however, decreased the accuracy by 1.3%. As seen, the increase and the decrease rates are all around 1.0%. This indicates that the impact of learning from the weather data—in addition to the bridge data—on the performance of the prediction, whether positive or negative, is marginal. This could be largely attributed to the low discriminating-power of the weather data. The weather data in a given region are quite similar because of geographical

Table 90.5 The impact of learning from weather data on the performance of the data-driven, ML-based bridge deterioration prediction

Bridge element	Bridge deterioration prediction accuracy		
	Bridge data only (%)	Bridge data + partial weather data (%)	Bridge data + full weather data (%)
Deck	89.4	89.7	88.7
Superstructure	87.9	88.2	86.6
Substructure	90.0	90.1	88.3
Average[a]	89.1	89.3	87.8

[a]The average prediction accuracy over the bridge elements

proximity. But, the bridges in the same region do have different condition ratings. Therefore, the weather data did not improve the ability to distinguish different deterioration patterns—on the contrary, the data even sometimes introduced noise to the classifiers (e.g., when the dimension of the additional weather features is high). As a result, learning from weather data only marginally impacted the performance of the bridge deterioration prediction.

90.5 Conclusions, Limitations, and Future Work

A pilot evaluation study was conducted to better evaluate the impact of learning from weather data, in addition to bridge data, on the performance of data-driven, ML-based bridge deterioration prediction. A set of experiments were conducted to select a suitable sampling method that can deal with the data imbalance, and to compare the prediction accuracies, with and without weather data. The experimental results show that the random over-sampling method, although simple, was effective and suitable for dealing with the imbalance. The results also indicate that the impact of further learning from the weather data, in addition to the bridge data, could be positive or negative, depending on the types of weather data used. However, in either case, the impact was found marginal.

One main limitation of this paper is acknowledged. For this pilot study, the bridge data only included those about the bridge characteristics collected from 2017 NBI. When training/testing the prediction model, the dataset was split using a 10-fold cross validation. As a result, the applicability of the model was limited to learning from static bridge characteristic data to predict the condition ratings of decks, superstructures, and substructures that were not inspected during an inspection year. While this model is sufficient for the purpose of conducting the pilot evaluation study, it would not be sufficient to adequately support bridge maintenance decision making, especially when it comes to providing information about which defects that a bridge could develop in the future and which maintenance action is most cost-effective to repair existing defects and prevent the predicted potential defects.

In their ongoing/future work, the authors will focus on developing new ML algorithms for learning from heterogeneous bridge data from different sources, in order to better predict bridge deterioration for enhanced bridge maintenance decision making. Two main directions will be explored. First, the authors will explore ways to use ML to capture bridge deterioration patterns across time for predicting bridge deterioration—in terms of condition ratings, defect types, and maintenance action types—in the future years. Second, while learning from a big size of the bridge data, the authors will further test the performances of sampling methods in supporting such a complex ML-based prediction task.

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References

1. Rafiq, M.I., Chryssanthopoulos, M.K., Sathananthan, S.: Bridge condition modelling and prediction using dynamic Bayesian belief networks. Struct. Infrastruct. Eng. **11**(1), 38–50 (2015)
2. Morcous, G., Lounis, Z., Cho, Y.: An integrated system for bridge management using probabilistic and mechanistic deterioration models: application to bridge decks. KSCE J. Civ. Eng. **14**(4), 527–537 (2010)
3. Federal Highway Administration: The LTBP deterioration modeling algorithm. https://www.fhwa.dot.gov/publications/ltbpnews/15073.cfm. Accessed 10 Apr 2018
4. Liu, K., El-Gohary, N.: Ontology-based semi-supervised conditional random fields for automated information extraction from bridge inspection reports. Autom. Constr. **81**, 313–327 (2017)
5. Liu, K., El-Gohary, N.: Unsupervised named entity normalization for supporting information fusion for big bridge data analytics. In: Smith, I., Domer, B. (eds.) Proceedings of 25th International Workshop on Intelligent Computing in Engineering, pp. 130–149. Springer, Cham (2018)
6. Liu, K., El-Gohary, N.: Feature discretization and selection methods for supporting bridge deterioration prediction. In: Proceedings of the 2018 ASCE Construction Research Congress, pp. 413–423. American Society of Civil Engineers, Reston (2018)
7. Lusa, L.: Class prediction for high-dimensional class-imbalanced data. BMC Bioinform. **11**, 523 (2010)
8. Huang, Y.: Artificial neural network model of bridge deterioration. J. Perform. Constructed Facil. **24**(6), 597–602 (2010)
9. Li, L., Sun, L., Ning, G.: Deterioration prediction of urban bridges on network level using Markov-chain model. Math. Probl. Eng. (2014)
10. Chang, M., Maguire, M., Sun, Y.: Framework for mitigating human bias in selection of explanatory variables for bridge deterioration modeling. J. Infrastruct. Syst. **23**(3), 04017002 (2017)
11. Qiao, Y., Moomen, M., Zhang, Z., Agbelie, B., Labi, S., Sinha, K.C.: Modeling deterioration of bridge components with binary probit techniques with random effects. J. Transp. Res. Board, 96–105 (2016)
12. Kim, Y.J., Yoon, D.K.: Identifying critical sources of bridge deterioration in cold regions through the constructed bridges in North Dakota. J. Bridge Eng. **15**(5), 542–552 (2009)

13. Huang, R., Mao, I., Lee, H.: Exploring the deterioration factors of RC bridge decks: a rough set approach. Comput.-Aided Civ. Infrastruct. Eng. **25**(7), 517–529 (2010)
14. He, H., Garcia, E.A.: Learning from imbalanced data. IEEE Trans. Knowl. Data Eng. **21**(9), 1263–1284 (2009)
15. Chawla, N.V.: Data mining for imbalanced datasets: an overview. In: Maimon, O., Rokach, L. (eds.) Data Mining and Knowledge Discovery Handbook, pp. 875–886. Springer, Boston (2009). https://doi.org/10.1007/0-387-25465-X_40
16. Goodfellow, I., Bengio, Y., Courville, A., Bengio, Y.: Deep Learning. The MIT Press, Cambridge (2016)

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Machine-Learning-Based Model for Supporting Energy Performance Benchmarking for Office Buildings

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Abstract

Buildings are dominant contributors of global energy consumption. Enhancing building energy efficiency has long been recognized as an important way to achieve energy saving goals and sustainability targets. In response, a body of building energy performance benchmarking models and tools have been proposed during the past decades. The degree of similarity between the compared buildings is the core of the benchmarking process. However, existing benchmarking tools mainly classify buildings only based on building use types, instead of fully considering a wider range of impacting factors. To address this gap, this paper proposes a machine-learning (ML)-based model for classifying buildings—based on building characteristics, occupant behaviors, and geographical and climate features—into three energy-consumption levels: low, medium, and high. Support vector regression models are then fitted to define the predicted energy consumption for benchmarking. The proposed ML-based building energy consumption prediction model was tested on the office buildings in the commercial building energy consumption survey (CBECS) dataset. Principal component analysis (PCA) was used for data dimensionality reduction and feature extraction. Different ML algorithms were tested and compared, including Naïve Bayes (NB), support vector machines (SVM), decision trees (DT), and random forests (RF). The classification algorithms were evaluated in terms of precision and recall; the regression models were evaluated in terms of root mean square error; and the energy consumption prediction results were further compared with the prediction results by EnergyStar. The performance results indicate that, compared with EnergyStar, the proposed model can reduce the prediction error by 13%.

Keywords

Energy benchmarking • Energy consumption • Classification • Machine learning • Office buildings

91.1 Introduction

Human beings spend an average of 87% of their time inside buildings [1], which indicates a large amount of energy demand for supporting indoor activities and thermal comfort. With the rapid urbanization around the world, enhancing building energy efficiency is becoming more crucial for achieving energy saving goals and global sustainability targets. Energy benchmarking is a key first step to understand the energy efficiency of buildings. It evaluates the energy consumption of an individual building by comparing it to its peers. The benchmarking result can provide important decision support for identifying energy conservation opportunities, when the assessed building consumes more energy than other similar buildings.

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A number of building energy performance benchmarking models and tools have been proposed during the past decades, including energy performance indices (e.g., energy usage intensity [2]), point-based rating systems (e.g., Leadership in Energy and Environmental Design (LEED) [3]), simulation-based systems (e.g., EnergyPlus [4]), and statistical models (e.g., ordinary least squares models [5] and EnergyStar [6]). Despite the importance of the existing efforts, the way they select similar buildings for benchmarking is limited. The degree of similarity between the compared buildings is the core of the benchmarking process, because the energy performance of the target building needs to be compared to that of other similar buildings. However, existing benchmarking models/tools only classify buildings based on a single characteristic. For example, EnergyStar classifies buildings only by building use types, instead of fully considering a wider range of impacting factors, which can provide unreliable results when assessing the building energy performance [7].

To address this gap, this paper proposes a machine-learning (ML)-based model for supporting building energy consumption benchmarking. The proposed model first classifies buildings into three energy consumption levels—low, medium, and high—based on a range of features (e.g., building characteristics, occupant behaviors, and geographical and climate features). Separate support vector regression models are then fitted to define the predicted energy consumption for each class. The proposed model considers the impacts of a large amount of features that could impact building energy performance, and discovers the underlying similarities between the buildings, which could provide more robust prediction results and can better assist the building stakeholders in improving building energy efficiency. To limit the scope of this paper, only the electricity consumption of office buildings was considered.

In the remainder of this paper, Sect. 91.2 briefly introduces the background. Section 91.3 presents the research methodology for the proposed model. Section 91.4 discusses the preliminary results. Finally, Sect. 91.5 summarizes the conclusions and future work.

91.2 Background

Numerous building energy benchmarking models/tools have been developed since the 1990s. The existing energy benchmarking methods can be divided into five categories: energy performance indices, point-based rating systems, simulation-based systems, statistical models, and ML-based models.

Energy performance indices are commonly obtained by normalizing the building energy use relative to a primary determinant of energy use [8]. For example, energy use intensity (EUI) provides normalized energy use per building floor area per year. However, such simple indices can be unreliable because they only consider a single factor (e.g., building floor area) without accounting for other impacting factors.

Point-based rating systems, such as LEED, use predefined standards or guidelines to measure the energy efficiency of a building. However, they do not allow comparisons against other buildings, and the scoring system without considering actual energy consumptions can be misleading [7].

Simulation-based systems compare the actual building energy consumption with the energy use of simulated buildings. Although this method considers a wide range of impacting factors, the simulation results might be inaccurate because of insufficient calibration to the actual building data.

Statistical models generate a regression line between the actual energy consumption and its impacting factors, like in EnergyStar [6]. However, such models are highly sensitive to outliers, which could provide wrong conclusions because of the skewed regression line.

Recently, some efforts have used ML-based models (e.g., artificial neural networks [9]) for energy benchmarking. These models aim to learn from data of similar buildings. However, they select similar buildings based on building type only (e.g., office, residential).

As such, all five categories of models have a common drawback: they only define similarity of buildings (i.e., classify buildings) based on a single characteristic (e.g., building type), which can provide unreliable results when predicting the energy consumption of a building. Therefore, there is a need for a building classification and energy consumption prediction model for supporting a more accurate energy performance benchmarking.

91.3 Research Methodology for the Proposed ML-Based Model for Supporting Energy Performance Benchmarking

The proposed ML-based building classification and energy consumption prediction model for supporting energy performance benchmarking is composed of four main steps (as per Fig. 91.1): (1) data preparation; (2) feature extraction; (3) model development; and (4) model evaluation.

91.3.1 Data Preparation

Feature Prescreening and Data Cleaning. Feature prescreening aims to remove the data attributes that are irrelevant, redundant, and/or with mostly missing values. Each data sample has a total of 516 data attributes (not including imputation flags and weights). But they contain a large amount of irrelevant and redundant attributes, as well as attributes with many missing values. For example, the attribute "natural gas used for cooling" is irrelevant, because the scope of this study is focused on electricity consumption. The attribute "computer used" is redundant in the presence of the attribute "number of computers". And, 90% of the data samples have an empty value for the attribute "central plant in building". After feature screening, the original 516 data attributes were reduced to 193 attributes. The attributes are composed of building characteristics (e.g., square footage, year of construction, and floor to ceiling height), occupant behaviors (e.g., principal building activity, number of businesses, and percent occupancy), and geographical and climate features (e.g., census division, heating degree days, and cooling degree days).

Data cleaning then aims to removes the data entries with incomplete building information or with zero electricity consumption data, as well as duplicate data entries. Only three building samples were removed as a result of data cleaning.

Data Transformation and Standardization. The dataset includes a mixture of categorical and continuous data attributes. For example, the attributes "wall construction material", "main heating equipment", and "census division" are categorical, while the attributes "total hours open per week", "square footage", and "heating degree days" are continuous. Data transformation and standardization aims to transform the mixed-type data into a standard format for the training and testing of the ML models.

For categorical data, a standard one-hot encoding method was conducted. The data samples with n categories were expanded into $n-1$ dummy variables. For example, for the feature $x_i = k(k \in 1, 2, 3, \ldots, n)$, x_i was expanded to $n-1$ dummy variables, where the kth variable is 1, and the rest is 0.

Continuous data have different magnitudes. For example, the gross floor area of the buildings ranges from 1001 to 1.5 million square feet. The high-valued variables are likely to dominate the prediction [10]. Therefore, the datasets need to be normalized, to scale the continuous data with different magnitudes down to a common scale. In this study, the continuous data were normalized by using the min-max normalization method, as shown in Eq. (91.1), where x_i' and x_i are the normalized and original data, respectively; and $\max(x)$ and $\min(x)$ are the maximum and minimum values of x, respectively.

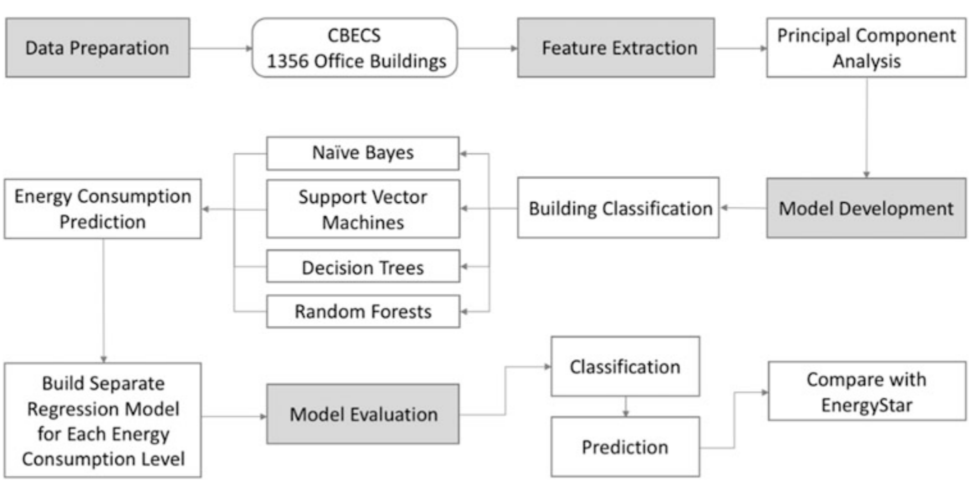

Fig. 91.1 Proposed ML-based building energy performance benchmarking framework

$$x_i' = \frac{x_i - \min(x)}{\max(x) - \min(x)} \tag{91.1}$$

Energy Consumption Discretization. The continuous target value is the total annual electricity consumption, which needs to be discretized to a few categories for building classification. In this study, three energy consumption levels were defined, i.e., low, medium, and high. Quantile-based discretization method was used for dividing the continuous target value into the three intervals. Figure 91.2 shows a boxplot of the logarithmic electricity consumption for all the three energy consumption levels.

91.3.2 Feature Extraction

All the data attributes can be used as features of the ML-algorithms. As the feature space was largely expanded by the one-hot encoding in the data transformation step, the high dimensional dataset and the large amount of correlated features could deteriorate the prediction performance of the ML-algorithms. Feature extraction aims to reduce both the curse of dimensionality and the multicollinearity deficiency of the data. This study used principal component analysis (PCA) for feature extraction and dimensionality reduction.

PCA projects the raw features to a lower dimensional space by using singular value decomposition (SVD). It thus constructs a series of linear combinations of the original features. The results of PCA are a set of independent orthogonal vectors, which are called principal components (PCs). The PCs maintain the major characteristics of the original features, and are ranked based on the magnitudes of their corresponding eigenvalues [11]. For example, the first PC is the most important PC, which has the largest eigenvalue and explains the largest possible variance of the original dataset. Each subsequent PC represents the largest remaining variance. By only using the several PCs that rank first, the number of features can thus be reduced.

91.3.3 Model Development

The ML-based model is composed of two parts: (1) building classification and (2) energy consumption prediction.

Building Classification. This step aims to classify the buildings—based on the building characteristics, occupant behaviors, and geographical and climate features—into three predefined classes: low-, medium-, and high-energy-consumption buildings. This research selected four of the most-popular ML algorithms, including Naïve Bayes (NB), support

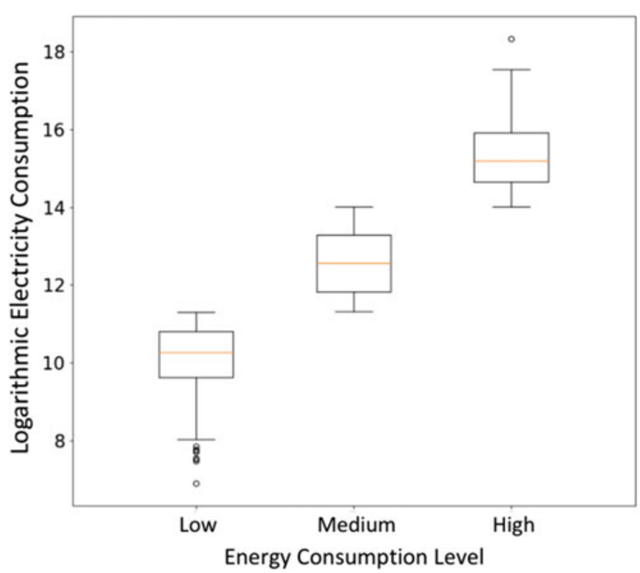

Fig. 91.2 Boxplot of logarithmic electricity consumption for the three levels

vector machines (SVM), decision trees (DT), and random forests (RF). The dataset was randomly partitioned into two—90% training and 10% testing. The aforementioned ML algorithms were implemented using the Scikit-learn module [12] written in Python programming language.

Energy Consumption Prediction. This step develops separate regression models for each of the three classes. When testing, the class label of each testing sample is first determined, then the regression model of the corresponding class is used to determine the target energy consumption value. Support vector regression (SVR) was selected for developing the regression models, because it has been found in other studies (e.g., [13–15]) to outperform other machine learning algorithms (i.e., artificial neural networks, multiple linear regression, etc.) in solving the nonlinear energy consumption prediction problem.

91.3.4 Performance Evaluation

The model was evaluated based on the testing data. The performance evaluation includes the evaluation of the classification algorithms, the regression models, and the overall energy consumption prediction results. The classification algorithms were evaluated in terms of precision and recall; the regression models were evaluated in terms of root mean square error (RMSE); and the prediction results were further compared with the prediction results generated by EnergyStar.

Precision indicates the proportion of the positive identifications that were actually correct. Recall indicates the proportion of the actual positives that were identified correctly. RMSE indicates how close the model's predicted values are to the observed data points. The definitions of these three metrics are shown in Eqs. (91.2)–(91.4), where TP, FP, FN refers to true positive, false positive, and false negative class predictions, respectively; y_i and $\hat{y}_i$ are the actual and predicted energy consumption value at the ith data point, respectively; and N is the total number of data points in the dataset.

$$\text{Precision} = \frac{TP}{TP + FP} \tag{91.2}$$

$$\text{Recall} = \frac{TP}{TP + FN} \tag{91.3}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{91.4}$$

The performance of the overall energy consumption prediction results was evaluated by comparing it to that of the prediction results generated by EnergyStar. EnergyStar is the best-known and most technically-robust building energy benchmarking tool [7]. It is developed based on an ordinary least squares (OLS) regression model. The OLS model for benchmarking office buildings developed by EnergyStar only considers the following features: gross floor area, weekly operating hours, number of workers, number of computers, percentage of area heated, percentage of area cooled, and heating/cooling degree days. Therefore, for this step, the same set of features were used to generate an OLS model. And the prediction results by the proposed ML-based model and the OLS model were compared in terms of RMSE.

91.4 Preliminary Results and Discussion

Figure 91.3 shows the cumulative percentage of explained variance of the PCs. As the feature space has been expanded to 655 features by the data transformation step, PCA produced a total of 655 PCs. As shown in Fig. 91.3, the top 112 PCs can represent more than 85% of the variance. Therefore, only the top 112 PCs were selected as the new features for model development. Figure 91.4 shows the percentage of explained variance by each selected PC.

Table 91.1 presents the performance of the building classification algorithms. Comparing the algorithms, SVM performed best in terms of both precision and recall. It achieved an average precision and recall of 86%. Decision trees performed the worst, with an average precision and recall 16% lower than SVM. Naïve Bayes and random forests achieved a similar performance, but random forests performed slightly better. The high performance of the SVM algorithm indicates that SVM is suitable for handling and capturing the nonlinearity of the building classification problem.

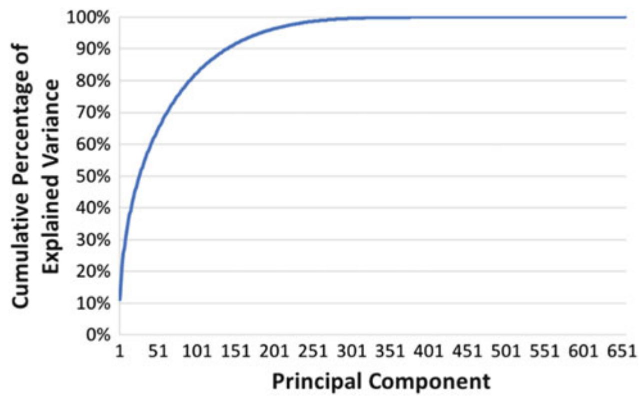

Fig. 91.3 Cumulative percentage of explained variance of principal components

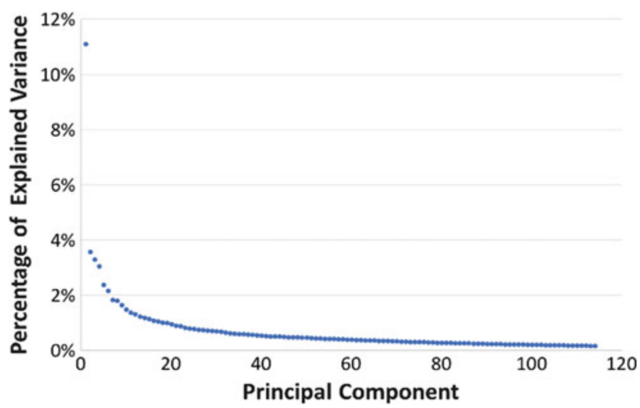

Fig. 91.4 Percentage of explained variance by each principal component

Table 91.1 Performance of the building classification algorithms

Algorithm	Performance	Energy consumption level			Average
		Low	Medium	High	
Naïve Bayes	Precision (%)	82	70	78	76.7
	Recall (%)	82	64	84	76.7
Decision trees	Precision (%)	59	62	89	70.0
	Recall (%)	74	50	87	70.3
Random forests	Precision (%)	73	79	85	79.0
	Recall (%)	85	61	96	80.7
Support vector machines	Precision (%)	83	82	93	86.0
	Recall (%)	85	80	93	86.0
Average precision (%)		74.3	73.3	86.3	77.9
Average recall (%)		81.5	64.8	90.0	78.4

For the classification of the buildings, the building class with high energy consumption had the best performance. For example, on average, the prediction precision and recall for the high-consumption buildings is 86.3 and 90.0%, respectively, compared with 74.3 and 81.5% for the low-consumption buildings and 73.3 and 64.8% for the medium-consumption buildings. This result indicates that the high-consumption buildings are easier to identify, because they have more distinctive features than the other two classes, such as much larger gross floor area, more occupants, and more energy consuming appliances. However, the classification of the low- and medium-consumption buildings might be more challenging and sensitive, which could be attributed to the different occupant behaviors in the buildings with similar weather and physical features.

The classification model generated by the SVM algorithm was further used in predicting the amount of building energy consumption. The RMSE of the proposed model is 2.7×10^6 kWh, while the RMSE of the EnergyStar model is 3.1×10^6 kWh. Overall, compared to EnergyStar, the proposed ML-based building classification and energy consumption prediction model reduced the prediction error by 13%.

91.5 Conclusions and Future Work

Building energy performance benchmarking provides important potential to increase building energy efficiency and reduce building carbon footprint. In this paper, the authors proposed a ML-based model for supporting building energy performance benchmarking. The proposed model is composed of two main components: (1) building classification, and (2) energy consumption prediction. The building classification aims to classify the buildings into three energy consumption levels: low, medium, and high, based on a wide range of building characteristics, occupant behaviors, and geographical and climate features. Four of the most popular ML algorithms, i.e., NB, SVM, DT, and RF, were tested and compared. The energy consumption prediction aims to build separate regression models by using the SVR algorithm for predicting the target energy consumption values of the buildings. The proposed ML-based model was tested on the office buildings from the CBECS dataset, and PCA was used for data dimensionality reduction and feature extraction. The preliminary experimental results indicate that: (1) for this problem, SVM outperforms all the other ML classification algorithms, which achieved 86% average precision and recall; and (2) the proposed energy consumption prediction model can reduce the prediction error by 13% compared to the most widely used model, EnergyStar.

The experimental results indicate the promise of the proposed ML-based model in supporting building energy benchmarking. But, the classification accuracy for the low- and medium-energy-consumption buildings still needs improvement. Therefore, in their future work, the authors will further improve the model by identifying better ways to classify these two groups of buildings. The authors will also extend the proposed model to the residential sector, apply it in different cities and contexts, and assess if and how it can enhance energy efficiency decision making.

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References

1. Klepeis, et al.: The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Sci. Environ. Epidemiol. **11**(3), 231 (2001)
2. Filippın, C.: Benchmarking the energy efficiency and greenhouse gases emissions of school buildings in central Argentina. Build. Environ. **35** (5), 407–414 (2000)
3. U.S. Green Building Council: LEED v4 for Building Design and Construction. https://new.usgbc.org/leed-v4. Last accessed 27 Apr 2018
4. U.S. Department of Energy: EnergyPlus. https://energyplus.net. Last accessed 27 Apr 2018
5. Chung, W.: Review of building energy-use performance benchmarking methodologies. Appl. Energy **88**, 1470–1479 (2011)
6. U.S. Environmental Protection Agency (EIA): EnergyStar. https://www.energystar.gov. Last accessed 27 Apr 2018
7. Gao, X., Malkawi, A.: A new methodology for building energy performance benchmarking: an approach based on intelligent clustering algorithm. Energy Build. **84**, 607–616 (2014)
8. Sharp, T.: Energy benchmarking in commercial office buildings. Proc. ACEEE Summer Study Energy Effic. Build. **7996**, 321–329 (1996)
9. Yalcintas, M.: An energy benchmarking model based on artificial neural network method with a case example for tropical climates. Int. J. Energy Res. **30**, 1158–1174 (2006)
10. Grolinger, K., Capretz, M.A., Seewald, L.: Energy consumption prediction with big data: balancing prediction accuracy and computational resources. In: IEEE International Congress on Big Data Congress, pp. 157–164 (2016)
11. Roth, J., Rajagopal, R.: Benchmarking building energy efficiency using quantile regression. Energy **152**, 866–876 (2018)
12. Pedregosa, F., et al.: Scikit-learn: machine learning in Python. J. Mach. Learn. Res. **12**(10), 2825–2830 (2011)
13. Wang, L., El-Gohary, N. M.: Data-driven residential building energy consumption prediction for supporting multiscale sustainability assessment. In: Computing in Civil Engineering 2017, pp. 324–332. ASCE (2017)

14. Wang, L., El-Gohary, N. M.: Data-driven approach to identify the impacts of urban neighborhood characteristics on building energy consumption. In: Construction Research Congress 2018, pp. 664–674. ASCE (2018)
15. Edwards, R.E., New, J., Parker, L.E.: Predicting future hourly residential electrical consumption: a machine learning case study. Energy and Build. Energy Build **49**, 591–603 (2012)

Occupants Behavior-Based Design Study Using BIM-GIS Integration: An Alternative Design Approach for Architects

92

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Abstract

Occupant behavior is considered as one of the important factors that can influence the energy consumption of a building, therefore knowing occupant behavior as supporting data can help architects to design more resilient, and sustainable architecture. Employing this data in the design and construction can help with creating more efficient buildings. Simulation can help us to experiment and understand the behavior of the system using these data by creating logical, justifiable, and valid models. Recently, occupancy behavior data has been used in different simulation tools. However, most of the research focusing on indoor navigation does not consider Building Information Modeling (BIM) and its properties while making the occupancy behavior simulation. When it comes to the energy performance of the building, building model should be taken into account as it would help the design team to with a better understanding of the project. In this paper, we used a BIM-GIS platform, to demonstrate how the occupant tracking and behavior pattern extracted from a simulation model using stochastic data can be used as a facilitating information for the design process.

Keywords

BIM-GIS • Occupant behavior • Modeling simulation

92.1 Introduction

As city population and density grow, the environmental impact of buildings becomes more important as how we build our community directly affects the behavior of people [1]. Designers have a decisive role and can make a huge impact on the society by their approach to design. According to the International Energy Agency (IEA), different variables such as climate, building envelope, indoor design criteria and the occupant behavior are considered as factors that affects the energy usage of buildings [2, 3]. As stated by Clevenger and Haymaker [4], unlike other factors, occupant behavior and how people behave and move in the building is highly subjective, which can bring an uncertainty and a significant amount of margin of error to the energy modeling behavior. The type of human-building interactions such as using air conditioner and turning light switches on and off result in consuming a significant amount of energy in buildings [5]. During operational stages, significant energy consumptions and environmental impacts are registered. According to Bottaccioli et al. [6], users behavior leads to 30% energy waste 30% inside the buildings. Moreover, during the occupancy phase, not all the building space is in use and occupied at the same time, this factor leads to a waste of great amount of energy. Therefore, it is important to consider this factor as a benchmark for reaching a passive design as an approach with the goal of reducing the energy consumption by employing natural resources [7].

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The stochastic occupancy pattern can be detected by occupancy sensors, which are commonly installed in today's smart buildings. Therefore, it is a rational idea to utilize the occupancy information in order to reduce the energy consumption caused by human-building interaction while maintaining occupants' comfort. The occupant variable and the behavior tracking are crucial for defining operational and rational services based on the real needs of users, which leads to avoiding energy waste [6, 8]. Many diverse techniques for indoor location and human tracking related to the problem can be found in the literature. The expense and time required to install, configure, and maintain these systems have prohibited general deployment to date. One solution to this problem is to employ occupancy simulation modeling to simulate the behavior and movement of people inside the building using probability distribution and stochastic models [9, 10].

This paper discusses the possible methodologies and techniques for collecting occupancy behavior data, when many inefficiencies of the building process arise and when it is crucial to tailor the services to the occupancy variable patterns. For this reason, a literature review was completed to explain the different methods used by scholars regarding the collection of the users' data in the indoor environment. In the next step, we integrated a BIM-GIS platform with the occupancy behavior information to facilitate the designers into designing a more sustainable, efficient structure.

92.2 Background

In the rising age of technology and smartphones, almost everyone uses Geographical Positioning System (GPS) for navigating between different places. While this satellite-based system is widely used for outside positioning, it is considered inaccurate for indoor tracking and locating applications, therefore, it is not considered as a valid tool in this scenario [11]. While considerable research practices have focused on precise indoor tracking methods, there is still a major scarcity of using indoor tracking in practice [12, 13].

Gathering and analyzing data driven from the occupant movement inside the building can be used for numerous applications. Berbakov et al. [14] used indoor tracking systems in emergent situations, where this system can facilitate occupants' evacuation process, as it can help firefighters to locate and access different parts of the building easily. Grönroos et al. [15] studied the application of using indoor navigation in healthcare settings and how it can be useful by coordinating the movements of the professional personnel. The construction industry also benefits from this system. Using Spot-R, which is a non-GPS system, contractors are able to track the workers and the equipment location in order to maintain the safety of their personnel during the construction process [16]. In addition, many researchers have used the occupant tracking information to achieve a passive design as occupant behavior is considered one of the major factors in building energy consumption [2, 3, 17]. While some of the effects of occupant behavior on the energy consumption, such as adjusting the thermostat and, opening and closing windows are obvious, latent effects of occupants on the comfort zone also exist. These latent effects include the internal heat gain in the space due to the human body temperature's emission into space through radiation, which in turn affects the room temperature [18]. Using an accurate occupant tracking method, the researchers are not only able to track and record the occupant's path and walking pattern inside the building but can also record the number of people in any space at any time. Therefore, using this system as an auxiliary tool can greatly help designers achieve a structure in accordance with the occupant's need, leading to reducing the energy consumption of the buildings. In this regard, Zhang et al. [12] designed and developed "Montage", a framework which facilitates recording real-time multi-user formation tracking and localization using smartphones.

92.2.1 Tracking Devices

Radio frequency-based technologies, Wi-Fi, and Bluetooth are considered as the main methods for occupancy detection [17, 19, 20]. In radio frequency-based technologies such as Radio Frequency Identification (RFID), a particular object, known as Tag, transmit radio waves to the receiver and the receiver then sends the data to the computer [19]. RFID technology makes the building up of indoor localization system with low cost possible [21]. They are accurate but not applicable to phones [13, 22]. Also, the main disadvantage of this system is that it does not rely on the existing infrastructure, meaning that for occupancy tracking, many tags and receivers, depending on the area of the study, must be purchased and installed into the building [19]. Some of the existing methods rely on fingerprints are considered as user intensive and environment restrictive in data collection stage [13].

On the other hand, systems such as WiFi and Bluetooth positioning do not require any addition to the existing infrastructure as almost all of the public spaces nowadays are equipped with WiFi internet system. In addition, WiFi and Bluetooth are the two preferred methods by the Inlocation alliance (ILA), a foundation which focuses on facilitating a high accurate indoor positioning system [23]. WiFi tracking system uses every router as a spotter, getting signals from the smartphone device of the subject that is tracking, this signal is sent to the main server, showing the user location [24]. Çiftler et al. [25] proposed a zone-based occupancy monitoring system in order to broaden the coverage area of the WiFi tacking system. Shin and Cha [26] introduced an indoor user tracking system. The system constructs a topological map with Wi-Fi signal calibrations, assigns semantically meaningful labels into the map, and estimates the semantic location of the user based on the current Wi-Fi observation. Bottaccioli et al. [6] correlated different information by integrating Internet of Things (IoT) devices with BIM and GIS technologies. They used BIM models for monitoring and modeling the energy performance of the building and GIS for providing geo-referenced information about building, distribution systems and deployed IoT devices. Spot-R, which was mentioned previously, is another system which integrates with the BIM model in order to help and accelerate the process of locating and helping construction workers when an accident happens on the jobsite [16].

92.2.2 Simulation Modeling

While employing tracking devices and performing experimental studies can be considered time consuming and costly, model simulation is considered as a tool for developing and experimenting the behavior [27]. Computer simulations can create a model that represents the overall logic of various activities and resources of a project. Feng et al. [28] have used Discrete Event Simulation (DES) process—a process that codifies the behavior of a complex system as an ordered sequence of well-defined events—to model the occupant behavior inside the building. Using this approach, the researcher is able to study the occupant movement inside of the simulated building layout, which will result in more accurate results [9]. In order to employ the data from tracking devices such as WiFi, real time data is needed which due to security and privacy concerns, are not shared by many buildings. In addition, based on the discussed literature, another important criterion than leverages using simulation process instead of tracking devices is the fact that for using devices such as Wi-Fi tracking or Bluetooth, we need an actual, built model. This would limit our degree of freedom in altering the design. On the other hand, simulation can be used as early as the schematic design phase, giving the designers the ability to change their model according to the simulation result in the earlier phase of design and construction process.

92.2.3 BIM-GIS

Unlike the traditional approach to design and construction, the construction industry is now leaning towards integrating data, driven from different resources into the design [29]. Employing dynamic and static data has numerous benefits and advantages such as cost optimization, jobsite and worker safety, accurate estimating, coordination, and communication [30]. BIM is considered the ideal platform for this approach as it contains data and information, using BIM models these factors can be checked and processed automatically which saves time, minimizes the possibility of errors, and leads to a better quality design for the users [29, 31, 32]. Therefore, BIM is currently used in most of the studies which focus on energy analysis, however there is a lack of research which studies the occupant behavior in a building using a BIM-GIS platform.

Geospatial Information System (GIS) data help us to visualize, record, and analyze the geographical information of every data. Building Information Modeling (BIM) as an intelligent technology helps the design-build team to form, manage, and perform more efficient buildings [33]. Many researchers [34, 35] have applied BIM-GIS systems in order to make the construction procedure more efficient. However, in this research, we tend to use BIM-GIS integration to simulate the occupant behavior in confined spaces. It enables the researcher to model any spatial and geographical data in the building while considering all aspects of the building. Using BIM-GIS technology, architects are able to better project and more intuitively describe the occupant behavior in a design scheme, and conduct the analysis based on relevant building technologies and simulation results, to provide a strong basis for evaluation and performance quantification.

92.3 Methodology

The aim of this study was to investigate the application of using occupant behavior and its effect on facilitating the designers and architects toward a more sustainable, resilient design. In order to achieve this goal, a mixed methods approach, including qualitative and experimental studies, was used. First, the study reviewed different methodologies and approaches available

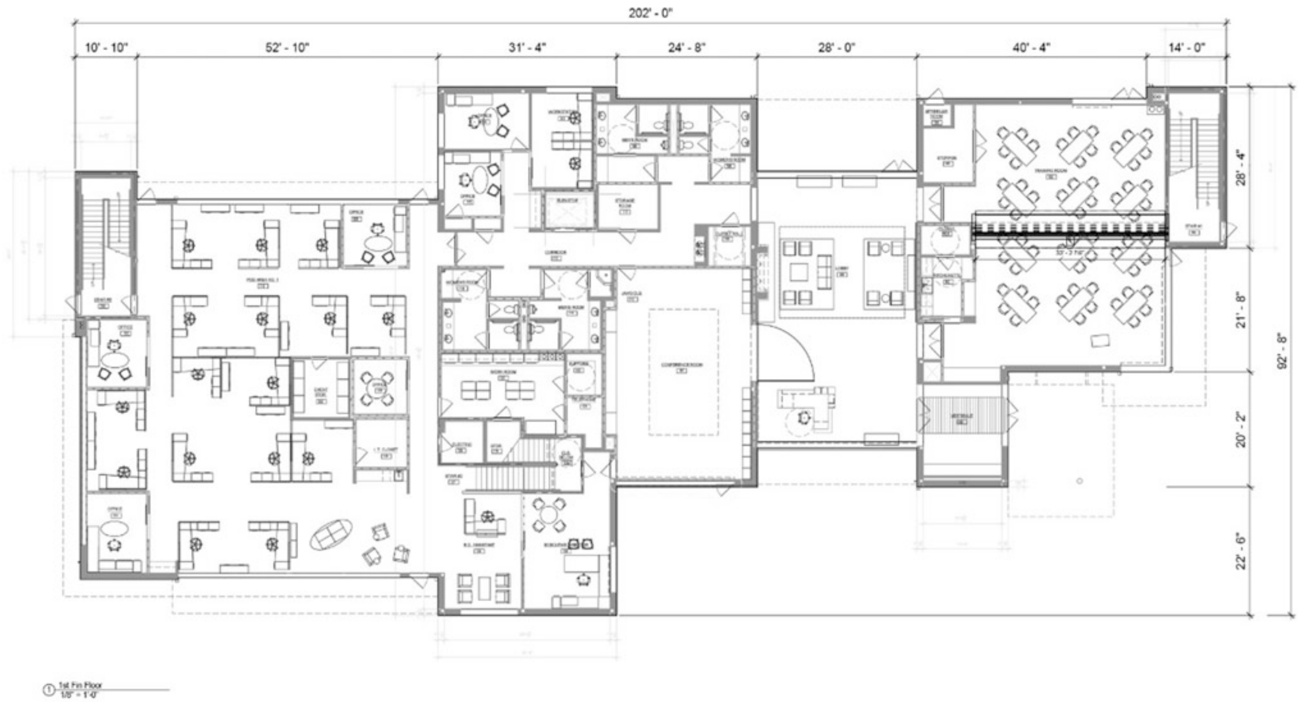

Fig. 92.1 First floor plan

for tracking occupant behavior and discussed their features based on the existing literature. In the next step, in order to show how the data from modeling the human behavior can interact with a BIM-GIS system, we modeled the first floor of an office building located in Dallas, Texas with a total floor area of 13,000 square feet (SF) using Autodesk Revit® and then imported the model into ArcGIS® desktop. The required layers included in the model are polylines as the representation for walls, stairs and doors, and the polygons for spaces. The spaces are important to show the location of occupants and time spent in the space. As shown in Fig. 92.1, this office building contains a large Lobby, a bullpen area with open offices, a conference room, 15 private offices, and restrooms. Occupancy Simulator app version 1.3.2, developed by Lawrence Berkeley National Laboratory, was used to calculate the number of people working and using the building floor at any given [28].

The Markov chain model, a probability distribution simulator tool was used to model occupant behavior inside the building [28]. Each space was defined manually in the simulator system, based on the size and the functionality of the space (e.g. private office, 250 SF). By inputting the space type and the area to the simulator, the number of occupants in each space was calculated by the program based on space density suggested by the Database for Energy Efficiency Resources (DEER) building prototypes. In the next step, the occupancy type was defined based on the pattern of people entering the building. In this scenario, the days of operation for the building was set on weekdays (Monday through Fridays) from 8:30 in the morning to 5:30 in the evening, with the variation of ±30 min. The date and time set for the simulation was April 12 from 8:00 am to 6:00 pm. The result from the whole building simulation is shown in Fig. 92.2.

The results from the simulation were extracted to an Excel® spreadsheet and include the number of individuals in every space through a discrete time of every 10 min, helping the researchers to model the occupant presence and movement inside the building by room. Table 92.1 shows the attribute table for each space. Using the spreadsheet, the researchers selected two peak times during the day which represent the times at which the building is occupied more than the other times during the day. We considered 9:40 and 12:20 pm as two indicators for our model where the total number of occupants in the building is 200 and 240 which are highlighted in Table 92.1.

According to the data shown in Table 92.1, a set of random points was placed into each space using the point feature in ArcGIS®. Each point represents individual occupants and visitors in the building on a weekday during the specified hours. A shapefile was then created as the occupant behavior layer and saved to the office building dataset. The next step involved the aggregation of occupants in each space with the whole building to find what spaces could be considered energy usage hot spots. In order to achieve this goal, the occupant behavior layer dispense was modeled to find the hot spots through the kernel density tool in ArcGIS®. The workflow is shown is Figs. 92.3 and 92.4. The kernel density shapes show the

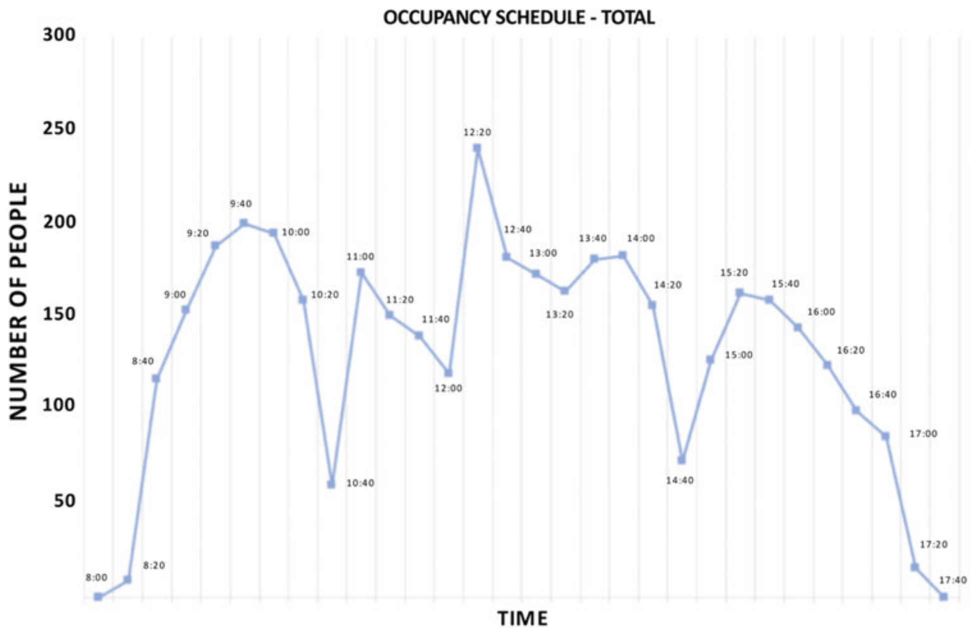

Fig. 92.2 Simulation result

Table 92.1 Simulation result table

Time	Office-Open1	Office-Open2	Office-Open3	Office-Open4	Office-Open5	Office-Open6	Office-Open7	Office-Open8	Office-Open9	Office-Open10	Office-Private1	Office-Private2	Office-Private3	Office-Private4	Office-Private5	Office-Private6	Office-Private7	Office-Private8	Office-Private9	Office-Private10	Office-Private11	Office-Private12	Office-Private13	Office-Private14	Office-Private15	Conference Room	Restroom	Lobby	Whole
8:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8:20	1	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	3	0	1	0	9
8:40	1	1	1	16	0	4	1	1	0	16	1	1	1	0	16	1	0	0	16	1	1	16	16	2	3	0	1	0	117
9:00	0	1	1	16	1	3	1	5	0	16	11	1	11	1	16	1	1	0	16	1	1	16	16	12	3	0	2	1	154
9:20	11	1	12	16	1	1	1	1	6	16	1	1	11	2	16	1	1	0	16	1	1	16	16	12	3	2	5	17	188
9:40	1	1	12	16	3	17	1	1	17	16	1	5	1	1	16	1	6	1	16	1	1	16	16	2	3	10	1	17	200
10:00	1	1	12	16	3	17	1	1	17	16	1	5	2	2	16	1	6	1	16	1	2	12	12	2	3	10	1	17	195
10:20	1	1	12	1	7	17	1	1	17	1	7	20	1	1	1	1	8	1	5	19	1	1	1	2	3	10	1	17	159
10:40	1	1	1	4	1	1	1	1	1	14	7	1	1	1	0	1	1	1	1	1	1	1	1	2	3	9	1	1	60
11:00	1	1	1	9	16	1	1	14	1	1	16	1	16	1	16	1	1	16	1	1	16	1	1	0	16	9	1	14	174
11:20	1	1	1	1	16	0	1	0	1	1	16	1	16	1	16	1	1	16	1	1	16	1	0	15	16	9	0	1	151
11:40	11	0	0	0	16	0	1	0	1	0	16	0	16	1	16	1	11	16	1	0	16	1	0	0	16	0	0	0	140
12:00	1	1	1	1	16	1	0	0	0	0	16	0	16	0	16	0	1	16	0	1	16	0	0	0	16	0	1	0	120
12:20	0	16	1	16	1	16	16	17	0	19	18	1	0	17	12	1	17	1	0	17	18	0	0	16	0	0	4	16	240
12:40	0	16	0	16	1	16	16	17	1	1	0	7	0	17	0	1	17	0	1	17	0	1	1	16	0	0	4	16	182
13:00	1	16	0	16	0	16	16	17	1	1	0	0	1	17	0	1	17	0	3	17	0	1	1	2	0	9	4	16	173
13:20	1	17	17	1	0	1	17	1	1	17	1	14	1	1	1	17	1	1	0	17	0	1	4	2	15	9	5	1	164
13:40	16	17	17	1	1	1	17	1	14	17	1	1	1	1	1	17	6	1	1	17	1	1	1	2	3	9	1	14	181
14:00	16	17	17	1	1	15	17	1	1	17	1	1	19	1	1	17	1	1	1	17	1	1	1	2	3	10	1	1	183
14:20	16	17	17	1	1	1	17	1	1	17	1	1	1	6	1	17	1	1	1	17	1	1	1	2	3	10	1	1	156
14:40	16	1	1	1	1	1	1	1	1	1	1	1	1	4	9	1	1	0	1	1	1	1	1	2	12	9	1	1	73
15:00	16	1	1	1	0	1	1	1	14	1	1	1	1	8	15	11	1	0	14	1	1	12	1	2	3	9	8	1	127
15:20	16	17	6	17	17	1	5	1	1	1	1	1	1	9	11	12	1	0	1	11	1	1	1	2	17	9	1	1	163
15:40	16	1	20	1	1	1	1	1	1	17	1	1	1	19	1	13	17	1	3	3	1	5	1	2	3	9	1	17	159
16:00	16	6	1	7	1	1	1	1	1	17	10	15	1	1	1	3	17	1	1	1	1	16	1	2	3	0	1	17	144
16:20	16	10	1	1	1	10	1	1	1	17	1	0	1	1	1	1	17	0	1	1	1	16	1	2	3	0	1	17	124
16:40	1	2	1	1	1	1	1	1	1	17	1	1	1	5	0	1	17	0	1	1	1	1	19	2	3	0	2	17	100
17:00	0	3	1	0	0	1	1	1	0	17	1	1	0	0	0	1	17	0	1	1	1	1	15	0	3	0	3	17	86
17:20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	1	0	11	0	0	0	0	0	16
17:40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

probability distribution of people in the space, with the center having the most probability of people being there, and the possibility decreases as it gets to the margins of the shape.

92.4 Results

In this paper, we integrated the occupancy behavior data from a simulation app with a BIM-GIS system to create a visual tool to help architects design spaces and buildings based on the anticipated behavior of occupants. Using the proposed method, we were able to zone this office building based on the number of occupants using the space through the day. As shown in Figs. 92.3 and 92.4, the building could be separated into four different zones, where each zone had its own energy usage pattern and strategy. For example, in Fig. 92.3 there is a high concentration of occupants in regions A, B, and C at 12:20 pm. Knowing this information, designers can amend their drawings with the focus on these regions. For example,

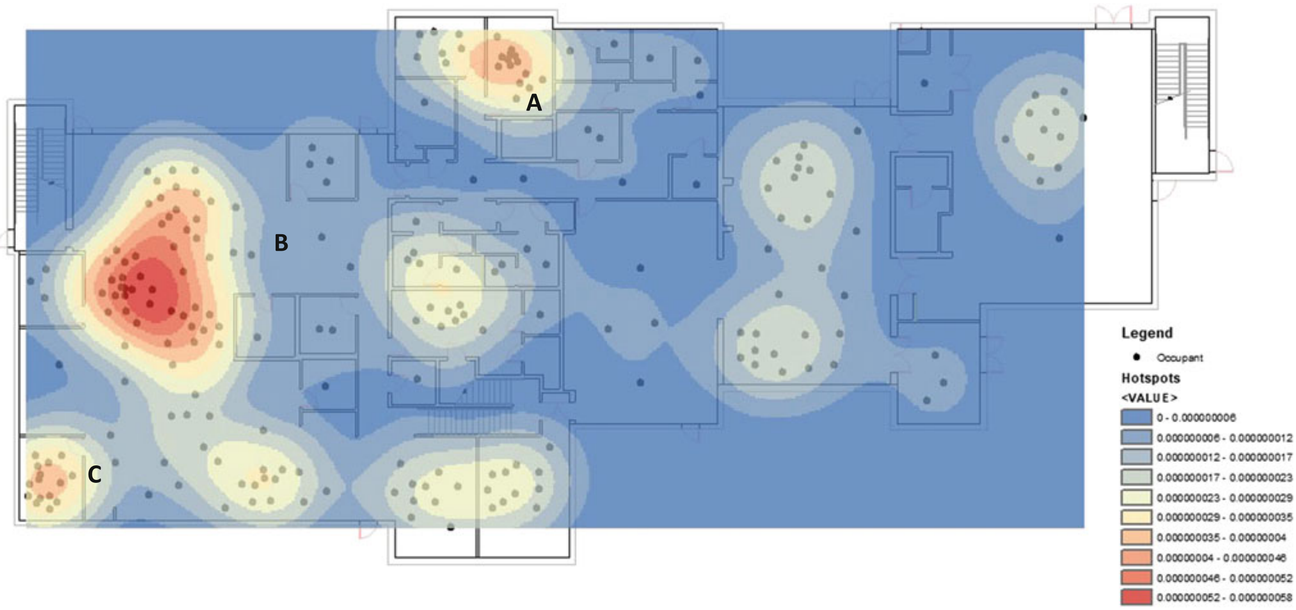

Fig. 92.3 Occupants' probability distribution at 9:40

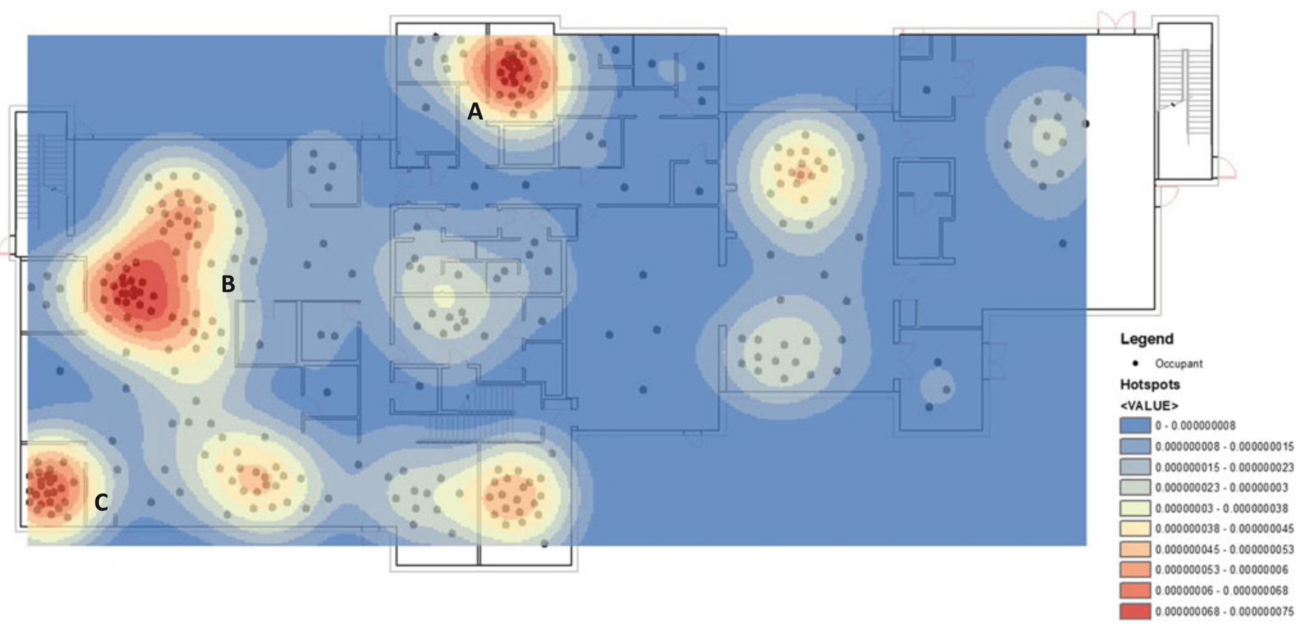

Fig. 92.4 Occupants' probability distribution at 12:20 pm

providing more natural ventilation for these regions or designing in a way that these regions could benefit from natural daylighting could be the result of this simulation.

92.5 Conclusion

This paper presents one way in which a BIM-GIS system could be employed as a platform for the architecture and construction industry to study the occupancy movement and develop more specific, occupant-based design. Integrating the BIM model with the data driven from the simulation using GIS can help to divide the building into different zones based on the occupancy rate and percentage. This visualization and modeling technique serves as a visual tool, helping the architect to design not only according to the building usage, but also according to the occupants of the building and their needs. This zoning would help architects to consider the number of occupants and occupancy peak in different areas a variable in their design, leading to a more optimized design, where different design strategies such as natural ventilation are targeted, located, and created based on the occupant need. Instead of considering the whole building as one static model, the engineers could look at each building individually as a dynamic model.

References

1. Lall, S.V., Deichmann, U.: Density and disasters: economics of urban hazard risk. World Bank Res. Observer **27**(1), 74–105 (2010)
2. Yoshino, H., Hong, T., Nord, N.: IEA EBC annex 53: total energy use in buildings—analysis and evaluation methods. Energy Build. **152**, 124–136 (2017)
3. Yan, D., O'Brien, W., Hong, T., Feng, X., Gunay, H.B., Tahmasebi, F., Mahdavi, A.: Occupant behavior modeling for building performance simulation: current state and future challenges. Energy Build. **107**, 264–278 (2015)
4. Clevenger, C.M., Haymaker, J.: The impact of the building occupant on energy modeling simulations. In: Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada, pp. 1–10 (2006)
5. Von Grabe, J.: How do occupants decide their interactions with the building? From qualitative data to a psychological framework of human-building-interaction. Energy Res. Soc. Sci. **14**, 46–60 (2016)
6. Bottaccioli, L., Aliberti, A., Ugliotti, F., Patti, E., Osello, A., Macii, E., Acquaviva, A.: Building energy modelling and monitoring by integration of IoT devices and building information models. In: IEEE 41st Annual Conference on Computer Software and Applications (COMPSAC), vol. 1, pp. 914–922 (2017)
7. Yasue, R., Habara, H., Nakamichi, A., Shimoda, Y.: Modeling the occupant behavior relating to window and air conditioner operation based on survey results. In: Proceedings of the 13th Conference of International Building Performance Simulation Association, *Chambery*, France (2013)
8. Goyal, S., Ingley, H. A., Barooah, P.: Occupancy-based zone-climate control for energy-efficient buildings: complexity vs. performance. Appl Energy **106**, 209–221 (2013)
9. Chen, Y., Liang, X., Hong, T., Luo, X.: Simulation and visualization of energy-related occupant behavior in office buildings. In: Building Simulation, vol. 10, No. 6, pp. 785–798. Tsinghua University Press (2017)
10. Chen, Y., Hong, T., Luo, X.: An agent-based stochastic occupancy simulator. In: Building Simulation, vol. 11, No. 1, pp. 37–49. Tsinghua University Press (2018)
11. Fang, Y., Cho, Y.K.., Zhang, S., Perez, E.: Case study of BIM and cloud–enabled real-time RFID indoor localization for construction management applications. J. Constr. Eng. Manag. **142**(7), 05016003 (2016)
12. Zhang, L., Liu, K., Jiang, Y., Li, X.Y., Liu, Y., Yang, P., Li, Z.: Montage: combine frames with movement continuity for realtime multi-user tracking. IEEE Trans. Mob. Comput. **16**(4), 1019–1031 (2017)
13. Chintalapudi, K., Padmanabha Iyer A., Padmanabhan, V.N.: Indoor localization without the pain. In: Proceedings of the Sixteenth Annual International Conference on Mobile Computing and Networking, pp. 173–184. ACM (2010, September)
14. Berbakov, L., Pavković, B., Vraneš, S.: Smart indoor positioning system for situation awareness in emergency situations. In: 26th International Workshop on Database and Expert Systems Applications, pp. 139–143 (2015)
15. Grönroos, S., Peltonen, L.M., Soloviev, V., Lilius, J., Salanterä, S.: Indoor positioning system for movement path analysis in healthcare institutions. Finnish J. eHealth eWelfare **9**(2–3), 112–120 (2017)
16. Team, Purdue ECT, "Spot-R by Triax": ECT Fact Sheets. Paper 236. http://dx.doi.org/10.5703/1288284316632 (2018)
17. Akkaya K., Guvenc I., Aygun R., Pala N., Kadri A.: IoT-based occupancy monitoring techniques for energy-efficient smart buildings. In: IEEE Wireless Communications and Networking Conference (WCNC), pp. 58–63 (2015)
18. Thomas, V.C.: Internal Heat Gains (IHG). Received from http://energymodels.com/internal-heat-gains-ihg (2013)
19. Bai, Y.B., Wu, S., Wu, H.R., Zhang, K.: Overview of RFID-based indoor positioning technology. In: GSR (2012)
20. Dardari, D., Closas, P., Djurić, P.M.: Indoor tracking: theory, methods, and technologies. IEEE Trans. Veh. Technol. **64**(4), 1263–1278 (2015)
21. Jin, G.Y., Lu, X.Y., Park, M.S.: An indoor localization mechanism using active RFID tag. In: IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing, vol. 1, p. 4. IEEE (2006)
22. Jin, Y., Soh, W., Wong, W.: An indoor localization mechanism using active RFID tag. In: Proceedings of the IEEE International Conference on Sensor Networks, Ubiquitous Trustworthy Computing (2006)
23. Ball, M.: New Indoor Positioning Indoor Alliance, In-Location, Promotes Indoor Services and Solutions. Received from http://informedinfrastructure.com/1624/new-indoor-positioning-indoor-alliance-in-location-promotes-indoor-services-and-solutions/ (2013)
24. Sapiezynski, P., Stopczynski, A., Gatej, R., Lehmann, S.: Tracking human mobility using wifi signals. PLoS ONE **10**(7), e0130824 (2015)
25. Çiftler, B. S., Dikmese, S., Güvenç, İ., Akkaya, K., Kadri, A.: Occupancy counting with burst and intermittent signals in smart buildings. IEEE Internet Things J. (2017)
26. Shin, H., Cha, H.: Wi-Fi fingerprint-based topological map building for indoor user tracking. In: IEEE 16th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), pp. 105–113. IEEE (2010, August)
27. AbouRizk, S.: Role of simulation in construction engineering and management. J. Constr. Eng. Manag. **136**, 1140–1153 (2010)
28. Feng, X., Yan, D., Hong, T.: Simulation of occupancy in buildings. Energy Build. **87**, 348–359 (2015)
29. Ma, Zhiliang, Ren, Yuan: Integrated application of BIM and GIS: an overview. Procedia Eng. **196**, 1072–1079 (2017)

30. Farnsworth, C.B., Beveridge, Simon, Miller, Kevin R., Christofferson, Jay P.: Application, advantages, and methods associated with using BIM in commercial construction. Int. J. Constr. Educ. Res. **11**(3), 218–236 (2015)
31. Solihin, W., Eastman, C.: Classification of rules for automated BIM rule checking development. Autom. Constr. **53**, 69–82 (2015)
32. Schwabe K., Liedtke S., König M., Teizer J.: BIM-based construction site layout planning and scheduling. In: International Conference on Computing in Civil and Building Engineering (ICCCBE) (2016)
33. Wu, B., Zhang, S.: Integration of GIS and BIM for indoor geovisual analytics. In: Halounova, L., Li, S., Šafář, V., Tomková, M., Rapant, P., Brázdil, K., Shi, W., Anton, F., Liu, Y., Stein, A., (eds.) XXIII ISPRS Congress, Commission II, pp. 455–458 (2016)
34. Irizarry, J., Karan, E.P., Jalaei, F.: Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. Autom. Constr. 241–254 (2013)
35. Alreshidi, E., Mourshed, M., Rezgui, Y.: Factors for effective BIM governance. J. Build. Eng. **10**, 89–101 (2017)

93 Standardization of Whole Life Cost Estimation for Early Design Decision-Making Utilizing BIM

Mariangela Zanni, Tim Sharpe, Philipp Lammers, Leo Arnold, and James Pickard

Abstract

It is becoming increasingly clear that there is a gap between the expected and actual performance of buildings. A growing body of evidence suggests that the most common barrier to achieving design intent is the absence of comprehensive information during design and construction stages, leading to poor decision-making which impacts on performance and Whole Life Cost (WLC). Building Information Modelling (BIM) has the potential to facilitate a more comprehensive and accurate design approach from the early stages. A detailed and accurate model can allow designers and clients to understand the wider impacts of design changes, and to track this information through construction stages. However, dependencies between design decisions and WLC have yet to be understood. This paper is based on a project that focuses on the Private Rental Sector (PRS), which is the fastest growing new sector in the UK housing market, also known as Build-to-Rent (BTR). The study adopts a mixed method approach for the development and validation of a structured standardised process for more accurate WLC estimation through BIM. As a result, the main problems in WLC BIM management are identified, and coordinated into a reverse-engineered systematic process that uses the Integrated DEFinition (IDEF) 3 structured diagramming modelling technique, and the Industry Foundation Classes (IFC) as a basis for large dataset management. The research outputs aim to enhance BIM lifecycle management through a smart decision-making approach that is integral to the natural design development process.

Keywords

Building information modelling (BIM) • Process modelling • nD modelling • Whole life cost (WLC) • Integrated definition (IDEF) language

93.1 Introduction

Several UK construction industry reports have documented the fact that the sector has been suffering from low innovation, and underperformance in terms of productivity and quality of the final product [1, 2]. Hence, the UK Government's target is to achieve a 20% reduction in the capital cost of buildings (CapEx) [1] and a 33% reduction in Whole Life Cost (WLC) [2]. In fact, research has shown that over a 30-year life, the cost of operating the asset could be as much as four times the cost of designing and constructing the building, and that 80% of the operation, maintenance, and that replacement costs of a building can be influenced in the first 20% of the design process [3, 4]. However, buildings rarely perform as expected [5, 6]. This can impact on sustainability and building performance, but also factors such as energy consumption and operational costs (OpEx) [3, 7]. It has been argued that the most common barrier to achieving design intent is the absence of

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comprehensive information during design and construction stages, leading to poor decision-making, which impacts on performance and WLC [8, 9].

As a consequence, the need for a more holistic approach to building design is gaining momentum. There are several technologies that are expected to play a part in the transition from linear to circular economic growth: the internet of things, the cloud, big data, and Building Information Modelling (BIM). BIM has proven its potential to facilitate the building development process during planning, designing, construction, and operation [10]. Nevertheless, to date, BIM has focused on the design and construction of the built asset. Therefore, although the use of BIM for calculating CapEx has become commonplace, its potential to be used for estimating WLC is not yet utilized. Several BIM software solutions have been developed with the aim of calculating WLC, but none of them offers the complete solution [11]. Thus, there is the need to bring together different approaches into a standardised framework that utilises the existing technological enablers by establishing links between them. More importantly, it is essential to specify information requirements and exchange procedures.

To achieve this step change, current working processes have to be re-examined and re-engineered [12] so as to follow a more concurrent approach for WLC assessment [3]. Concurrent Engineering (CE) principles have been successfully implemented in manufacturing, for mapping the design process so as to make it explicit. Process mapping (using structured diagramming techniques) helps in the identification of tasks that add value to the project, and the elimination of bottlenecks. However the mapping of building design processes presents bigger challenges since its nature and variability is fundamentally different from the manufacturing process [8], particularly due to the bespoke nature of buildings. Nevertheless, it is believed that a CE approach would ensure sustainable development at every stage of the building life cycle, hence upholding the principles of designing to a cost, as opposed to costing a design [13]. A detailed and accurate model can allow designers and clients to understand the wider impacts of design changes, and to track this information through construction stages.

This paper is based on a project that examines how BIM policies, technologies, and processes can facilitate more accurate prediction of WLC more efficiently in terms of time and effort involved to achieve quality assurance. As such, WLC considers all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements. This holistic approach could produce high-performance buildings that are both cost-effective and sustainable, but also mitigate risks to building owners. The project will demonstrate how cost information related to maintenance and performance of a completed building can be incorporated during design delivery, from the early stages, in order to make decisions that are critical for the timely assessment of WLC. This paper provides an overview of the state-of-the-art of WLC assessment through BIM, investigating factors that affect its efficient implementation. Then, it describes a standardised approach for its implementation using conceptual process modeling and the Integrated DEFinition (IDEF) 3 structured diagramming technique.

93.2 Background and Related Work

The project focuses on the Build-to-Rent (BTR) housing sector [14]. Affordable housing tenure under a single management, and assessed viability that recognizes distinct tenure economics are key principles for increasing the quality and quantity of BTR [15]. Thus, for the investor, assessing the long-term viability of such developments is a critical issue. For that reason, WLC evaluation must provide a careful breakdown of cashflow that goes beyond the CapEx. This includes level of amenities offered along with maintenance decisions. Nevertheless, current research that demonstrates performance gaps [5, 6] represents a significant threat. It is proposed that BIM can provide a more integrated and rigorous approach for assessing viability of BTR schemes while maintaining high performance standards for quality, thus offering a competitive approach through improved customer service.

93.2.1 WLC Definition and Scope

WLC has been defined in BSI ISO 15686-5:2008 [16] as a methodology for systematic economic consideration of all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements over a period of analysis, as defined in the agreed scope. Nevertheless, researchers have stressed the lack of standard methods and format for calculating WLC as the main barrier for its implementation [17]. This creates the urgent need for the development of standardised protocols for BIM-enabled WLC estimation, integrated from the early design stages. However, WLC cannot be the only measure for assessing a project's viability, nor the only indicator that should be used as a method for future-proofing a design. Intangibles such as user comfort, amenity and efficiency lead to increased occupant satisfaction, and are associated with financial implications [3].

93.2.2 Sources of Data

The accuracy of WLC assessment substantially depends on the quality and availability of data from all phases of a building [12]. Sources of data can be [7]: (i) Unstructured historical data; (ii) Structured historical data; (iii) Data from modelling; and (iv) Data from manufacturers, suppliers and specialist contractors. While historical data are used for prediction during design, dynamic data from sensors are used for monitoring actual performance so as to make comparisons. Over time, the data could also be used to generate a historical database that in turn will be used for briefing, as well as predictive design. At present the literature suggests lack of longitudinal studies that focus on monitoring the performance and reliability of systems [18, 19]. A major problem that limits the effectiveness of building decision support tools is the difficulty to obtain accurate data from various sources related to a building [20].

93.2.3 Integrative Design Process

During development, WLC integration can assist designers to identify optimal solution and areas where performance may be threatened. Such decisions placed in a strategic (organizational) framework, can create added value for the asset and help to identify the most cost-effective operations and maintenance regime. Related research efforts have attempted to integrate aspects of WLC within BIM processes by linking CapEx assessment to design development [21, 22], while others have focused on environmental aspects [20, 23, 24]. Studies that aimed to integrate WLC with BIM have resulted in solutions that are not comprehensive [11], or require manual inputting of cost data [25]. A CE process enables decision-making to be integrated within the design development process, creating soft-gates between hard-gates (design stages) during phase-gate review. Following this principle, conflicts are highlighted, compared to the initial plan, and thus resolved in a timely manner.

93.3 Research Strategy and Methods

This study adopts an abductive approach, utilizing mixed methods, for the development and validation of a structured standardised process for more accurate WLC estimation through BIM.

93.3.1 Framework Development

The first phase of the research was exploratory. Methods implemented include literature review and purposive sampling, which included a series of interviews and workshops with a design team, two tier-1 contractors, two major national developers, engineers, product manufacturers, software providers/developers, an insurance company, and a cost consultant specialist in WLC for the BTR. Thematic analysis [26] was implemented to develop a theoretical framework that identified the main problems in WLC BIM management.

93.3.2 Conceptual Process Modeling Using IDEF3

The second phase is an iterative process of developing a detailed model that clearly links information requirements to design decisions that are critical for the timely assessment of WLC during the delivery of BTR projects. The chain of interdependencies is determined following the Critical Decision Method [27]. These are coordinated explicitly into a reverse-engineered systematic process that uses the IDEF3 structured diagramming modelling technique [28]. The research outputs aim to enhance BIM lifecycle management through a smart decision-making approach that is integral to the natural design development process. The IDEF3 method was selected due to its high descriptive power, which is considered appropriate for detailed processes that handle know-how knowledge. IDEF3 captures descriptions about sequences of activities, while also identifying critical decision points, or milestones, of the process from different perspectives [28]. IDEF3 has specifically been developed to model stories (situation or process) as an ordered sequenced of events and activities [29]. It is a scenario-driven process flow modelling method created to map descriptive activities. The goal of IDEF3 is to provide a structured method for expressing the domain expert's knowledge about how a particular system, or organization, works (ibid.).

93.4 Findings and Results

The following aspects of WLC estimation have been found to be critical for its successful implementation through BIM.

93.4.1 WLC Software Capabilities

Selection of the most appropriate software is extremely important in order to streamline the working process and achieve doing more with less effort [30]. The questions that designers should consider regarding a software tool fall within the categories of ease of use, time and cost, interoperability, input, output, and accuracy [31]. Furthermore, in terms of transparency, computer-based WLC programs can be distinguished between glass box and black box ones depending on the visibility of the process [7]. Table 93.1 contains a comparison of the WLC assessment software tools reviewed. It has been found that while the use of BIM for calculating CapEx has become commonplace, its potential for calculating OpEx has not yet been utilized. Some tools (CATO by Causeway, and Impact from BRE) have claimed that are able to estimate WLC, but further investigation has revealed that they implement simplistic approaches. For example, CATO has no links to databases containing cost data, whereas WLC estimation is based on a simple entry of a service life for the whole building, resulting in a high-level generic estimation. The BRE Impact cost database is static (does not get updated) and its current focus has shifted towards environmental assessment. Bionova's One Click LCA has been found to be the most comprehensive option for WLC estimation, since it utilizes data from several cost databases that get updated on a regular basis, while also being compliant with British Standards [3].

93.4.2 Interoperability and Data Structure

It has been inferred that the BIM-enabled estimation process is not completely automatic, as BIM-based quantity take-offs do not provide all the necessary data to create the cost estimate and a bill of quantities [32]. In fact, researchers have claimed that the bill of quantities exported from the BIM is often unreliable and inaccurate [33]. Nevertheless, review of state-of-the-art readily available software tools, and demonstrations by their providers, has shown a fully automated process for extraction of quantities. Further research is necessary to determine the quality of information extracted, which is dependent partly on the modelling method followed, but also on technological limitations, irrespectively of the modelling method used.

The use of open standards is recommended for enabling information exchange that is not restricted by proprietary formats, assisting in better communication between project team members that utilize specialised software tools. This study

Table 93.1 Comparison of WLC estimation software tools

Tool	CapEx	OpEx	LCA	BIM	Location
Causeway CATO	X	X		X	UK
One Click LCA	X	X	X	X	Finland
IMPACT	X	X	X	X	UK
Butterfly	X	X	X		UK
Beck Tech Destini	X			X	Texas
CostX	X			X	UK
RICS BCIS		X			UK
Tocoman	X			X	Finland
Trimble VICO	X			X	USA

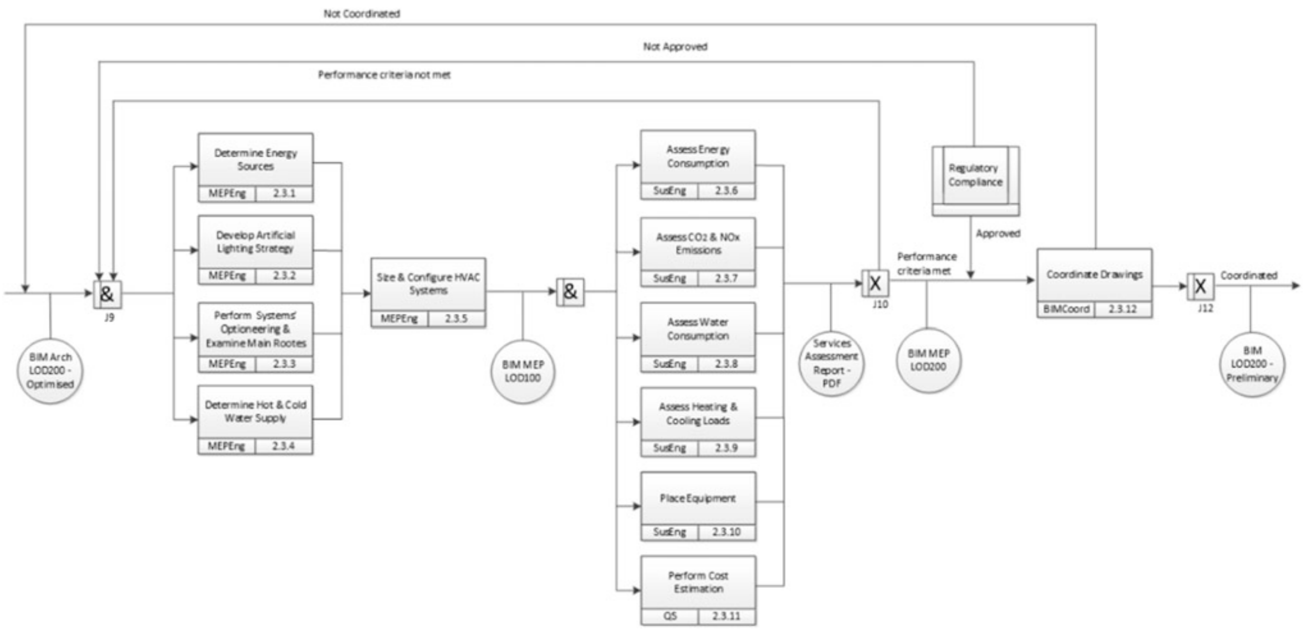

Fig. 93.1 IDEF3 decomposition of UOB "configure mechanical services"

utilizes the IFC, which has a hierarchical structure. Its basic building blocks are equivalent to real elements, including their properties. Although the IFC format can cover a wide range of data, various BIM systems do not fully comply with this standard [34]. To find out how much of WLC information can be integrated into the BIM model (as it is used for Level 2 compliance), the Construction Operations Building Information Exchange (COBie) and IFC structures have been mapped to indicative economic lives (CIBSE Guide M) and maintenance data requirements (SFG20).

93.4.3 Information Flows—Process Model Development

Previous research supports the idea that traditional processes cannot be employed to achieve complex high-performing buildings, and that a CE design process approach to WLC assessment is essential [8, 9]. During the traditional building design process, each stakeholder passes fixed information to the next one, which results in compromised design outcomes. What the CE approach suggests, is that design solutions are developed, assessed, and revised collaboratively, as design progresses [35]. Thus, a single linear prescribed process is not viable, because the complexity, amount of specialization and individual project needs do not permit the process to be defined without iterations.

In fact, the importance of decision points has been stressed in PAS 1192-2:2013 [36] as a critical aspect of the collaborative process. For this reason, this research strives to identify the critical decision points for WLC and align these with the appropriate WLC considerations and criteria. The decision points comprise two types of gates; hard-gates when the design freezes until the review is conducted, and soft-gates that allow the project to proceed in parallel, enabling a CE approach. It is suggested that the hard-gates serve the purpose of committing to decisions collectively, while soft-gates are identified throughout the process so that critical decisions occur in parallel. Instead of design participants working in isolated silos, between the hard-gates (start and end of design stages), the soft-gates identified during the Work-in-Progress (WIP) phase can facilitate communication by triggering design tasks so as to clarify the process for practitioners and reduce uncertainty. Figure 93.1 shows an example of a detailed IDEF3 decomposition of UOB "Configure Mechanical Services".

93.5 Discussion and Conclusion

The paper discusses the need for a holistic approach to BIM management through a dynamic process of integrating WLC estimation gradually during design development as opposed to costing a design at specific stages. Defining information requirement granularity, while considering trade-off relationships between economic and environmental factors, streamlines the design development process, and allows committing to decisions safely, reducing rework and delays. However, the lack of common methodologies for WLC in the construction industry has resulted in issues such as scope and definition rarely being clearly recorded [3]. The research findings support the idea that BIM technologies can assist in the accurate estimation of WLC of an asset, from the early design stages, through the implementation of standardised information exchange procedures as it enables a more holistic approach to what is currently a fragmented development system. It can therefore be assumed that, for BTR, repeatable tasks and similar workflow patterns, roles and responsibilities can be identified. This finding enables the development of a systematic approach for BIM-enabled WLC assessment, based on CE principles [35]. This approach would allow lessons learnt from operation to be incorporated in the design of future buildings and bridge the design/operating performance gap by providing the feedback loop that is so lacking at present. Thus, it is argued that BIM processes have the potential to optimize performance of all design and construction stages, and during post-occupancy, closing the loop of the building design delivery, reducing performance gaps, and achieving the triple-bottom-line goals of sustainability. Despite the potential, there remain many challenges to be faced before accomplishing fully automated, integrated, and interoperable data, as described by the Level 3 BIM maturity definition.

93.5.1 Challenges to WLC Estimation Using BIM

The study revealed several issues that hinder the use of BIM for a whole-of-life approach:

- Models delivered by project team members are not fit for purpose containing insufficient or unproperly structured information.
- Technological capabilities limit the integration of WLC information into BIM models.
- Availability, accuracy, reliability of cost and performance data as well as accessibility and structure of available data.
- Skills and involvement of design team's members and facilities' managers (e.g. lack of experience to interrogate the quantities/assessments produced).
- Procurement strategies are focusing on CapEx instead of OpEx.

93.5.2 Next Steps

Further work needs to be done to establish the effectiveness of the developed process. The next step is to test this concept through the design of a BTR project (or several PRS projects at different design stages) in order to inform and refine the initial model. Moreover, Post Occupancy Evaluation (POE) studies will supplement the validation of the process model by identifying gaps between actual and predicted performance, and more importantly the reasons that cause them. For that purpose, both qualitative and quantitative data need to be collected so as to triangulate the research findings. More research is also required to determine:

- Granularity of information that is possible and efficient to be incorporated into the BIM model (including dynamic feedback from sensor data).
- Criticality of design decisions, prioritization of design criteria, and trade-offs between design parameters.
- Tolerances that can be estimated and attributed to BIM components in order to reflect the level of uncertainty of performance and cost predictions.
- Ways to analyze and visualize WLC assessment results into simpler representations so that they can be used by the design team to set performance targets and inform decision-making during design development.

References

1. Cabinet Office: Government Construction Strategy, GOV.UK (2011)
2. Government, H.M.: Construction 2025: Strategy, GOV.UK (2013)
3. BSI, British Standards Institution: BS ISO 15686-5:2017 Buildings and constructed assets—service-life planning. Part 5: Life-cycle costing (2017)
4. White, G., Boyne, P.: Facilities management. In: BIM and Quantity Surveying. Routledge (2016)
5. BSRIA: BG 64/2016—Building Performance Evaluation in Domestic Buildings—A BSRIA Guide (2016)
6. Sharpe, T., McGill, G., Gupta, R., Gregg, M., Mawditt, I.: Characteristics and Performance of MVHR Systems—A Meta Study of MVHR Systems Used in the Innovate UK Building Performance Evaluation Programme (2016)
7. RICS: RICS Professional Guidance: Life Cycle Costing. RICS (2016)
8. Zanni, M.A.: Communication of sustainability information and assessment within BIM-enabled collaborative environment. PhD Thesis, Loughborough University (2017)
9. Zanni, M.A., Soetanto, R., Ruikar, K.: Towards a BIM-enabled sustainable building design process: roles, responsibilities, and requirements. Archit. Eng. Des. Manag. **13**, 101–129 (2017)
10. Eastman, C.C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Engineers and Contractors. Wiley, Designers (2011)
11. Dawood, S., Lord, R., Dawood, N.: Development of a visual whole life-cycle energy assessment framework for built environment. In: Winter Simulation Conference, pp. 2653–2663 (2009)
12. Krigsvoll, G.: Life cycle costing as part of decision making—use of building information models. Construction 433–440 (2007)
13. Matipa, W.M., Kelliher, D., Keane, M.: How a quantity surveyor can ease cost management at the design stage using a building product model. Constr. Innov. **8**, 164–181 (2008)
14. Urban Land Institute (ULI): Build to Rent Best Practice Guide, 2nd edn. ULI UK Residential Council (2016)
15. Mayor of London: Homes for Londoners: affordable housing and viability supplementary planning guidance (2017)
16. British Standards Institution.: Standardized method of life cycle costing for construction procurement: a supplement to BS ISO 15686-5:2008 Buildings and constructed assets—service life planning—Part 5: life cycle costing. BSI (2008)
17. Opoku, A.: The application of whole life costing in the uk construction industry: benefits and barriers. Int. J. Archit. Eng. Constr. **2**, 35–42 (2013)
18. Pittard, S., Sell, P.: BIM and Quantity Surveying. Routledge (2016)
19. Fu, C., Kaya, S., Kagioglou, G., Aouad, M.: The development of an IFC-based lifecycle costing prototype tool for building construction and maintenance. Constr. Innov. **7**, 85–98 (2007)
20. Kulahcioglu, T., Dang, J., Toklu, C.: A 3D analyzer for BIM-enabled life cycle assessment of the whole process of construction. HVAC R Res. **18**, 283–293 (2012)
21. Sabol, L.: Challenges in Cost Estimating with Building Information Modeling (2008)
22. Cheung, F.K.T., Rihan, J., Tah, J., Duce, D., Kurul, E.: Early stage multi-level cost estimation for schematic BIM models. Autom. Constr. **27**, 67–77 (2012)
23. Basbagill, J., Flager, F., Lepech, M., Fischer, M.: Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build. Environ. **60**, 81–92 (2013)
24. Wang, W., Zmeureanu, R., Rivard, H.: Applying multi-objective genetic algorithms in green building design optimization. Build. Environ. **40**, 1512–1525 (2005)
25. Kehily, D., Underwood, J.: Embedding life cycle costing in 5D BIM. J. Inf. Technol. Constr. **22**, 145–167 (2017)
26. Braun, V., Clarke, V.: Using thematic analysis in psychology. Qual. Res. Psychol. (2006)
27. Klein, G.A., Calderwood, R., Macgregor, D.: Critical decision method for eliciting knowledge. IEEE Trans. Syst. Man Cybern. **19**, 462–472 (1989)
28. Mayer, R.J., Menzel, C.P., Painter, M.K., Dewitte, P.S., Blinn, T., Perakath, B.: Information Integration for concurrent engineering (IICE)—IDEF3 process description capture method report. DTIC Document (1995)
29. Mayer, R.J.: IDEF Family of Methods for Concurrent Engineering and Business Re-engineering Applications. College Station, Texas (1992)
30. Smith, D.K., Tardif, M.: Building information modeling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers. Wiley, Hoboken (2012)
31. AIA: An Architect's Guide to Integrating Energy Modelling in the Design Process. The American Institute of Architects (2012)
32. Monteiro, A., Martins, J.P.: A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. Autom. Constr. **35**, 238–253 (2013)
33. Aibinu, A., Venkatesh, S.: Status of BIM adoption and the BIM experience of cost consultants in Australia. J. Prof. Issues Eng. Educ. Pract. **140**, 04013021 (2014)
34. Kogut, P., Tomana, A.: 4D and 5D applications in BIM technology (2013)
35. Love, P.E.D., Gunasekaran, A.: Concurrent engineering in the construction industry. Concurr. Eng. **5**, 155–162 (1997)
36. BSI: PAS 1192-2:2013—Specification for information management for the capital/delivery phase of construction projects using building information modelling. CIC (2013)

Data Model Centered Road Maintenance Support System Using Mobile Device

94

Satoshi Kubota

Abstract

Maintenance management is an essential operation that should be carried out effectively for maintaining, repairing, and rehabilitating highways and roads. It is necessary to accumulate information produced during the entire life cycle of roads in order to analyze problems and find solutions within a temporal sequence and to maintain them strategically and effectively. The primary objective of this study is to solve above problems on road maintenance and maintain the road efficiency. This paper proposed a road maintenance support system based on product data model using mobile devices. Product data models enable the exchanging and sharing of road information among those involved in road maintenance. The system consists of two use cases: in office and on site. In road administrator's office, the system is based on two-dimensional paper-based maps and three-dimensional printed models output by a three-dimensional printer. It supports the discussion of maintenance plans and enables sharing the maintenance plan and existing inspection results by using photographs from tablet computers and smartphones in combination with radiofrequency identification (RFID) tags. The system accumulates the photographs of notes and supports referring to them on-site using RFID, QR codes, and a global navigation satellite system. This system consists of two parts: a method of indicating important inspection points on-site by using AR markers, and reference management of inspection and rehabilitation data by using RFID and QR codes. The proposed system was evaluated the usability and capability. The evaluation results indicated usability and capability on site usage.

Keywords

Road maintenance • Inspection • Product data model • Mobile device

94.1 Introduction

Roads are networks that connect civil infrastructure and facilitate the delivery of emergency services. Because of their importance, they should be safe and kept in good condition. Maintenance management is an essential operation that should be carried out effectively for maintaining, repairing, and rehabilitating roads. It is important that the maintenance process is effective and that the quality of inspection is ensured. Cost-effective and high-quality maintenance depends on reliable inspection and assessment of conditions [1]. Furthermore, the need for reliable maintenance information influences management systems [2]. Because existing management systems do not use standardized information, they cannot exchange, share, and reuse information. For effective road maintenance, it is necessary to develop a system in which the latest and highest-quality road information can be used and shared. This would facilitate road planning, design, construction, inspection, and repair.

The primary objective of this study is to solve the above problems related to road maintenance and efficiency. This paper proposed a road maintenance support system based on product data model using mobile devices. Product data models enable

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the exchanging and sharing of road information among those involved in road maintenance. The system consists of two use cases: in office and on site. In road administrator's office, the system is based on two-dimensional paper-based maps and three-dimensional printed models output by a three-dimensional printer. It supports the discussion of maintenance plans and enables sharing the maintenance plan and existing inspection results by using photographs from tablet computers and smartphones in combination with radiofrequency identification (RFID) tags. The system accumulates the photographs of notes and supports referring to them on-site using RFID, QR codes, and a global navigation satellite system. The proposed system is evaluated the usability and capability. Field data were taken along the Shiraito Highland Way, Nagano Prefecture, Japan. Shiraito Highland Way is a road defined by the Road Transportation Act, and it is maintained and operated by a private company. It is around 10 km in length, and its elevation varies from 1000 to 1400 m.

94.2 Road Data Model

Road data models are constructed so that the information within the information management system can be shared among those involved in road management. A road data model is defined as the product data model of a road structure. Product data model is examined in respect of the method representing product and shape information over life cycle of the product. It is defined as the model including shape, technology information of composing members, production information for fabricating and inspecting members, management information of addition, amendment, and deletion, and information for assembling members. Product data models of civil infrastructure facilities have been developed by various organizations and research institutions [3–9]. However, the attributes defined in these data models and in the data model schemas differ from those in road data models.

Road data models can be classified into two types: geometry information models and business information models. Geometry information models contain information associated with the constituent parts of roads. Business information models contain the information necessary for road management work as well as the results of information analysis produced as the result of such work. In constructing the geometry information models, design and dimensional information was extracted from the models. This includes information about the composition of particular structures, information from the design and construction stages, and information that should be stored for use in future road management work. Information regarding the composition of structures includes information about roads, slopes, bridges, tunnels, and ancillary items. Information that should be stored includes the results of work such as inspections, repairs, and strengthening of structures. In constructing the business information models, the information resulting from construction, inspection, detailed inspection, and repair and strengthening was extracted. Figure 94.1 shows a road data model. The location-based expressions "GM_Point," "GM_Surface," and "GM_Polygon" are defined so as to connect the road data model to map information. An information management system was developed on the basis of the proposed idea. A road data model is constructed such that information within the information management system can be shared among those involved in road management.

94.3 System Design

94.3.1 Design Concept

In this study, a road maintenance system is proposed for sharing decision making with road administrators and inspectors with the aim of performing inspection operations efficiently. Figure 94.2 shows the concept of the system design. The system targets discussion of road inspection in the road administrators' office and at road inspection sites. In the discussion of inspection, the proposed system uses two-dimensional paper-based maps and three-dimensional printed models in Fig. 94.2(1, 2). The road administrators and inspectors in local government and road administration offices are used to using the two-dimensional paper-based maps on their road maintenance works. A physical model has the ability to improve communication of spatial understanding. This could lead to improved productivity, reduction of errors, and better quality for construction tasks. The three-dimensional printed models have the capability which the road administrator and inspectors can recall actual shapes on their maintained roads. For the reasons stated above, this system used two-dimensional paper-based maps and three-dimensional printed models.

At the inspection sites in Fig. 94.2(3), inspectors use a tablet computer for referring to the existed inspection and repair results and other maintenance information, based on QR codes or RFID tags attached to kilo-posts. The inputted data are stored as a text file and photographs of inspection results.

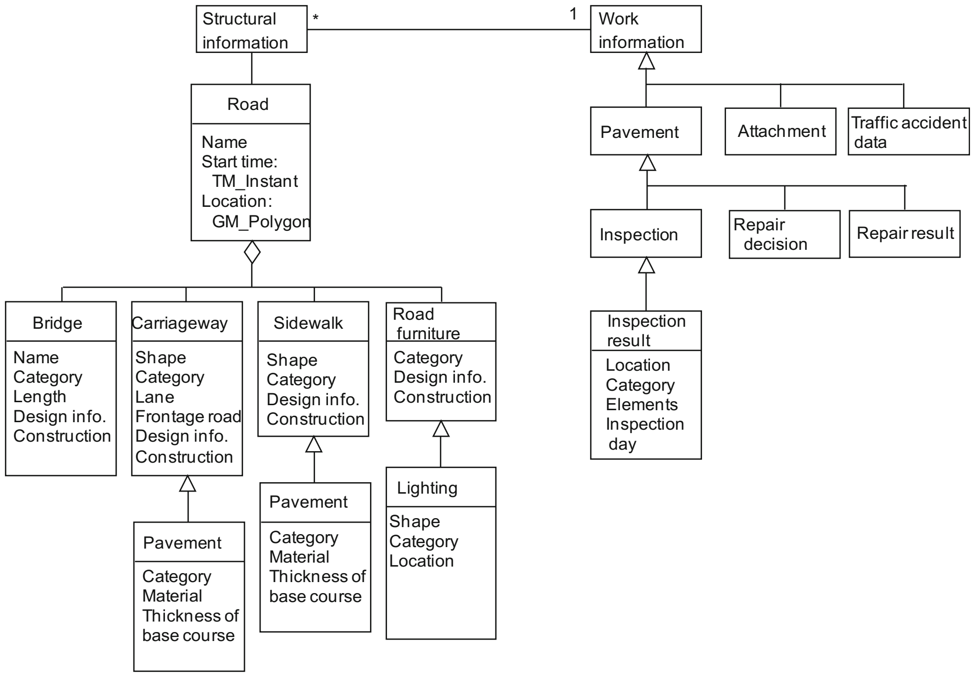

Fig. 94.1 Road data model

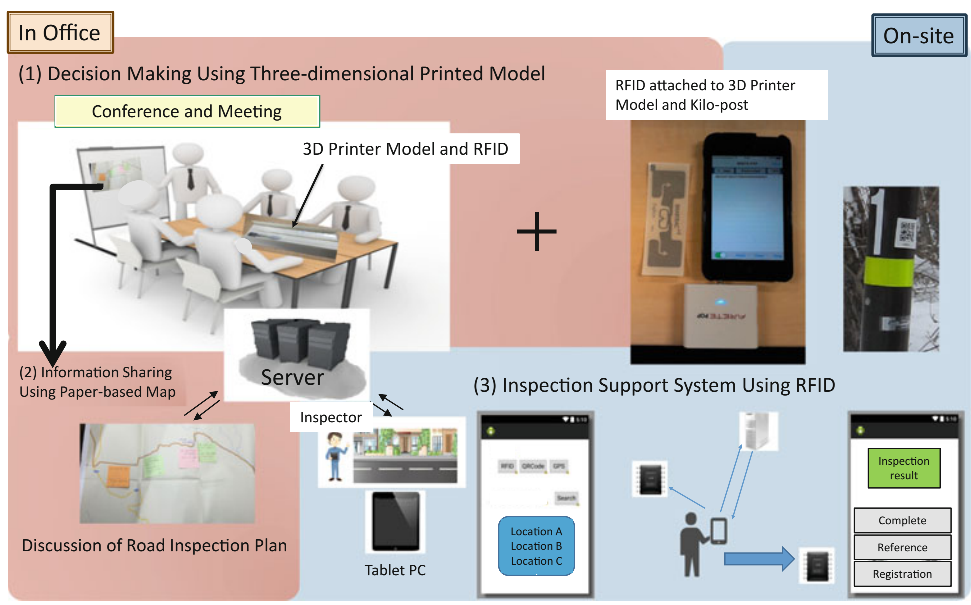

Fig. 94.2 System concept

94.3.2 Design Principles

Concept of Model Oriented Management System. For maintenance, a high-accuracy management system is required, and therefore, analyzed information in the life-cycle should be accumulated. This system is used in each phase of design, construction, inspection, soundness evaluation, deterioration forecasting, and maintenance planning. The system database serves to support each stage of the life-cycle. For operating the management system, standardized information should be accumulated and shared according to the product data models and the long-term service stage of roads. It is difficult to define

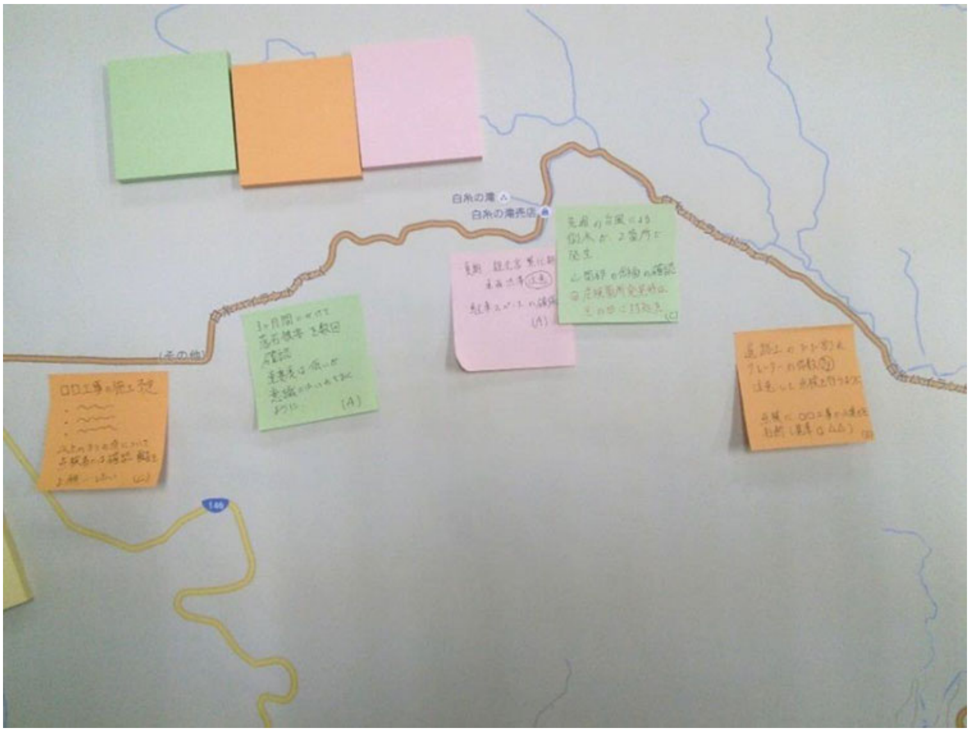

Fig. 94.3 Two-dimensional map for discussion

a unified set of information to be used in various existing systems and databases because of feasibility and operation. Standardized information can be exchanged and shared by exchanging maintenance information through the product data models in the maintenance management system and databases.

System Use in Discussion of Road Inspection. Road engineers discuss the important inspection points for constructing an inspection plan. In this system, two-dimensional paper maps (A0- or A4-sized), sticky notes, a three-dimensional printed model, RFID tags, and mobile devices are used. When road administrators discuss the inspection plan during a workshop, they record the key points to check during inspection and the points most likely to be overlooked on sticky notes and attach these notes to the two-dimensional paper map. The sticky notes capture details such as potholes, cracks, and wind-fallen trees. RFID tags are attached to the three-dimensional printed model. The three-dimensional model is used for understanding real landforms and the situation [10]. Figure 94.3 shows the two-dimensional map for discussion. Road engineers take a photograph of sticky notes and register them on the digital map of the system.

System Use at Inspection Sites. A road inspection support system is proposed and developed. This system has two main design principles, namely, the use of AR markers and QR codes, for accumulating and extracting maintenance information. An AR marker is used for indicating important inspection points, and a QR code is used for accessing and browsing maintenance information at the site. In this research field, it is difficult to use a global navigation satellite system because trees grow thickly over the road. Mobile devices such as smartphones and tablet PCs are used for reading the AR markers and QR codes.

94.4 Development of System

94.4.1 Construction of Three-Dimensional Printed Model

The road structures are printed in three dimensions by a three-dimensional printer. Models of this kind can represent the physical layout [10]. In this study, the three-dimensional printer was the MF-2000 (Mutoh Engineering). RFID tags were attached on the three-dimensional printed model.

94.4.2 RFID Usage

The three-dimensional model with attached RFID tags is used in the office. Road engineers discuss previous inspection results, using RFID tags attached to the model for understanding the inspection operation and previous results. The RFID reader has a range of about 1 m and can read multiple tags. This system uses RFID tags (rather than barcodes or QR codes) for collecting and retrieving maintenance information about the sites. Figure 94.4 show an RFID tag, a reader, and a three-dimensional printed model. And, it shows a three-dimensional printed model with RFID tags. The system uses ARETE POP (PHYCHIPS) for RFID readers, the corresponding SDK for system programming, and DogBone M4D Wet (SMARTRAC) for RFID tags.

94.4.3 System Functions

The proposed system has two functions: registration and serving as reference for registered information. The registration function has two subfunctions used in the office: registration of sticky notes on the paper map, as captured by photographs of the paper map after discussion; and reading and writing the tag information on the three-dimensional printed model, which is done by the Android application. There are two functions used at sites: inputting the inspection results and storing photographs of damage, cracks, and places chosen as relevant by inspectors. Maintenance information is registered using the markers on the digital map.

AR and QR Code Function. The AR function was used for indicating important inspection points on road structures. This function indicates these points using the AR marker method. It is difficult to use a marker-less method in this research field because there are cases in which a three-dimensional AR model cannot be represented owing to shade and other environmental characteristics. AR markers are attached to the past damage points of main girders, crossbeams, and drainages. Figure 94.5 left shows s three-dimensional model of an AR marker on a bridge (indicted by an arrow).

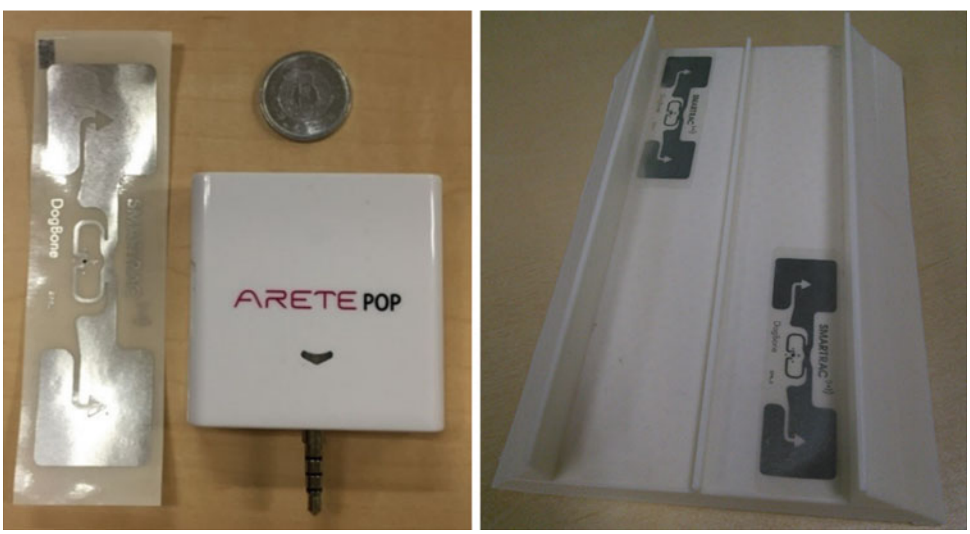

Fig. 94.4 RFID tag and compatible reader and three-dimensional printed model

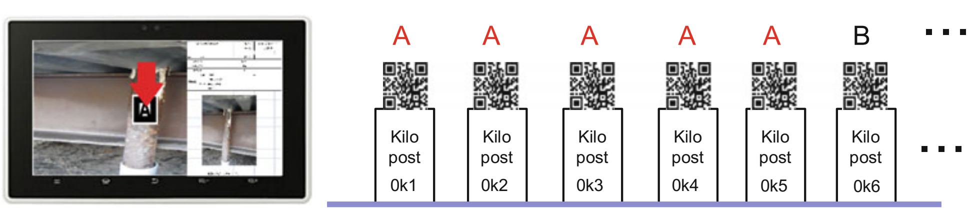

Fig. 94.5 AR marker on bridge and QR code on kilo post

The QR code function was used for referring to the inspection and repair data on-site. QR codes are attached to kilo posts, as shown in Fig. 94.5 right. When mobile devices read a QR code, they access the server and call up the inspection data of pavements, road slopes, directional arrows, and signs with kilo posts at 100-m intervals. Shiraito Highland Way is around 10 km in length. Therefore, there are 100 kilo posts, each with QR code. The inspection data, taken from 2013 data about Shiraito Highland Way, are stored in Microsoft Excel files, and they include the inspection and damage records of bridges, pavements, road slopes, directional arrows, and signs. The same QR code is attached to five kilo posts, 0k1, 0k2, 0k3, 0k4, and 0k5.

94.5 Evaluation of System

94.5.1 Experimental Scenario

The proposed system was evaluated on Shiraito Highland Way for confirming its usability, applicability for a local road administrator, and operation of the system. An experiment was conducted on January 29 and 30, 2015 and January 19, 2016. Four users participated in the evaluation, including three members of the road administration staff and one construction consultant engineer. In the experiment, QR codes were attached to the upper end position and side of 20 kilo posts from the origin to 2 km. A laptop PC was used as the server. The users used a tablet PC (Android ASUS Memo Pad HD7). Figure 94.6 shows a user reading the QR code and referring to the inspection data. In office, the participants discussed the inspection plan, using a prepared two-dimensional paper map and a three-dimensional printed model with RFID tags. The proposed system was used to register photographs and to both reference and register inspection results via RFID tags. And, Fig. 94.6 shows a scene from discussion using the proposed system. Finally, participants used the system at the site. An RFID tag was attached to the upper end position and side of the kilo-post. Figure 94.6 shows a user reading the RFID tag and referring to the inspection data. The proposed system displays are shown in Fig. 94.7.

94.5.2 Consideration

The authors conducted a semi-structured interview with the three users to evaluate the system. The KJ method (sometimes called the "affinity diagram method") was applied to qualitatively analyze the interview results. The KJ method is a group consensus technique. It named for its inventor, Jiro Kawakita (the Japanese put their last names first), allows groups to quickly reach a consensus on priorities of subjective, qualitative data.

Figure 94.8 shows the result of the KJ method. The opinions of engineers were classified to usability and applicability of the system and function requirements. The KJ-Method really does work to get an objective group consensus out of a collection of subjective, opinionated data. It is simple and easy to do. It focuses the group on the task at hand and is excellent at eliminating unnecessary discussion and distractions from the goal.

Usability. The users could refer to inspection data without the need for detailed operating instructions and could understand which places were discussed because the two-dimensional map was matched to a digital map by the system. The

Fig. 94.6 Experimental scenes in office and on site

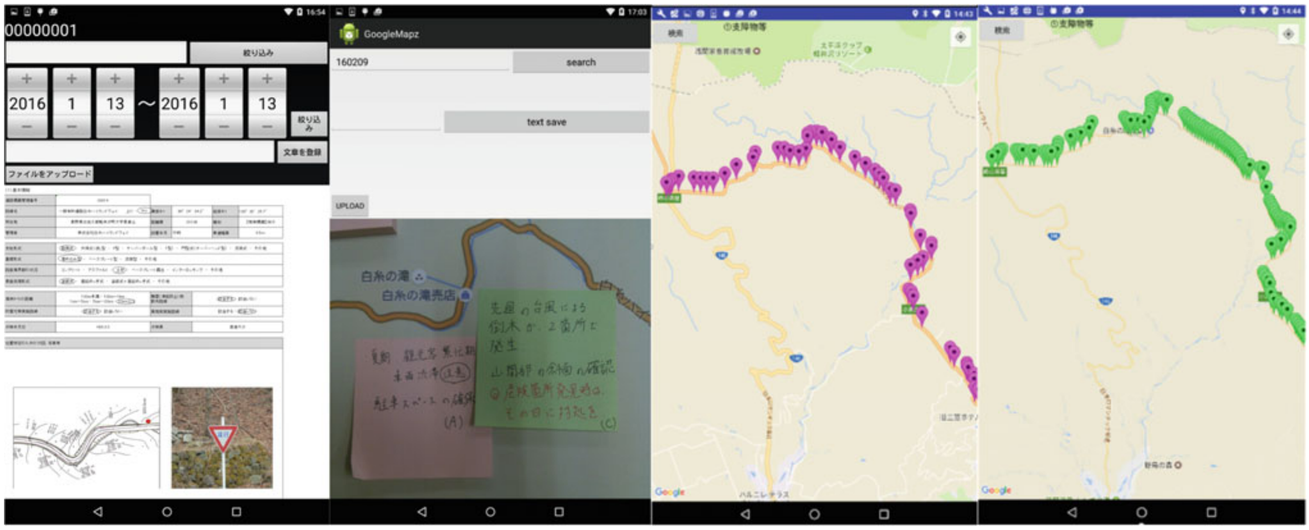

Fig. 94.7 Screenshots of proposed system

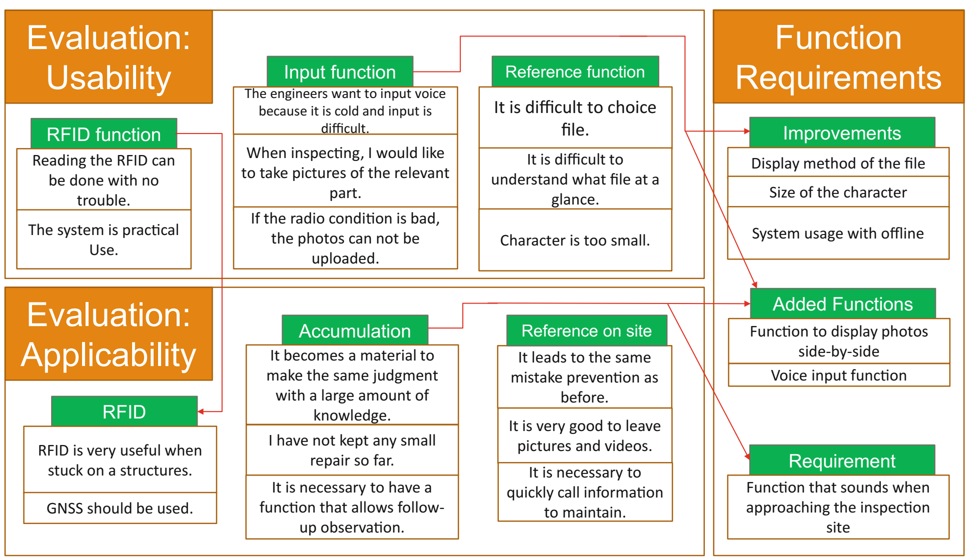

Fig. 94.8 Interview result using KJ method

design concept is suitable because road administrators can use the system with a tablet computer both in office and on-site without requiring a detailed manual. However, the users said that it was difficult to coordinate files without support from the system for Japanese-language file names and that a voice input function would improve usability. The users said that it was useful to refer to the inspection data of pavements, directional arrows, and so on based on the nearby kilo posts. By providing the ability to refer to inspection data on-site, the need to bring road ledgers is avoided. Furthermore, the user said that the system would be more effective if daily inspection data, the amount of which will continually increase, are stored and managed in this system.

Applicability. In terms of application capability, the system can be used to share the decision-making process between engineers in an office and inspectors at the field site. The system has some useful features, such as indicating important inspection points using AR markers and managing the temporal nature of the stored data by using QR codes. And, by using a two-dimensional paper-based map, the inspectors can check the points which have an inclination to miss on the sites in an accustomed manner. It seems to indicate that using a mobile device to access data is helpful using product data model concept. It is better to share the discussion information between office and site than the existing method using only information system. By using a three-dimensional printed model and RFID tags, inspectors could understand the inspection location visually. The proposed system can indicate important inspection points and manage the maintenance information. This system seems likely to be practical for use in road maintenance. The system has some useful features, such as indicating important inspection points by using RFID tags on a three-dimensional printed model.

However, it has a few shortcomings that may limit its practical use, as mentioned above. The AR marker and QR code should be used together. The AR markers could be used in an office meeting to represent the three-dimensional model of road structures and road curves using AR. The QR codes could be used for maintaining construction equipment. Furthermore, the system should provide registration function for inspection and repair data. And, the three-dimensional printed model and two-dimensional paper map could be used in an office meeting to support making decisions about inspection. Furthermore, the users said that the system would be more effective if daily inspection data, the amount of which will continually increase, were to be stored and managed in this system.

94.6 Conclusion

This study proposed a road maintenance system for sharing maintenance information between engineers of different skill levels and for understanding decision-making about inspections. This system used AR markers for indicating important inspection points and QR codes for referring to the inspection data of pavements, road slopes, directional arrows, and signs. And the system is based on two-dimensional paper-based maps and three-dimensional printed models output by a three-dimensional printer. A road data model was constructed based on the product data model concept.

The proposed system supports discussion and sharing of maintenance plans and retrieving maintenance plans and existing inspection results by using photographs taken with a tablet computer and smartphone along with RFID tags. The discussion results are attached to the two-dimensional map after being written on sticky notes. The system accumulates photographs of the sticky notes and supports referring to them at the site; for this, it uses RFID tags, QR codes, and a global navigation satellite system. A three-dimensional printed model is constructed to simulate the road structures, and RFID tags are attached to the model.

The suitability of the proposed system was evaluated through experiments on Shiraito Highland Way, Nagano Prefecture, Japan. The results indicated that the system is suitable for discussing and sharing maintenance information in office and on site and is suitable for its task. The proposed system could possibly be used practically for road maintenance.

The main contribution of this study is a significant effort to extend the applicability of the product data model. The system approach is based on a road data model. It is necessary to update the road data model to use these data for maintenance operations. The proposed system has a data model framework that can be applied to road asset management.

References

1. Osama, A., Hussien, T.A.: As-built information model for bridge maintenance. J. Comput. Civil Eng. **17**(2), 105–112 (2003)
2. Thompson, P.D., Sobanjo, J.O., Kerr, R.: Florida DOT project-level bridge management models. J. Bridge Eng. **8**(6), 345–352 (2003)
3. Stumpf, A., Ganeshan, R., Chin, S., Liu, L.: Object-oriented model for integrating construction product and process information. J. Comput. Civil Eng. **10**(3), 204–212 (1996)
4. Karim, A., Adeli, H.: OO information model for construction project management. J. Constr. Eng. Manag. **125**(5), 361–367 (1999)
5. Hastings, J., Kibiloski, J., Fischer, M., Haymaker, J., Liston, K.: Modeling to support construction planning of the Stata Center project. Leadership Management Engineering **3**(2), 86–90 (2003)
6. Chau, K., Anson, M., Zhang, J.: Four-dimensional visualization of construction scheduling and site utilization. J. Constr. Eng. Manag. **130**(4), 598–606 (2004)
7. El-Diraby, T., Lima, C., Feis, B.: Domain taxonomy for construction concepts: toward a formal ontology for construction knowledge. J. Comput. Civil Eng. **19**(4), 394–406 (2005)
8. Owolabi, A., Anumba, C.J., El-Hamalawi, A., Harper, C.: Development of an industry foundation classes assembly viewer. J. Comput. Civil Eng. **20**(2), 121–131 (2006)
9. Halfawy, M.M.R., Froese, T.M.: Component-based framework for implementing integrated architecture/engineering/construction project systems. J. Comput. Civil Eng. **21**(6), 441–452 (2007)
10. Dadi, G.B., Goodrum, P.M., Taylor, T.R.B., Maloney, W.F.: Effectiveness of communication of spatial engineering information through 3D CAD and 3D printed models. Vis. Eng. **2**(9), 1–12 (2014)

Ontology-Based Semantic Modeling of Disaster Resilient Construction Operations: Towards a Knowledge-Based Decision Support System

95

Sunil Dhakal and Lu Zhang

Abstract

Construction sites are dynamic and complex; they are the most vulnerable environments to natural disasters such as hurricanes. Wind-caused damage to the construction sites could cause millions of dollar losses, considerable schedule delays, and threats to both worker safety and public safety. Therefore, there is sorely a need to enhance the overall resilience of construction projects and implement resilient construction operations. However, there is a lack of research that focuses on enhancing the resilience of construction operations during the construction phase as most existing research focuses on enhancing the structural resilience of the completed buildings or infrastructures. There is a lack of holistic and systematic knowledge that ensures whole life-cycle disaster management of construction projects. To address the gap, this paper aims to develop an ontology-based semantic model of disaster resilient construction operations to formally represent and reason about the knowledge of resilient construction operations during wind disasters. This paper starts by presenting the research method, and it follows by presenting our initial modeling and validation efforts towards a formal semantic model on disaster resilient construction operations. Finally, the paper discusses our proposed framework for a knowledge-based decision support system that allows for knowledge access, classification, and transfer on disaster resilient construction operations. The model, together with its potential application of the knowledge-based system would allow construction professionals to share and transfer domain-specific knowledge on construction disaster resilience, which will eventually contribute to enhance the whole life-cycle disaster resilience of construction projects.

Keywords

Ontology • Semantic model • Disaster resilient construction operation • Disaster resilience • Knowledge management • Decision support system

95.1 Introduction

Disasters, either natural or man-made, are responsible for approximate 57 billion annual cost in the U.S., in terms of injuries and life cost, property destruction, emergency services, etc. [11, 15]. Construction sites, comparing to completed infrastructures and buildings, are more vulnerable to disasters as they include incomplete structures and unsecured materials and equipment. They are the most vulnerable environments to natural disasters such as hurricanes [1]. In addition to the wind-caused property damage to the construction sites, disasters could cause significant schedule delays, millions of dollar losses, and they also threaten the safety of both the construction workers and the public. For example, during Hurricane Irma,

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three construction cranes at South Florida construction sites bent and collapsed, which caused severe losses to the projects and posed major threats to the public safety [18]. Therefore, there is sorely a need to enhance the overall resilience of the construction sites as well as construction operations before, during and after disasters.

Despite the evident needs of enhancing construction resilience, there are several theoretical and practical gaps that remain unresolved. First, there is a lack of research that primarily focuses on enhancing the resilience of construction operations during the construction phase. Although there is an abundant of existing research (e.g., [7–9, 20]) in the areas of resilient buildings and infrastructures, most of this research focuses on enhancing the resilience of completed buildings or infrastructures. For example, Cerè et al. [8] focused on analyzing the effects of geo-hazards and enhancing the resilience of the structures of completed buildings. Campanella [7] focused on the practices during the disaster preparedness phase for enhancing the resilience of urban infrastructures to minimize the loss of life. Thus, most of the studies on disaster resilience, especially hurricane disaster resilience, have been limited to completed buildings or infrastructures, and less attention has been paid on how hurricanes could damage the vulnerable construction sites and their surrounding environments. Second, the existing practices and safety rules for the construction operations (e.g., [16, 17]) are limited in supporting overall disaster resilience as they include the general plans that primarily focus on the mitigation and preparedness phases of disaster management such as transporting building materials and equipment to a safe place, bracing equipment and structures at the hurricane warning phase. Therefore, there is a lack of holistic and systematic knowledge before, during and after the disasters that ensures whole life-cycle disaster management of construction projects.

To fill these gaps, we aim to propose an ontology-based semantic knowledge-based decision support system (DSS) that allows for the access, classification, and transfer of knowledge on disaster resilient construction operations (DRCOs). As the first step of the work, this paper focuses on discussing our proposed ontology-based semantic model of DRCOs to formally represent and reason about the knowledge of DRCOs. The model serves as the foundation for developing the semantic knowledge-based DSS. This paper presents our initial modeling and validation efforts towards a formal semantic model on DRCOs. It also discusses our proposed framework for the knowledge-based DSS.

95.2 Methodology

We benchmarked and adapted the methodology of ontology development by El-Gohary and El-Diraby [10]. First, the domain, purpose, potentials users, and scope of the proposed semantic model of disaster resilient construction operations (DRCOs-Onto) were defined. Second, a set of competency questions (CQs) were developed for which the semantic model should be able to answer [10, 12]. These questions were used to formulate and evaluate the DRCOs-Onto. Three main types of CQs were developed: (1) inheritance CQs that define "is-a" relationships between concepts (e.g., what are the sub-concepts of a DRCO?) (2) modality CQs that define DRCO modalities and modality families (e.g., is incomplete structural integrity enhancement a physical resilient operation?) (3) relational CQs that define relationships between concepts (e.g., who is involved in a DRCO)? Third, the taxonomy (concept hierarchy) was built through two main iterative steps: (1) extraction and identification of the main concepts of the domain and (2) organization of these main concepts into a hierarchical taxonomy. The concepts of the domain were extracted based on the review of the specific literature about the construction process, operations, and disaster resilience in construction (e.g., [3, 5, 11, 13, 19, 21, 22]). Fourth, the ontology model was evaluated by checking conformance with CQs. We will also conduct expert interviews and application-oriented evaluation to evaluate the representation, coverage, consistency, clarity, conciseness, extendibility, and applicability of the DRCOs-Onto as part of our future work.

95.3 Main DRCOs-Onto Model

The DRCOs-Onto is composed of concepts, relations between the concepts, and axioms. Concepts represent the "things" that describe the process of DRCOs. Relations define the interactions between the different concepts. Axioms specify the definitions of concepts and relations, they also define the rules and requirements for DRCOs.

The upper-level model, which shows the most abstract concepts of the model, is depicted in Fig. 95.1. As per Fig. 95.1, the DRCOs-Onto has the following main concepts: disaster resilience technique operation, actor, resource, disaster resilient technique, constraint, disaster resilience objective, disaster resilient outcome, and context.

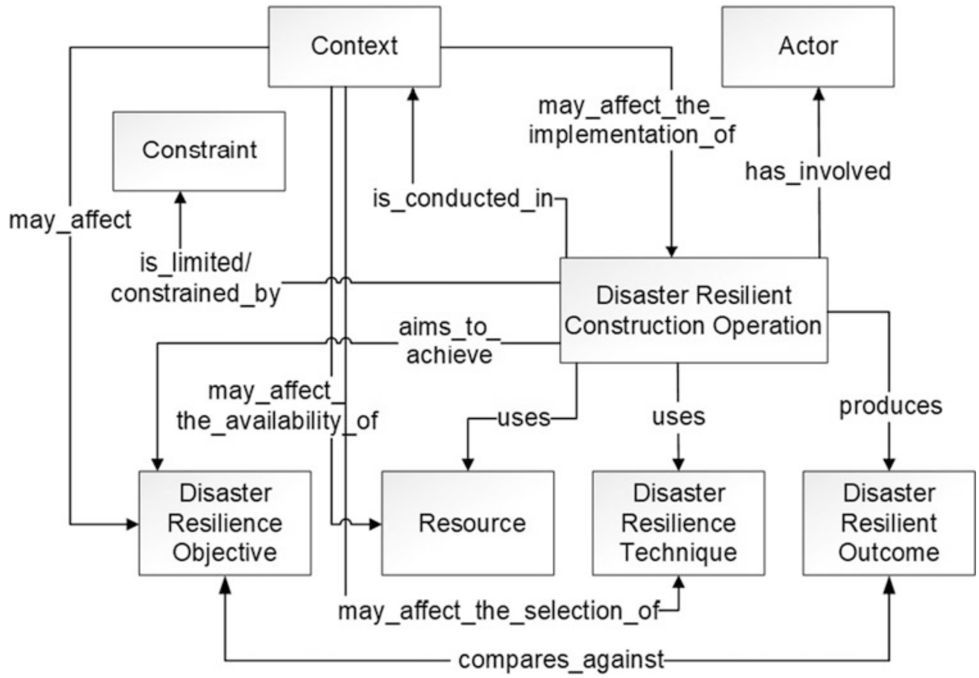

Fig. 95.1 Main DRCOs-Onto model

A "disaster resilient construction operation" has an "actor" involved. An "actor" is the personnel that plays a role in disaster resilient construction, such as a superintendent, a field engineer, an emergency personnel, etc. A "disaster resilient construction operation" aims to achieve a "disaster resilience objective" using a "resource" and a "disaster resilience technique". A "resource" is defined as the source and supply of the required items for a DRCO to obtain a disaster resilient outcome. It is a physical resource (e.g., material, equipment, human resource), a financial resource (e.g., budget of the project), and a knowledge item (e.g., construction schedule report). A "disaster resilience technique" is defined as a method or a technique that operates a DRCO, and it is a disaster resilience guideline (e.g., risk mitigation strategy), a disaster resilience method (e.g., risk management technique), and a disaster resilience measure (e.g., impact test, ductility test). A "disaster resilient construction operation" aims to achieve a "disaster resilience objective", and it produces a "disaster resilient outcome". A "disaster resilience objective" is a specific goal that a DRCO aims to achieve, such as generating knowledge of construction disaster resilience or building a disaster resilient structures; while a "disaster resilient outcome" is a consequence or an effect of implementing a DRCO. A "disaster resilient construction operation" is limited or constrained by a "constraint". A "constraint" is a specific condition that limits a DRCO. It is either an internal constraint (e.g., project budget, project specification, stakeholder's requirement) or an external constraint (e.g., engineering practice, regulatory body, work environment condition). A "disaster resilient construction operation" is conducted in a "context". A "context" is a set conditions, circumstances or parameters that affects or has an influence on a DRCO. A "context" may affect the implementation of a "disaster resilient construction operation". For example, the location of a residential building project (e.g., in Miami) may affect the selection of construction materials (e.g., concrete blocks, high strength masonry cement) that can withstand the category five hurricanes.

95.4 Disaster Resilience Concept Hierarchy

As a preliminary effort in developing the DRCOs-Onto, in this paper, we focus on presenting the concept hierarchy for DRCOs. The concept of DRCO was classified according to the different modalities to support polymorphic views of the same concept. Modality is used to define the belonging criteria of a concept to a family [10]. For example, "incomplete structure integrity enhancement" can be viewed as a "physical resilient operation", a "robust operation", and a "disaster mitigation operation" depending on the perspectives of construction operation impact, resilience characteristic, or disaster management cycle.

95.4.1 Construction Operation Impact Modality View

In the DRCOs-Onto, the main modality view is the construction operation impact modality view (as shown in Fig. 95.2). Construction operations have an impact on or change human society in different dimensions, such as the physical buildings or infrastructures, the society, the economy, and the environments. Therefore, a DRCO can be classified as a "physical resilient operation", a "social resilient operation", an "economic resilient operation", or an "environmental resilient operation". By benchmarking the literatures in the disaster resilience domain (e.g., [2, 6, 19, 22]), the definitions of the sub-level concepts are described below.

For physical resilient operations, six sub-level concepts were defined:

(1) Integrity enhancement is an operation that enhances the ability of either an under-construction structure (i.e., incomplete structure) or an equipment to support a designed load without breaking during the disasters.
(2) Quality control is an operation that aims to ensure the appropriate use of disaster-resistant materials and equipment to support disaster resilience.
(3) Resource management is a process that ensures the availability of labor/manpower, equipment, and materials and utilizes them in the most effective way during the disasters.

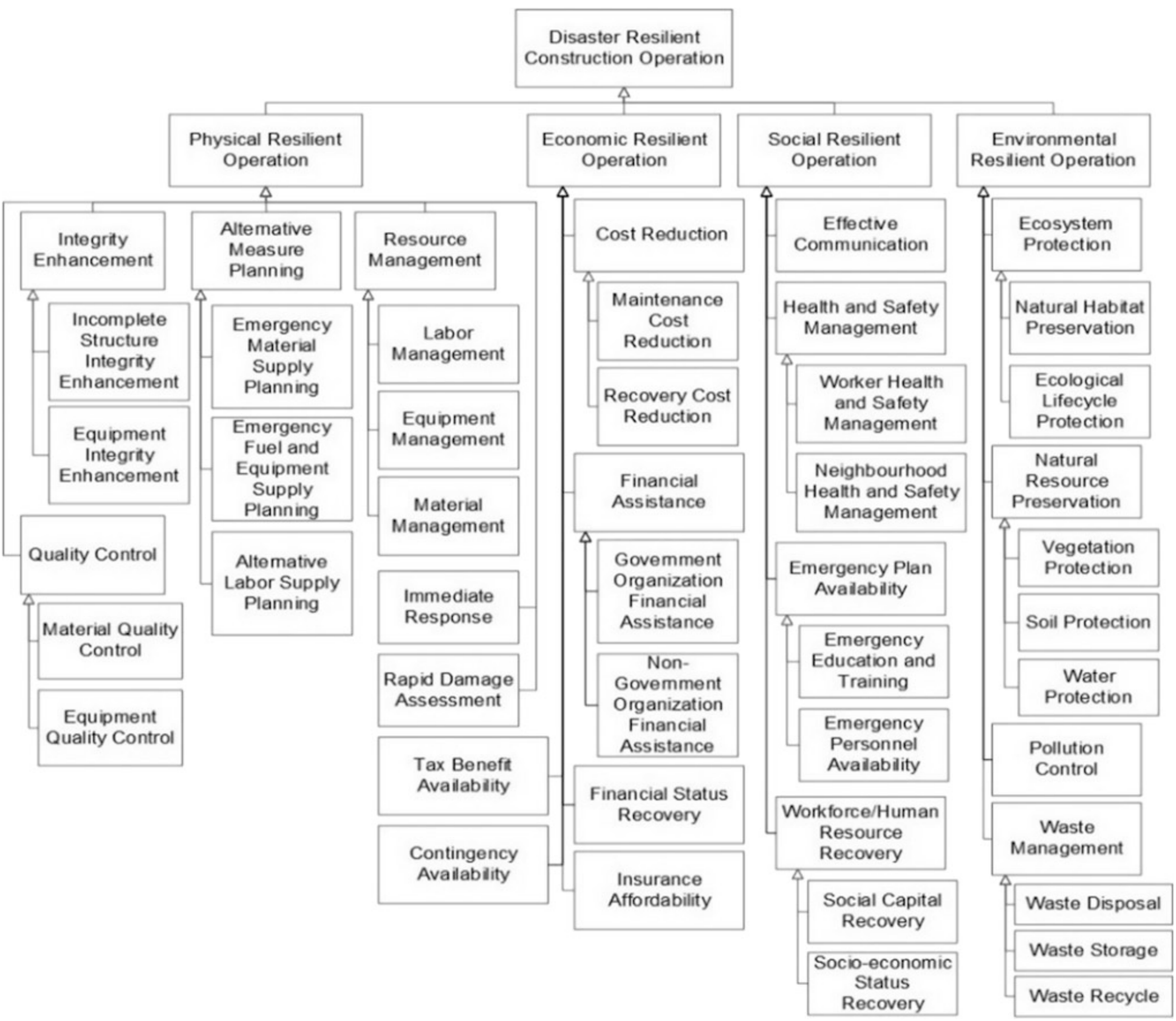

Fig. 95.2 Construction operation impact modality view

(4) Alternative measure planning is a process that provides a back-up plan for emergency supply of materials, equipment, labor, and services to ensure the functioning of the construction projects after the disasters.
(5) Immediate response is an action that is performed immediately after the disasters to save lives and mitigate property damage.
(6) Rapid damage assessment is an operation that is conducted immediately after the disasters to estimate or assess the resources needed to recover from the disasters.

For economic resilient operations, six sub-level concepts were defined:

(1) Cost reduction refers to the reduction in maintenance cost and recovery cost after the impact of the disasters.
(2) Financial assistance refers to the assistance provided by either the government or non-government organizations to recover the construction projects to its original functional level.
(3) Tax benefit availability refers to the provision of tax exemptions or benefits to support DRCOs.
(4) Insurance affordability refers to the affordability of insurance to support the recovery of property (e.g., incomplete structure, equipment) damage during the disasters.
(5) Contingency availability refers to the availability of reserved fund that could be utilized to recover in case of property damage due to the disasters.
(6) Financial status recovery refers to the recovery of financial situation of the construction projects after the disasters.

For social resilient operations, four sub-level concepts were defined:

(1) Health and safety management refers to the operation that supports the health and safety of workers and neighborhood around the construction sites during and after the disasters.
(2) Effective communication refers to the operation that facilitates effective communication between the individuals or organizations that are involved in the construction projects during the disasters.
(3) Emergency plan availability refers to the availability of an emergency plan that is used to mitigate the impact of disasters.
(4) Workforce or human resource recovery refers to the operation through which individuals or organizations attain their wellness or their full potential level after the disasters.

For environmental resilient operations, four sub-level concepts were defined:

(1) Ecosystem protection refers to the operation that is concerned with the preservation and restoration of surrounding ecosystems before the disasters.
(2) Natural resource preservation refers to the operation that is concerned with maintaining the water quality, soil, and vegetation during and after the disasters.
(3) Pollution control refers to the operation that is concerned with reducing the pollution in and around the construction sites after the disasters.
(4) Waste management is defined as the operation that deals with reduction, disposal, handling, and storage of the waste in and around the construction sites after the disasters.

95.4.2 Resilience Characteristic Modality View

The same concepts of DRCOs showed in the construction operation impact modality view is reclassified based on the characteristics of the disaster resilience: robustness, resourcefulness, redundancy, and rapidity. These four concepts are commonly used in describing disaster resilience in different domains (e.g., [2, 3, 6]). A robust operation refers to the operation that can withstand the disturbance and damage caused by the disasters, such as equipment integrity enhancement, ecological protection, etc. A resourceful operation refers to the operation that identifies the problems, mobilizes, and utilizes resources by setting up priorities during the disasters, such as natural resource preservation, financial assistance, etc. A redundant operation refers to the operation that provides alternative options or back-up plans for the construction projects to function in case of disasters, such as alternative measure planning (e.g., emergency material supply planning), contingency availability, etc. A rapid operation refers to the operation that optimizes the time for recovery to the original functioning level, such as immediate response, workforce/human resource recovery, etc.

95.4.3 Disaster Management Cycle Modality View

The concepts of DRCOs can also be classified based on the disaster management cycle: disaster mitigation, preparedness, response, and recovery [11]. A disaster mitigation operation is the action taken before the disasters to reduce and eliminate the impacts of the disasters, such as incomplete structure integrity enhancement, material quality control, insurance affordability, etc. A disaster preparedness operation refers to the preparations and plans made in advance to prepare for the disasters, such as emergency material supply planning, emergency personnel availability, etc. A disaster response operation refers to the immediate action during or after the disasters to save lives and to avoid further damage to the construction projects, such as immediate response, rapid damage assessment, etc. A disaster recovery operation refers to the action that helps to return to the pre-disaster states, such as pollution control, waste management, etc.

95.5 Evaluation of DRCOs-Onto

The proposed DRCOs-Onto was initially evaluated through answering competency questions (CQs). CQs are commonly used to evaluate semantic models [22]. In our proposed model, some examples of CQs are "who is involved in a DRCO?", "what affects the implementation of a DRCO?", "what are the sub-concepts of a DRCO?", "is integrity enhancement a physical resilient operation?", and "is recovery cost reduction an economic resilient operation?" The upper level concepts and relations of the DRCOs-Onto were manually checked for their ability to answer all CQs. The DRCOs-Onto successfully answered all CQs.

As part of our future work, we will further evaluate the representation, coverage, consistency, clarity, conciseness, extendibility, and applicability of the DRCOs-Onto by conducting expert interviews and application-oriented validation (through applying the DRCOs-Onto in a knowledge-based decision support system).

95.6 Application of DRCOs-Onto in a Knowledge-Based Decision Support System

Our proposed DRCOs-Onto will serve as a foundation for the development of a knowledge-based decision support system (DSS). This system can support the classification, access, and transfer of the knowledge of DRCOs, thus facilitating decision making on selecting and implementing the best disaster resilient operations on the construction sites. Our proposed knowledge-based DSS consists of four main modules: knowledge access module, knowledge classification module, knowledge summarization module, and knowledge recommendation module.

This paper focuses on discussing the knowledge recommendation module. This module aims to recommend different types of knowledge regarding DRCOs based on the users' profiles, project contexts, and users' interests. The system is structured based on the DRCOs-Onto. For example, the users' profiles are linked to the "actor" in the DRCOs-Onto; the project contexts are linked to the "context"; and the users' interests are linked to the "disaster resilient construction operation" with its different modality views. The system is able to retrieve the data on the users' profiles, the contexts of the projects, and the users' specific interests on DRCOs (e.g., disaster mitigation operation, social resilient operation, disaster recovery operation), and then delivers and recommends all relevant knowledge to the users. The system is connected to the publicly available online database, online journals, web pages that are created by individual researchers, organizations, professional societies, etc.

To illustrate how the DRCOs-Onto would serve as a foundation for the recommendation of knowledge on DRCOs, a use case scenario is provided (as shown in Fig. 95.3). In this scenario, a junior field engineer is involved in a project of a 5-story residential building in the City of Miami. The field engineer is not familiar with the regulations or specific natural conditions of the State of Florida, and he/she wants to know the robustness and disaster mitigation aspects of the DRCOs in Miami.

The knowledge-based DSS automatically extracts the data of the user's profiles, project contexts, and users' interests based on the DRCOs-Onto. For example, the data about the actor that is involved in the operation is extracted as "field

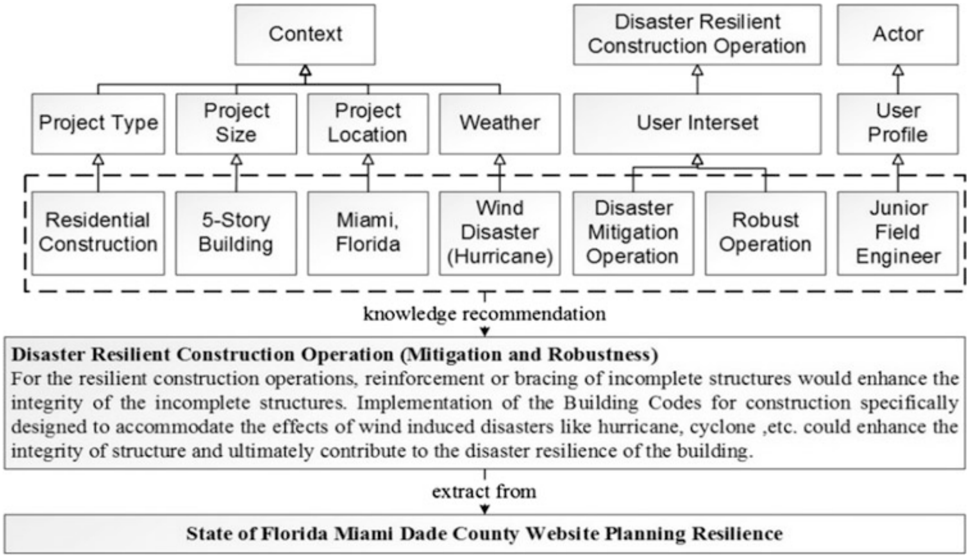

Fig. 95.3 Knowledge recommendation module in the proposed knowledge-based decision support system: an example use case scenario

engineer", and the data about the contexts are extracted as "5-story (project size)", "residential building construction (project type)", and located in "Miami" (project location). The system then filters and recommends the relevant knowledge on robust operations and disaster mitigation operations. The recommendations are customized based on the modality views in the DRCOs-Onto. In this case, the recommendation generated is constricted or filtered using the two interest areas: robustness and disaster mitigation. For example, one piece of knowledge related to reinforcing the incomplete structures is extracted from the Miami-Dade County website under "planning for resilience" section [14] and is recommended to the field engineer.

95.7 Conclusions and Future Work

This paper proposes an ontology-based semantic model that represents and reasons about the knowledge of disaster resilient construction operations (DRCOs-Onto). The proposed DRCOs-Onto is composed of concepts, inter-concept relations, and axioms. This paper focuses on discussing the higher-level model and the concept hierarchy of DRCOs. The proposed model aims to serve as the foundation for a knowledge-based DSS that allows for knowledge classification, access, and transfer on DRCOs, thus supporting the selection of the best DRCOs to implement. The model along with its potential application of knowledge-based DSS would allow construction professionals and stakeholders to receive, share, and transfer domain-specific knowledge on disaster resilience of construction operations.

In the future work, the authors will further develop and evaluate the proposed model. The model will also be implemented in the proposed knowledge-based DSS, and the performance of the different modules (i.e., recommendation, access, classification, summarization modules) will also be evaluated.

References

1. Abunemeh, M., Hijaze, I., Mebarki, A., Shahrour, I.: Hazards, vulnerability and interactions at construction sites: spatial risk mapping. J. Inf. Technol. Constr. (ITcon) **22**(4), 63–79 (2017)
2. Atreya, A., Kunreuther, H.: Measuring community resilience: the role of the community rating system (CRS). https://ss.com/abstract=2788230 (2016)
3. Berkeley, A.R., Wallace, M.: A framework for establishing critical infrastructure resilience goals. Final Report and Recommendations by the Council, National Infrastructure Advisory Council (2010)
4. Bosher, L., Dainty, A.: Disaster risk reduction and 'built-in' resilience: towards overarching principles for construction practice. Disasters **35** (1), 1–18 (2011)

5. Bosher, L., Dainty, A., Carrillo, P., Glass, J.: Built-in resilience to disasters: a pre-emptive approach. Eng. Constr. Architectural Manag. **14**(5), 434–446 (2007)
6. Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., Winterfeldt, D.V.: A framework to quantitatively assess and enhance the seismic resilience of communities. Earthq. Spectra **19**(4), 733–752 (2003)
7. Campanella, T.J.: Urban resilience and the recovery of New Orleans. J. Am. Plann. Assoc. **72**(2), 141–146 (2006)
8. Cerè, G., Rezgui, Y., Zhao, W.: Critical review of existing built environment resilience frameworks: directions for future research. Int. J. Disaster Risk Reduction **25**, 173–189 (2017)
9. Cutter, S.L., Burton, C.G., Emrich, C.T.: Disaster resilience indicators for benchmarking baseline conditions. J. Homel. Secur. Emerg. Manag. **7**(1) (2010)
10. El-Gohary, N.M., El-Diraby, T.E.: Domain ontology for processes in infrastructure and construction. J. Constr. Eng. Manag. **136**(7), 730–744 (2010)
11. Gilbert, S.W.: Disaster Resilience: A Guide to the Literature. No. Special Publication (NIST SP)-1117 (2010)
12. Grüninger, M., Fox, M.S.: Methodology for the design and evaluation of ontologies. Workshop in Basic Ontological Issues in Knowledge Sharing, IJCAI-95, Montreal (1995)
13. Mannakkara, S., Wilkinson, S.: Build back better principles for post-disaster structural improvements. Struct. Surv. **31**(4), 314–327 (2013)
14. Miami-Dade County: Planning for Resilience. http://www.miamidade.gov/planning/resilience.asp. Last accessed 25 Apr 2018
15. National Academy of Sciences: Disaster Resilience: A National Imperative. NAC, Washington 216 (2012)
16. Occupational Safety and Health Administration: Protecting construction workers in confined spaces: small entity compliance guide. US Department of Labor Occupancy Safety and Health Administration, OSHA 3825-09 (2015)
17. Occupational Safety and Health Administration: Reducing falls during residential construction: installing the roofs. US Department of Labor Occupancy Safety and Health Administration, OSHA, FS-3478 (2011)
18. Smiley, D., Hanks, D., Flechas, J. (2018): Three Cranes at South Florida Construction Sites Have Snapped in Irma's Howling Winds. http://www.miamiherald.com/news/weather/hurricane/article172416297.html. Last accessed 25 Apr 2018
19. Taeby, M., Zhang, L.: Stakeholder value systems on disaster resilience of residential buildings. In: Proceedings of 2018 International Conference on Construction and Real Estate Management, ASCE, Reston, VA (2018)
20. Wilkinson, S., Chang-Richards, A.Y., Sapeciay, Z.: Investment in the Construction Sector to Reduce Disaster Risk Management (2014)
21. Zhang, L., El-Gohary, N.M.: Epistemic modeling for sustainability knowledge management in construction. In: Proceedings of ASCE International Workshop on Computing in Civil Engineering, pp. 202–209. ASCE, Reston, VA (2013)
22. Zhang, L., El-Gohary, N.M.: Epistemology-based context-aware semantic model for sustainable construction practices. J. Constr. Eng. Manag. **142**(3), 015084-1-015084-17 (2016)

A Methodology for Real-Time 3D Visualization of Asphalt Thermal Behaviour During Road Construction

96

D. S. Makarov, F. Vahdatikhaki, S. R. Miller, and A. G. Dorée

Abstract

Asphalt mixture temperature plays an essential role in the road construction process. For high-quality asphalt, it is crucial that the compaction is performed within a certain range of the temperature, known as the compaction window. The compaction of the asphalt at a temperature outside this range would compromise the quality of the final product considerably. The compaction window is predicated on a myriad of parameters such as the type of the asphalt mix, the ambient temperature, etc. However, the operators of the road construction equipment (e.g., rollers and pavers) currently rely on their professional intuitions and experiences to develop their operational strategies. This practice can be significantly improved if the operators can be provided with the real-time information about the temperature of the asphalt mat during the construction. The available solutions for the real-time monitoring of the asphalt are limited to capturing and presenting only the surface temperature or only core temperature of the asphalt mat. Given the complex behaviour of the asphalt with relation to the mixture type and the ambient conditions, this approach cannot best represent the asphalt behaviour during the construction. This paper presents an approach for capturing the real-time asphalt behaviour using multiple sensing technologies. In this approach, the core and surface temperatures of the asphalt are captured using thermologger and linescanner, respectively. These data are then translated into 3D temperature contour plots that represent the asphalt behaviour under the construction site settings in real time. Finally, the data is presented to the equipment operator via a user interface. A prototype is developed and tested to demonstrate the feasibility of the proposed approach. The case study indicates that the presented method can improve the asphalt operation by enabling the operators to better develop their operational strategies.

Keywords

Asphalt construction • Real-time condition assessment • Sensors • Operator guidance system • 3D visualization

96.1 Introduction

Roads play an essential role in the modern society, providing economic growth and facilitating communication and transportation between cities, regions, and countries. Because of this and given the growing size of the road networks in the world, it is becoming ever more important to improve the road quality to reduce the cost and disruptions caused by road maintenance work. In many countries, Hot Mixed Asphalt (HMA) is the preferred and dominant material for road construction. However, HMA is very sensitive to the construction process and it is vital to ensure that the construction process results in a quality comparable to the standards set during the design of HMA.

Conventionally, the asphalt density is perceived as the prime indicator of the quality of HMA work [1, 2]. There are sensor-based solutions that can measure the asphalt density during or after the construction [3–5]. However, research shows that the compaction needs to happen within an appropriate temperature range to ensure a high-quality HMA [6, 7]. This range

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is usually determined during the laboratory testing. The compaction force applied to the asphalt above or below an ideal temperature range would result in an over-stressed or an under-stressed condition, respectively [8]. Traditionally, operators of the road construction equipment would use their intuition and rules of thumb to determine when, where and how much to compact. This approach has been shown to be suboptimal [9]. The compaction practice can be significantly improved if the operators are provided with the real-time information about the temperature of the asphalt mat during the construction [8].

There are several solutions that are designed to provide the operators with real-time temperature data. The available solutions can be categorized into two major classes: (1) the behaviour of the HMA is approximated by theoretical models. In many instances, these theoretical models fail to account for construction conditions and, thus, can be inaccurate. Additionally, these solutions require a great deal of input data from users (e.g., paving and compaction period and time, environmental conditions, existing surface conditions, and mix specifications). The need for a considerable number of user inputs negatively impacts the system usability and practicality. (2) The HMA behaviour is modeled based on the real-time data collected from the site [10–12]. Since this class of solutions rely on actual data collected from the site, they tend to be more accurate and reliable. Nonetheless, the available data-driven solutions focus only on either the core or surface temperature of the asphalt. This can be misleading because depending on the weather condition and the type of the mixture, there can be a large temperature gradient between the core and surface of the asphalt. Additionally, there is an assumption that mixture delivered on the site has a uniform temperature gradient because it is remixed in the paver. This notion has been shown to be fallacious [9, 13]. The other expectations are that the core temperature of the asphalt mat is 'hotter' and more uniform in comparison with the surface temperature. This neglects the heat transfer and thermal conductivity that show the differences in temperature gradient. In these situations, the single temperature approach (be it that of core or surface) can lead the operators to adopt over-conservative (e.g. the asphalt mixture might be under compacted) or over-aggressive (e.g. the asphalt mixture might be over compacted) compaction strategies. Therefore, it is important to represent the temperature information in such a manner that the operators are well-informed about the gradient between the core and surface of the asphalt.

Motivated by the above-mentioned gaps in the research, this paper presents a comprehensive methodology for (1) developing a real-time system that integrates data from various sensors to automatically generate the real-time temperature contour plots of the asphalt considering both the core and surface temperatures, and (2) visualizing the asphalt temperature data in a 3D format that can help operators develop effective compaction strategies.

96.2 Real-Time Asphalt Temperature Monitoring and Prediction

96.2.1 Principles of 3D Temperature Contour Plots

There are several theoretical models that can be used to predict the asphalt temperature based on heat transfer law and thermal conductivity [14, 15]. However, given the complexity of the parameters that affect the behavior of the HMA, in this paper the focus is placed on the estimation of the temperature based on real-time measurement.

The temperature profile of the paved asphalt layer can be represented in 3D manner based on corresponding temperature values collected from layer's surface and core. This profile, namely a 3D temperature contour plot, can provide more insights into the temperature homogeneity of asphalt mixture, and real-time asphalt mixture thermal behaviour. Currently, the setup of sensors to measure temperature values at different locations of the paved section, can interfere with main asphalt team activities. To prevent possible interventions of asphalt construction, and to reduce the chance of collisions with construction machines on site, the non-intrusive strategy of site data collection is developed. The principles of temperature data collection for the generation of 3D temperature contour plot is shown in Fig. 96.1. As shown in this figure, at least four different types of temperature data need to be determined.

1. Reference Surface Temperature (RST): the surface temperature at a predefined and fixed reference point which is set up at the start of the project;
2. Reference Core Temperature (RCT): the core temperature at the reference point;
3. Target Surface Temperature (TST): the surface temperature of any other given points on the asphalt mat;
4. Target Core Temperature (TCT): the core temperature of any given points on the asphalt mat.

In the developed method, a reference point is a location on a construction site where RSTs and RCTs of the paved asphalt are collected continuously in real-time. The TST at the beginning of the asphalt construction is measured when the paver lays the asphalt mat. The following TST values are calculated based on Eqs. 96.1 and 96.2.

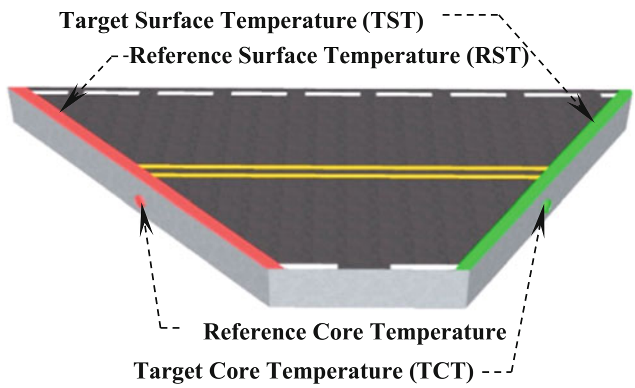


Fig. 96.1 Schematic representation of the data required for generating the 3D contour plot

$$\Delta RST_t = RST_t - RST_{t-1} \tag{96.1}$$

$$TST_{t,j} = TST_{t-1,j} + \Delta RST_t \tag{96.2}$$

where:

t is an index representing the time step of the data collection,
j is an index representing the location of the target point,
$\mathbf{\Delta RST_t}$ is the temperature gradient of the surface at the reference point at time t,
$\mathbf{TST_t}$ is the target surface temperature at time t.

Assuming that the thermal behavior of the asphalt mat is homogenous, the core temperatures of the paved asphalt section (TCTs) can be calculated based on TSTs at any given time (Eqs. 96.3 and 96.4).

$$\Delta RT_t = RCT_t - RST_t \tag{96.3}$$

$$TCT_{t,j} = TST_{t,j} + \Delta RT_t. \tag{96.4}$$

where:

$\mathbf{\Delta RT_t}$ is the temperature gradient between core and surface at the reference point at time t,
$\mathbf{TCT_t}$ is the target core temperature at time t.

Based on TST and TCT values of different parts of the road, the 3D temperature contour plot can be created. To capture the differences between surface and core temperature values and to be able to represent them on the edges of 3D plot the interpolation method is used (Eq. 96.5).

$$\left[\begin{array}{ll} T_x = \left(\frac{T_{S2}-T_{S1}}{L_1}\right) \times x, & S2 < x < S1 \\ T_x = \left(\frac{T_{S3}-T_{S2}}{L_2}\right) \times x, & S3 < x < S2 \end{array}\right. \tag{96.5}$$

where:

$\mathbf{T_x}$ is the core temperature of an asphalt layer at the depth x,
$\mathbf{T_{s1}}$, $\mathbf{T_{s2}}$, $\mathbf{T_{s3}}$ are surface and core temperatures of an asphalt, measured by sensors at surface point S1, and in depth S2, S3,
$\mathbf{L_1}$, $\mathbf{L_2}$ the corresponding differences between depths S2 and S1, S3 and S2,
x every depth along the thickness of the asphalt layer.

96.2.2 The Architecture of the Proposed System

The proposed real-time system intends to collect, analyze and merge two sources of data: (1) capture reference temperatures (RST, RCT) of the asphalt, and (2) generate a reliable representation of current temperature of the asphalt at different part of the mat (TST and TCT), using the principles explained in Sect. 96.2.1. For this purpose, two stations are developed, namely, the Reference Station and the Paver Station (Fig. 96.2).

The Reference Station is responsible to continuously measure the temperature of the asphalt at the core and on the surface of the asphalt and determine the corresponding temperature differences. The Paver Station, on the other hand, intends to measure the surface temperature of the asphalt behind the screed of paver and register this data. These two stations send their data to the Processing Centre, where the asphalt temperature gradient at the reference point is projected onto the surface temperature of the asphalt at different parts of the mat. Further the 3D temperature contour plots of the asphalt are created. The remainder of this section explains each one of these components in detail.

96.2.3 Reference Station

During the paving of any given segment, the temperature data from the relevant reference point is used. The data flow from the reference point should be continuous until the lower threshold of the compaction window is reached. To fit with a non-intrusive requirement, the thermologger which can read and transfer data from thermocouples and infrared channel, is used at the Reference Station.

The thermocouples are implemented into the asphalt layer just after the paver laid the corresponding section of the road. The depths at which thermocouples are placed should differ to get better representation of temperature profile of the asphalt

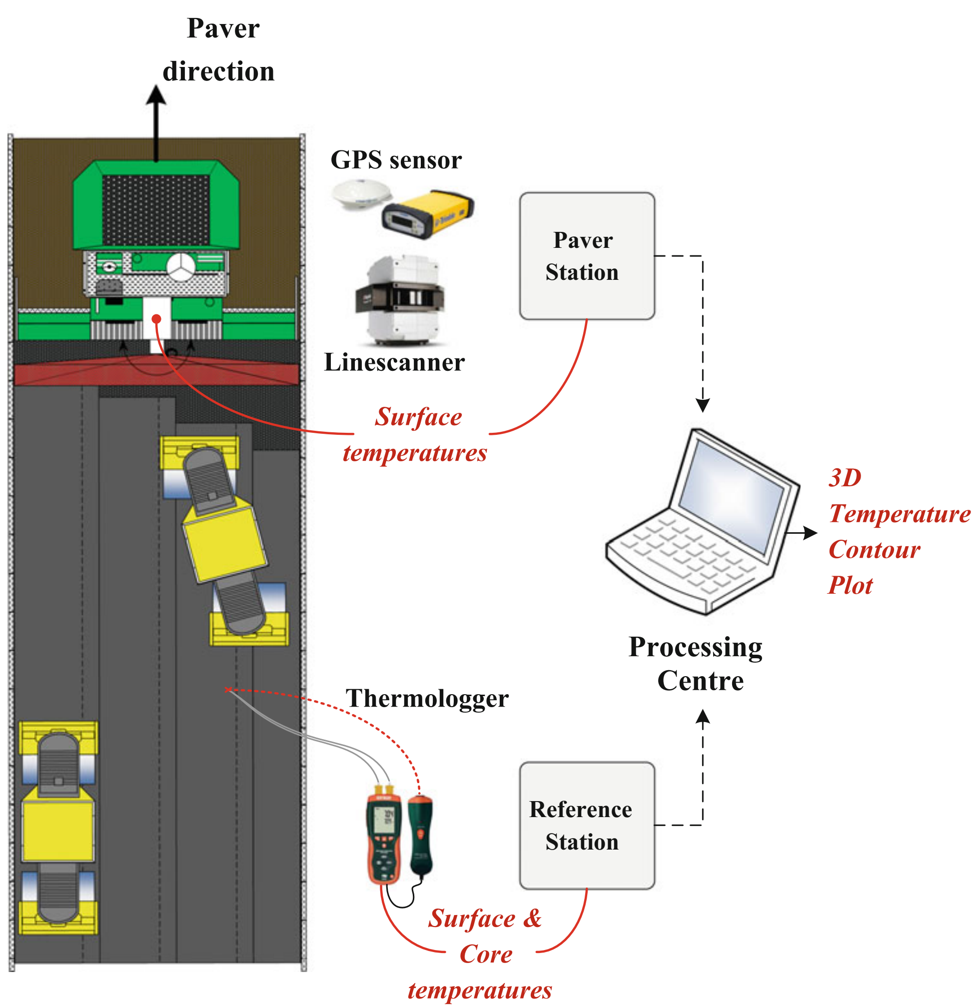


Fig. 96.2 Overview of the proposed system

section. The data set of surface and core temperatures at a reference point is processed on site and result are transferred to the Processing Centre for further analysis. Figure 96.3a shows the structure of the Reference Station. The Reference Station uses a router to transmit all the data to the Processing Centre, where these data are integrated with the data from Paver Station to generate the 3D temperature contour plots.

96.2.4 Paver Station

As explained in Sect. 96.2.1, it is assumed that the data gathered from the Reference Station represent the behaviour of the entire asphalt segment. However, to generate the 3D temperature contour plots based on the Eqs. 96.1–96.4, the surface temperatures of the asphalt at different parts of the mat need to be collected. This can be done by the temperature sensor that is mounted on a paver before the construction project starts. Like the Reference Station, the data collection in the Paver Station should be as much non-intrusive as possible to avoid delay and disruption of the work.

As shown in Fig. 96.3b, the Paver Station needs to collect and transmit two types of data, namely, coordinate of different target point on the mat and the surface temperature. The surface temperatures can be easily obtained without direct interaction with the surface using infrared temperature linescanner. Infrared temperature linescanner scans a strip of asphalt surface with an update rate between 1 and 150 Hz [16]. The width of this strip is determined by the speed of the paver, i.e., the faster the paver, the wider the strip. This strip is then split into N parts and the surface temperature of each part is measured and recorded by the linescanner. The linescanner is chosen because of its robustness, high update rate and reliability. As for the location data, Global Positioning System (GPS) is mounted on the paver. Both sets of data are sent to the Processing Centre using a router.

96.2.5 Data Analysis, Processing Centre Architecture

As shown in Fig. 96.2, Processing Centre is a station that collects data from both Reference Station and Paver Stations. The main purpose of this centre is to analyze the data and generate real-time 3D temperature contour plots.

Figure 96.4 illustrates the flowchart of the Processing Centre. At the beginning of the project, manager on site defines the temperature thresholds that will be used during data processing. The minimum and maximum temperature thresholds equal lower and upper limits of the compaction window respectively. This setup reduces the computational efforts.

During the main loop of the Processing Centre algorithm the data from Reference and Paver Stations are obtained and analysed in real-time for every time step (Δt). The Paver Station sends TSTs and paver's locations on site, which are filtered and combined by Processing Centre. Then the values for TSTs and TCTs for the paved asphalt section are calculated based on a stream from Reference Station (RSTs and RCTs values) with usage of Eqs. 96.1–96.4. Based on these analysis, the temperature contour plots of the asphalt at a given time are generated. The processed data is then stored in the Processing Centre and presented to interested parties on the site, e.g. the roller operators. Given that the plot is generated in real time, the

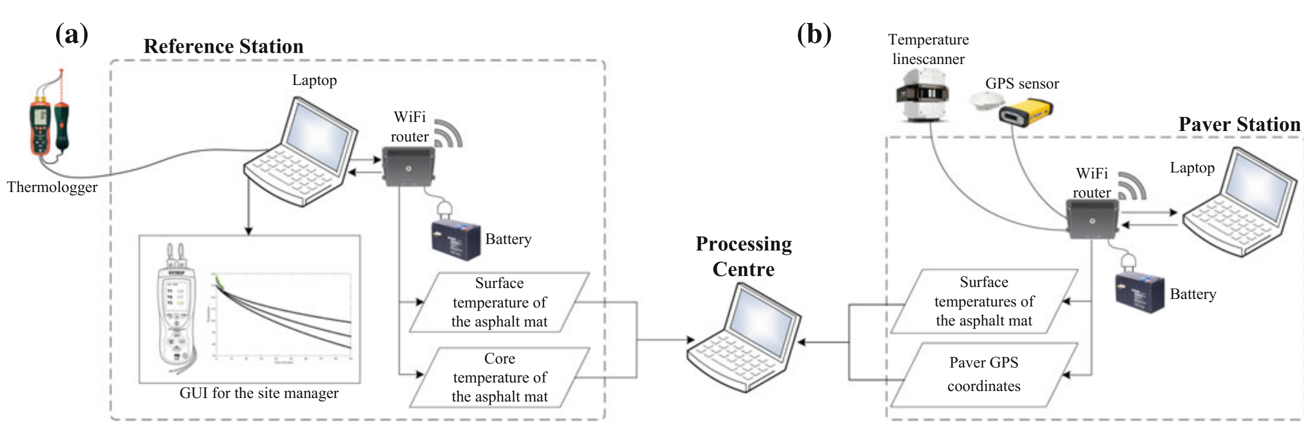


Fig. 96.3 **a** The architecture of the reference station, **b** the architecture of the paver station

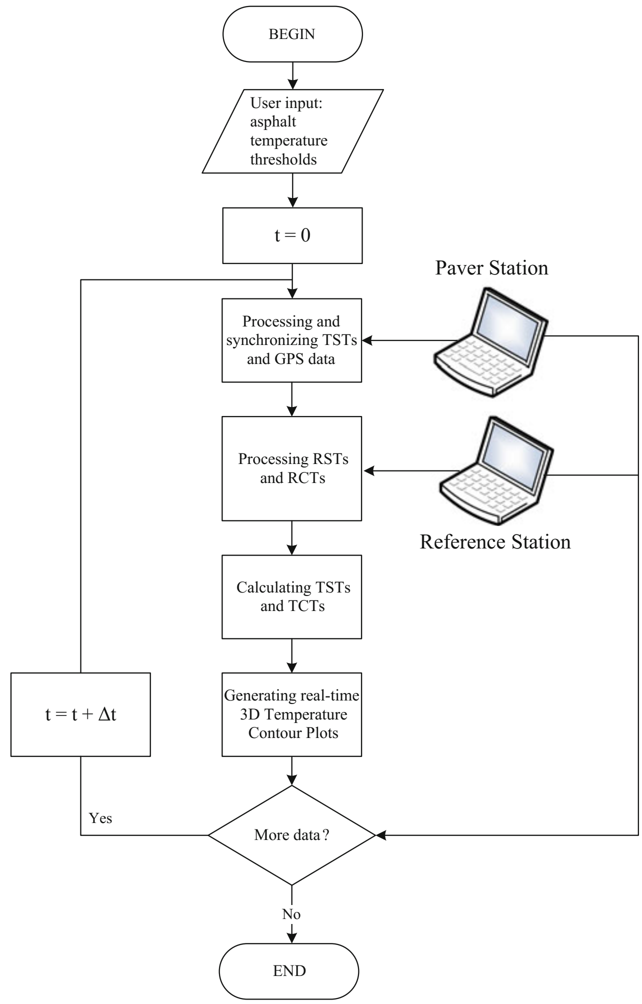


Fig. 96.4 The flowchart of the processing centre

graph dynamically updates to reflect the thermal behaviour of the asphalt. This real-time information enables the roller operators to better pinpoint spots that require compaction more urgently because they are reaching the lower bound of the compaction window. This can considerably reduce the chance of under- or over-compaction of the asphalt mat.

96.3 Implementation and Case Study

A prototype is developed to test and validate the proposed system. In this prototype, the Reference and the Paver Stations are designed and the server of ASPARi research unit at University of Twente, the Netherlands is used as the Processing Centre. Matlab is used to develop all the relevant algorithms and developments.

For the surface and core temperatures collection at reference point, the thermologger Extech HD200 [16] is used. The thermologger feeds the system with data from two thermocouples (i.e., to capture RCTs) and one additional infrared sensor (i.e., to capture RSTs). The MP150 Raytek linescanner [17] is used on the paver to capture TSTs. It was providing the system with the surface temperatures of the asphalt mat during paving procedure. As for the wireless communication, Vodafone MachineLink 4G [18] is used to establish the connection between the Processing Centre, Reference and Paver Stations. The implementation has been tested and validated on several projects since 2015. To provide evidence on the functionality of the system, a case study carried out in collaboration with Roelofs, the Dutch asphalt construction, on the N228 road (Montfoort, the Netherlands).

Figure 96.5a shows the setting of the project. The project was the construction of the road surface layer with stone-matrix asphalt mixture. During paving and compaction activities, two asphalt teams were involved. Before the start of the project, the temperature reference point for the thermologger setup was identified and the sensor was installed, as shown in Fig. 96.5b. The paver of the asphalt team was equipped with the linescanner as shown in Fig. 96.5c.

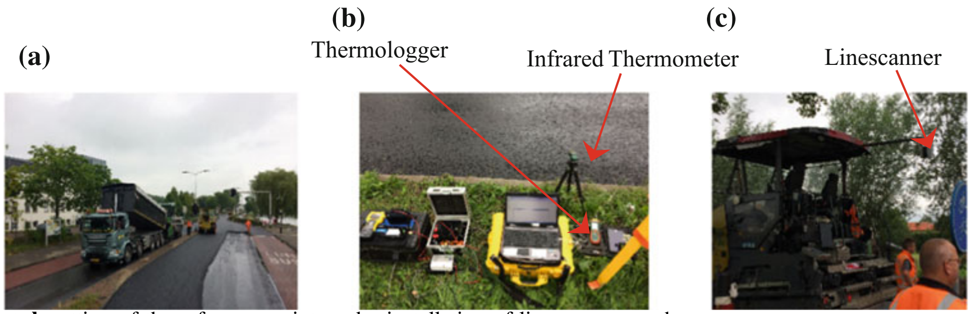
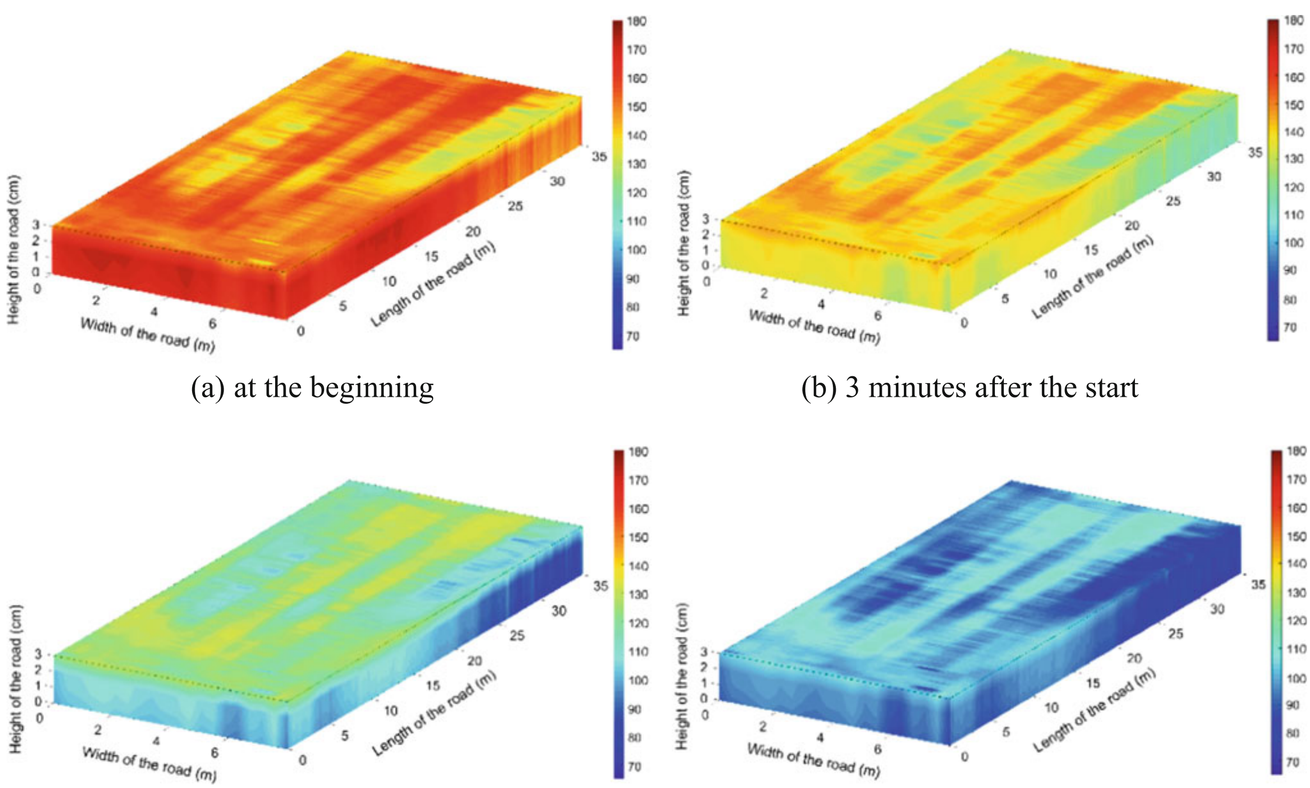


Fig. 96.5 **a** N228 project, **b** setting of the reference point, and **c** installation of linescanner on the paver

Upon the successful installation of the equipment, the prototype system was run when the pavement operation began. The system successfully generated the 3D temperature contour plots based on the input data from the Reference and Paver Stations with an update rate of 1 s. Figure 96.6a–d shows the snapshots of the plots generated by the prototype. Each 3D temperature contour plot represents the surface and core temperatures along the length, width and the thickness of the paved asphalt section. The three dimensional graphs provide deeper insights into the asphalt layer behaviour after paving and during the compaction. The clear visualization of the surface temperature of the asphalt mat already brings an understanding about the thermal processes that are happening after the asphalt has been re-mixed by paver augers. However, the core asphalt temperatures that are presented in the front and in the profile of a 3D plot provide the real-time thermal condition inside the asphalt mat. This approach of data representation does not depend on the theoretical assumptions about asphalt temperatures during construction, giving abilities for the asphalt team to react accordingly to current situation on site.

For instance, Fig. 96.6a shows that the temperature of the asphalt after paving (130–170 °C) is well above the compaction window for the stone-matrix asphalt mixture (i.e., 80–120 °C). In this situation, roller operators should wait for the appropriate temperature. Figure 96.6b represents the situation 3 min after the paving. Although the temperature of the central part of the road is not optimal for compaction, roller operators may focus on the left and right sides of the road.



(a) at the beginning
(b) 3 minutes after the start
(c) 8 minutes after the start
(d) 15 minutes after the start

Fig. 96.6 Snapshots of 3D temperature contour plots

Figure 96.6c, d indicate the site conditions 8 and 15 min after paving, respectively. Based on these plots, roller operators can focus more to the road center, and avoid passing over the road sides.

96.4 Conclusions

Based on the results of the case study, it can be concluded that there is a possibility to build 3D temperature contour plots of the laid asphalt. Relying not only on surface or core temperatures of an asphalt layer, but simultaneously collecting real-time values of both of these data sources, the system prototype can measure and visualize the temperature gradient within the asphalt layer efficiently. This provides the machine operators with appropriate visualizations of the current conditions of the asphalt mat. Having such information, equipment operators can improve working patterns in terms of pre-compaction and compaction strategies.

During the implementation of the system prototype on a construction site, all the sensors showed stable and reliable behaviour. Nevertheless, in the current setting, the Reference Station is limited to data from only one spot at the reference point. To make the Reference Station more accurate, a fibre optic sensor can be installed along and/or across the paved section. This can provide more accurate temperature data along and/or across the asphalt mat at the start of paving. Paver Station can be improved by wireless sensor or application of the infrared camera with a wider, in comparison with linescanner, field of view. A thorough comparison between the temperature estimation based on the proposed real-time measurements and the predictive/theoretical models will be conducted in the future.

References

1. Huerne, H.L. ter.: Compaction of asphalt road pavements using finite elements and critical state theory. Ph.D. Thesis, University of Twente, Enschede, The Netherlands (2004)
2. Decker, D.S.: State-of-the-practice for cold-weather compaction of hot-mix asphalt pavements. Factors Affecting Compaction Asphalt Pavements **27** (2006)
3. Minchin, R.E., Thomas, H.R.: Validation of vibration-based onboard asphalt density measuring system. J. Constr. Eng. Manag. 129–154 (2003)
4. Jaselskis, E.J., Han, H.C., Tan, L., Grigas, J.: Roller mountable asphalt pavement quality indicator. IDEA Program, Transportation Research Board, National Research Council (1999)
5. Praticò, F.G., Moro, A.: In-lab and on-site measurements of hot mix asphalt density: convergence and divergence hypotheses. Constr. Build. Mater. **25**(2), 1065–1071 (2011)
6. Willoughby, K., Mahoney, J., Pierce, L., Uhlmeyer, J., Anderson, K.: Construction-related asphalt concrete pavement temperature and density differentials. Transp. Res. Rec. J. Transp. Res. Board **1813**, 68–76 (2002)
7. Delgadillo, R., Bahia, H.U.: Effects of temperature and pressure on hot mixed asphalt compaction: field and laboratory study. J. Mater. Civ. Eng. **20**(6), 440–448 (2008)
8. Timm, D.H., Voller, V.R., Lee, E.B., Harvey, J.: Calcool: a multi-layer asphalt pavement cooling tool for temperature prediction during construction. Int. J. Pavement Eng. **2**(3), 169–185 (2001)
9. Miller, S.R.: Hot mix asphalt construction; towards a more professional approach. Ph.D. Thesis, University of Twente, Enschede, The Netherlands (2010)
10. Vasenev, A., Bijleveld, F., Hartmann, T., Dorée, A.G.: A real-time system for prediction cooling within the asphalt layer to support rolling operations. In: Euroasphalt and Eurobitume Congress 2012, (2012)
11. Vasenev, A., Hartmann T., Dorée, A.G.: Prediction of the in-asphalt temperature for road construction operations. In: Computing in Civil Engineering, pp. 469–476 (2012)
12. Dorée, A.G., Vasenev, A., Hartmann, T.: Real-time method for automated prediction of internal layer temperature of paving material during paving operations (2013)
13. Bijleveld, F., Miller, S., De Bondt, A., Dorée, A.: Too hot to handle, too 552 cold to control-influence of compaction temperature on the mechanical properties of asphalt. In: 553 Proceedings of the 5th Eurasphalt & Eurobitume Congress (Istanbul, Turkey), pp. A5EE-231 (2012)
14. Chadbourn, B.A., Newcomb, D., Voller, V., Desombre, R.A., Luoma, J.A., Timm, D.H. (1998). An asphalt paving tool for adverse conditions
15. Jordan, P.G., Thomas, M.E.: Prediction of cooling curves for hot-mix paving materials by a computer program. Transport and Road Research Laboratory Report 729, 1976
16. HD200, EXTECH Instruments. http://translate.extech.com/instruments/product.asp?catid=64&prodid=404. Last accessed 16 Apr 2018
17. MP150 Linescanner, Raytek. https://www.flukeprocessinstruments.com/en-us/products/infrared-temperature-solutions/infrared-linescanners/mp150-linescanner. Last accessed 16 Apr 2018
18. Vodafone, MachineLink 4G. http://www.vodafone.com/business/iot/iot-devices/integrated-terminals. Last accessed 16 Apr 2018

Eliminating Building and Construction Waste with Computer-Aided Manufacturing and Prefabrication

97

Gerard Finch and Guy Marriage

Abstract

Affordable computer-aided manufacturing has made possible a new category of timber structure. Components can now be intricately detailed to a high level of precision on a large scale. This approach has meant the increasing use of timber-only joints and more intelligent structural solutions that exploit the inherent qualities of the material. This study suggests that these construction parameters, enabled by computer-aided manufacturing, are advantageous when attempting to eliminate lifecycle building and construction waste. In this research existing and specifically designed low lifecycle waste construction solutions that have used computer-aided manufacturing are compared to conventional platform light timber framing. The study finds that using computer-aided manufacturing technology to fabricate advanced assemblies can lead a 67% reduction in the time required to recover building materials for reuse (versus the cost of reusing materials from traditional construction techniques). The use of a single material with integrated sophisticated jointing conditions is also seen to lead to the potential total elimination of adhesives and composite materials.

Keywords

Computer-aided manufacturing • Sustainable practices • Sustainable buildings

97.1 Introduction

Today more than 40% of all waste material produced globally comes from the building and construction industry [1]. To reduce this figure and improve the long term environmental impact of the sector, the way construction materials are deployed needs to change. Materials need to be shaped and assembled in a way that promotes effortless and economically attractive material reuse. Designing for reuse is widely recognised as the most effective waste management strategy as it pre-emptively eliminates the possible production of low-value materials. This preventative design approach excludes all fixings and adhesives that have the potential to damage or contaminate the principal materials.

It was hypothesised that computer-aided design and manufacturing (CAD/CAM) methods have the potential to enable high levels of material reuse though the mass-fabrication of simply assembled components. It was therefore the aim of this study to develop a highly efficient, computer-aided manufactured structural system that directly facilitated material reuse. As a final objective this analysis aimed to quantify the impact of CAM's ability to facilitate material reuse in the construction industry.

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97.2 Background, Motivation and Objective

The building industry has begun to address the problem of waste during the construction of buildings through the implementation of on-site waste sorting. Life-cycle waste production, however, remains a significant concern. Of note is the estimated 90% of construction waste (and therefore 38% of total global waste) that is a product of renovation and demolition practices [1–4]. This is waste material that is generated after the aforementioned recycling schemes have left the building site. Direct reuse of materials retrieved from a building at the time of renovation and/or demolition is rare as materials are often badly damaged and have no attractive reuse or recycling pathway. Strategic deconstruction of buildings using today's methods of construction is possible, yet the cost of doing so often exceeds the resale profit of the largely low-value materials that are recovered [5]. These barriers are a product of modern building techniques; the widespread use of construction adhesives, low-value materials, epoxy sealants and structural connections never intended to be reversed. Studies investigating the possible reuse of existing light timber frame members (platform and balloon framing) earmark economics and measurable structural performance of recovered members as key reuse limitations [5].

A potential solution to this long term sustainability and waste management challenge is to design buildings that facilitate material recovery and reuse. This approach is referred to as Circular Economy (CE) design: a process in which the architect ensures that all materials incorporated into the design of the building at the outset can be recovered in an economically viable way at the end of the structure's useful life [6]. The consequence of CE design is two-fold: materials are either specified or fixed in a way that ensures they can be easily recycled into new components, and/or, the materials are shaped in a way that enables reuse. Direct material reuse is the most desirable waste minimisation strategy as it calls for no additional material or energy inputs between use cycles. The applied result of a CE design approach like this are massively modular building elements with simple, durable connections that can be easily reversed. To eradicate the possibility of material contamination this design agenda also calls for components with geometric features that are simple to assemble and eliminate the need for supplementary contaminating/damaging fixings. This level of component detailing is beyond the scope of conventional modern construction approaches in which we rely on composite jointing mechanisms to enable rapid material assembly. It is foreseen that computer-aided manufacturing could address many of these circular economy design requirements in a way that was never previously possible. Not only can such manufacturing approaches deliver the necessary component detailing on a large and affordable scale, but they can also create products with a superior level of material efficiency.

The complex 'composite' nature of architectural assemblies makes it difficult to determine which specific building components need to be redesigned to enable material reuse of all components. The authors of this study identified the structural system was a critical starting point for enabling a CE. This choice was based on the influence a structural system has on determining how associated building elements are fixed into position. Similarly the structural system was also identified as a key influence on the modulation of the architectural geometry. This modulation effects how supplementary building layers in that architectural assembly are shaped. A distinctive lack of modulation may result in a large quantity of materials whose physical size make them undesirable, and therefore uneconomical, for reuse. Likewise some structural systems will integrate necessary envelope layers into a single product i.e. structurally insulated panels (SIPs) which include insulation and lateral and gravity load resisting structural elements. A structural system designed for a circular economy would reject the notion of permanently joined layers of differentiating materials (such as SIPs). Within the range of structural systems there are also a wide selection of possible materials. To control the scope of this study and better align it with the realities of the building industry (see below) structural materials were limited to manufactured plywood products. This allowed the research to focus primarily on fabrication, geometric and jointing conditions, with the design outputs potentially transferable to alternative materials in the future.

The researchers selected computer numerically controlled (CNC) routing/cutting as the core manufacturing process. This was seen as a tool that would provide the advanced manufacturing potential while ensuring the input timber material remained a readily available and affordable product with strong sustainability credentials. Within this lifecycle framework CNC routing permits the timber material to remain in a more authentic format versus that of additive manufacturing methods (3D printing) where timber is reconstituted and mixed with resin to form a wood/plastic composite. Supporting this agenda to maintain material purity there is a current push for the application of natural adhesives in sheet timber products (notably Ligate by SCION) and the use of natural moisture-resistant treatments [7]. These features would enhance the performance of such processes to deliver a circular economy based structural building solution where there is no risk of damage to environmental or human parties at any stage of the product's life cycle. CNC routing of timber components is also measurably more cost effective than current timber-composite additive manufacturing methods [8].

97.2.1 Summary of Study Aims

1. Develop a highly efficient structural system that directly facilitates material reuse and uses computer-aided manufacturing processes in its production.
2. Holistically quantify CAD/CAM's ability to facilitate material reuse in the construction industry versus conventional building methods.

97.3 Method

This study measures the holistic 'circular economy' performance of a given structural system that uses computer-aided manufacturing versus the performance of conventional platform timber framing. Key measures for 'Circular Economy' and 'waste-free' performance in this study included [3, 8] (see Table 97.1 for results):

- Weight of timber required for structure (kilograms) per unit of wall;
- Required cut length of CNC routing (meter) per unit of wall;
- Time taken to assemble (seconds) a unit of wall;
- Solid Waste produced at fabrication (kilograms) (where measurable);
- Sawdust Waste produced at fabrication (kilograms) (where measurable);
- Number of components—complexity (count) per unit of wall;
- Time taken to disassemble components (minutes) for a unit of wall;
- Time taken to prepare components for reuse (minutes) for a unit of wall;
- Recovery rate of materials (percentage) per unit of wall.

In all instances a lower score is perceived as better performing as this collection of measures works to quantify the waste reductions (if any) and improved material reuse potential of a given structural system. To produce accurate quantifiable comparisons all systems were detailed to meet the following criteria:

- Gravity/lateral load resisting capacity for light timber framed buildings (NZS3604).
- Internal finished lining (plasterboard or plywood fixed to framing members).
- Waterproof barrier (between cladding and framing members—differs for all tests).
- Visual cladding (fixed to exterior of framing members—same for all tests).
- Insulation (infill between framing members).

Table 97.1 Summary of results for various construction systems circular economy performance

Measure (per 1 m^2 of wall area)	Platform	Click-lock	Click-raft	X-frame
Timber structure weight (kg)	7.02	14.76	8.22	15.48
CNC routing cut length (m)	N/A	129.8	85.5	149.6
CNC with common edge (m)	N/A	87.5	53.5	85.1
Time to assemble (min)	20	18	16	15
Sawdust waste (kg)	1.12	2.16	0.72	1.45
Solid fabrication waste (kg)	0.78	0.37	0.12	0.12
Number of components	3	3	2	3
Disassembly time (min)	47	32	30	27
Time to prepare components for reuse (min)	18	0	6	0
Recovery rate (%)	58	78	96	97.5
Lifecycle waste (kg)	14.9	Unavailable	Unavailable	1.96

To produce the quantifiable values a portion of each system was built at full-scale and then deconstructed. Deconstruction took place in workshop conditions with only basic construction hand-tools. Additionally, recording the CNC router cut length for each system indicates the potential cost differential. Refer to section six to review potential limitations of this testing methodology.

97.3.1 Technical Summary of Examined Systems

Platform Light Timber Framing. Platform light timber framing (LTF) is the predominant construction method for low and medium density buildings (up to four stories) in the United States of America, Canada, Australia and New Zealand (Fig. 97.1). This system has been used as the comparative basis for measuring the circular economy performance

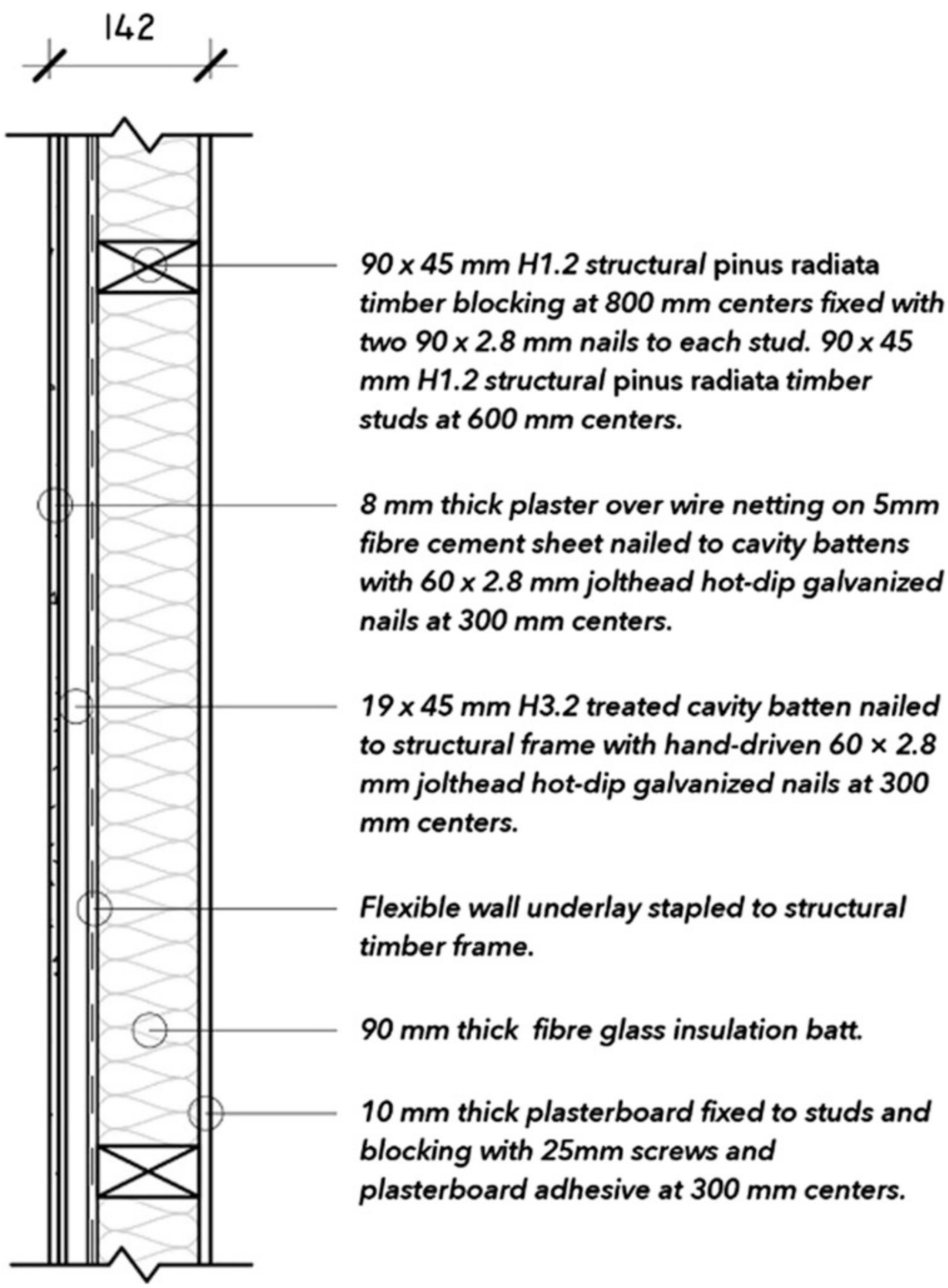

Fig. 97.1 Platform light timber framing wall section detail

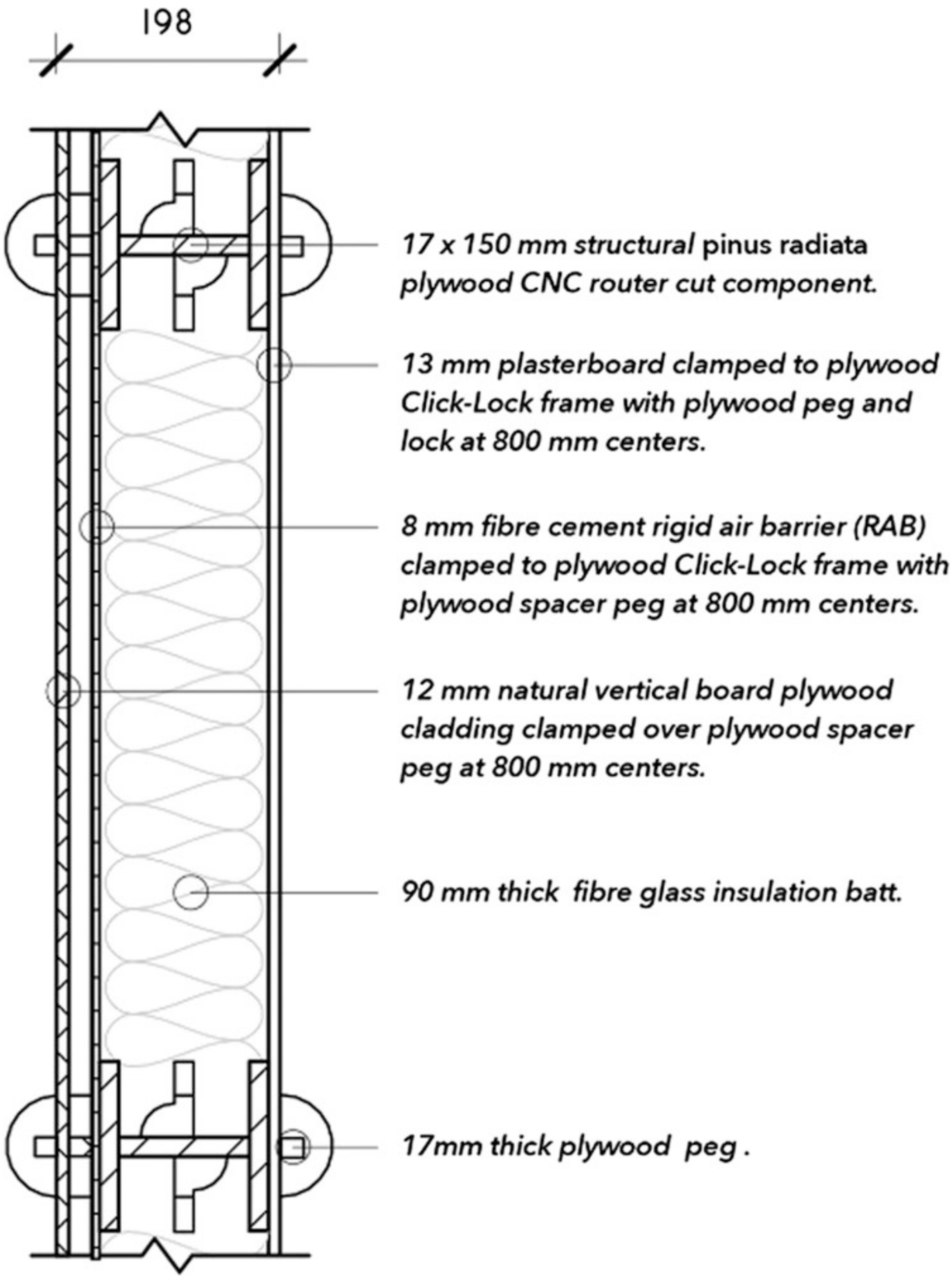

Fig. 97.2 CNC fabricated plywood click-lock wall section detail

improvements of construction systems that use computer-aided manufacturing methods. Platform framing typically comprises of a timber bottom plate, studs (vertical load bearing members), blocking (nogs/dwangs) and a top plate. These members are nailed together to form a gravity load resisting frame. To achieve sufficient lateral load resistance (against earthquakes and wind) LTF usually relies on sheet materials glued, screwed and/or nailed to the studs and blocking.

Click-Lock (Marriage & Warrander). Click-Lock is a CNC router-fabricated linear structural grid frame that uses 17 mm thick plywood [9] (Fig. 97.2). The frame is made up of three principal rectangular elements that 'click' and 'lock' together without the need of conventional fixings such as nails or screws. Click-Lock includes a modified double-stud detail that allows sheet linings to be fixed to the wall, again without the need for adhesives, nails or screws.

Click-Raft (Moller). Click-Raft is a sophisticated two-piece CNC router fabricated non-orthogonal structural frame [9] (Fig. 97.3). *Click-leaves* are slotted together under strain to from an inherently lateral-load resisting frame. Click-Raft can

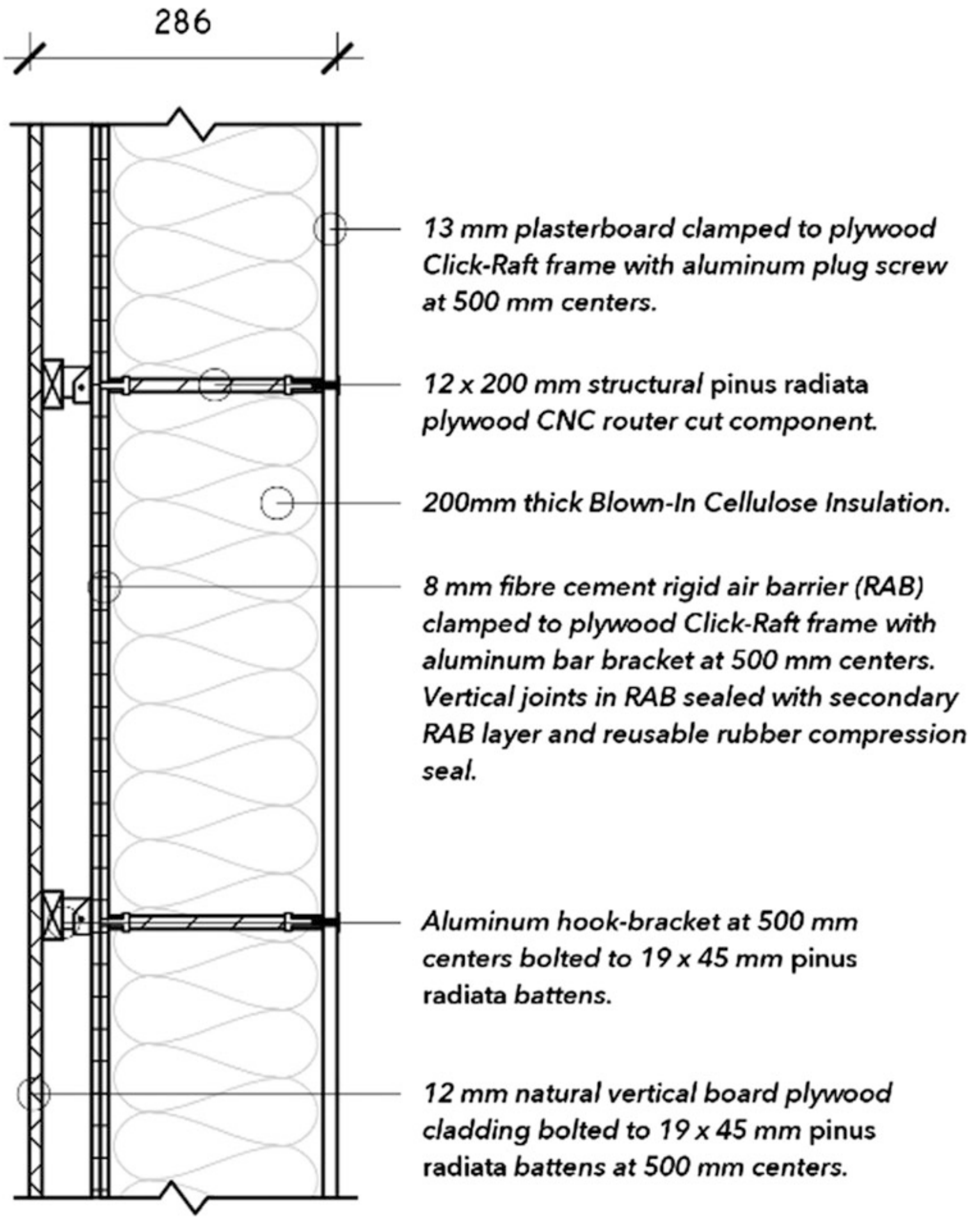

Fig. 97.3 CNC fabricated plywood click-raft wall section detail

use a range of various thickness plywood products depending on the required horizontal span loads. The authors have integrated a reversible waterproof, cladding and internal compression based lining layer system for this test. Moller's original proposal included a separate polycarbonate cladding system [10]. For the purposes of comparison this has been replaced with plywood sheeting.

X-Frame 7 (Author). X-Frame 7 is a product of this study and designed by the authors to specifically facilitate material recovery at the end of a building's useful life (Fig. 97.4). It uses 17 mm structural plywood in a modular diagrid geometry to create an inherently lateral-load resisting structural frame locked together by mortise and tenon plywood joints. The structure is designed to promote disassembly and reuse by being suitable for both horizontal and vertical building elements. The diagrid geometry is designed for maximum flexibility to allow windows and openings in the frame without the need for additional frame or beam (lintel) elements.

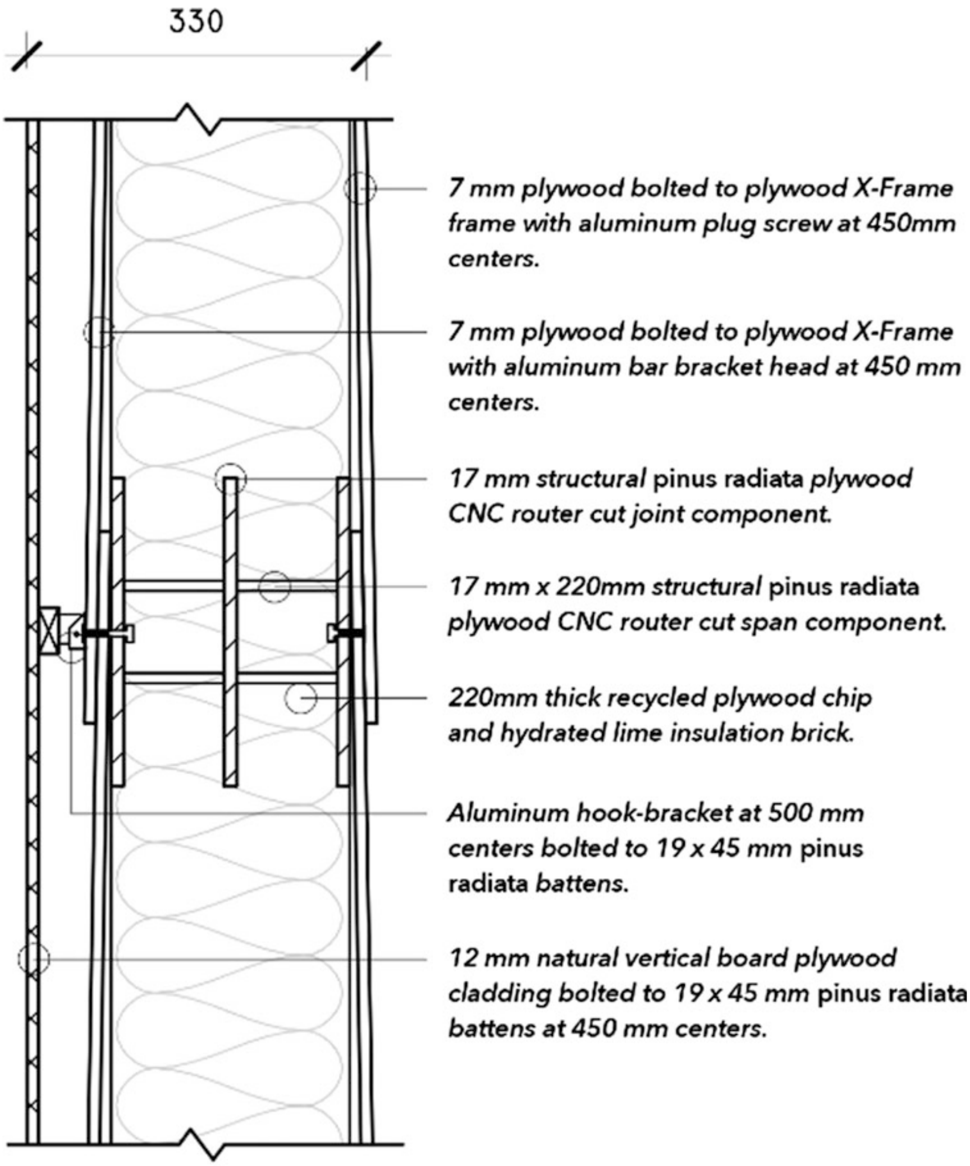

Fig. 97.4 CNC fabricated plywood X-frame wall section detail

97.4 Analysis Results

See Table 97.1.

97.5 Discussion

97.5.1 Overall Performance

These results suggest that computer-aided manufacturing has a significant role to play in enabling the faster recovery of materials from buildings with higher rates of recovery versus that of conventional light timber framing. The total elimination, in some instances, of the need to clean or process materials after their removal from a building, made possible by self-jointing materials, is significant. This allows materials to be recovered from one site and be taken directly to another for reuse. However, no construction approach achieved 100% material recovery. Even in the case of X-Frame, the system with the highest rate of retention, the woven and triangulated geometry had potential to snap during separation. This weakness is a consequence of an integral design feature of X-Frame and is therefore unlikely to be resolved easily. Click-Raft performed almost equally as well in maximizing the quantity of undamaged materials but was seen to suffer long-term deformation of the structural elements. This observation requires further testing in larger scale situations to identify if the deformation is a significant structural concern and barrier to reuse.

97.5.2 CNC Manufacturing

The key advantage offered by computer-aided manufacturing and the advantage being exploited here is the sophisticated detailing of timber components to integrate assembly parameters. This often took the form of mortise and tenon joints, as well as slotted and tabbed components with plywood pins. Critically these joints did not damage either the primary structural material or the joining component when separated after use. Integrated fastening capability effectively simplified the construction and deconstruction process. The majority of structural connections and load-bearing joints are inherently fulfilled by simply positioning the frame components in the desired shape and conveniently located connection details receiving each element. Integrated joints like these are made possible through precision CNC cutting with carefully controlled tolerances. Over the extended length of each use cycle, diverse environmental conditions, such as humidity and temperature, can affect the dimensional properties of the material. In a worse-case-scenario this would mean the swelling of plywood joints resulting in inseparable components and the irreversible damage to the structure during disassembly. The reliance of the systems on friction jointing is also a potential weakness through multiple reuse cycles. It was noted that plywood pins were more reliable over multiple reuse cycles versus mortise and tenon only connections.

A similar tolerance issue arose as a result of the material specification. Low-grade plywood (specified as C.D. grade in New Zealand) was selected to keep material costs competitive with platform framing. C.D. grade represents the 2nd lowest grade of plywood available at the time of testing. The lowest grade (D.D.) proved to have too many imperfections in the surface (knots and splits) to achieve sufficient adhesion to the vacuum bed of the CNC router. Providing the C.D. grade sheets were not warped, adhesion was adequate and manufacture was successful. Issues with C.D. grade plywood arose, however, during assembly tests. Due to plywood manufacturing inconsistencies there is a greater degree of thickness variation in the C.D. product than higher grades. In some instances the sheet thickness varied by more than 0.75 of a millimeter. This deviation was enough to result in jointing failures—friction based joints with insufficient resistance between elements. Preliminary experimentation suggests that this thickness variation is consistent in a range of alternatively branded plywood products. It is also important to note that any grade of plywood sheet stacked unevenly or stored in a location exposed to rapid moisture and/or temperature fluctuations was prone to warping. If this was not identified before cutting commenced the material would move around on the table of the router resulting in incorrectly shaped components. If a warped sheet was identified it was screwed to the sacrificial sheet (18 mm MDF) above the vacuum bed. This meant that almost any sheet could be cut successfully but at a cost of increased loading and unloading times.

It is widely accepted that reductive manufacturing technologies, such as CNC routing, are prone to producing large quantities of waste. This is a consequence of the pre-sized sheet material (in this instance 1200 mm by 2400 mm sheet plywood) conflicting with the desired forms being cut. Although the design can be highly optimized to make use of the available material there is always some degree of wastage (sometimes only the sawdust created by the thickness of the cutting piece). Click-Lock's geometry resulted in 16% of the input material being converted to low-value sawdust waste. It is important to note however that sawdust waste was revealed to not be directly related to the length of the CNC cut. The perimeter shaping of an element and its potential to be nested on a plywood sheet significantly affected waste produced at the time of fabrication. Computer-aided additive manufacturing (3D Printing) processes are recognised to have the capacity to entirely eradicate waste produced at the manufacturing stage as material is only 'consumed' or 'delivered' where needed. The research to date has not utilized this technology due to economic and material toxicity concerns. The aim of this study is to deliver a product that does not introduce barriers to total lifetime material management. The thermal composite material used to 3D print timber is limiting in this regard. Further investigations will aim to explore the potential of reusable cost-effective bio-polymer additive-manufacturing technologies.

A cost comparison of each system has not been published here, however, the required CNC router cutting length implies cost variations between each 'CAM' structural system. Within this comparison a significant concern was X-Frame and its requirement of 75% more routing than Click-Raft. This increased cut length translates directly into a more expensive manufacturing process that produces larger quantities of waste. Reacting to this concern steps were taken to improve fabrication efficiency and, as such, X-Frame components were nested using a common-edge cutting workflow. Common-edge nesting locates the components onto the sheet material in spacing's that correspond with the width of the router cutting piece. This allows a single head movement to cut two parallel lines at the same time. To further reduce the cost of manufacturing a 9.75 mm solid carbide compression bit was used in the CNC router. This made possible a single cutting pass through both 12 and 17 mm plywood sheet products. Using a compression bit also ensured that no finishing work was required to the cut components. For whole systems comparable cost examinations refer to Defab; Prefabricated Architecture for a Circular Economy [8] and Experimental Construction in a Timber House [9].

97.6 Study Limitations and Continuations

This quantifiable comparative analysis does not take into consideration the additional complications of incorporating openings and spatial allocations that do not match the module parameters of a prefabricated system. Under these measures X-Frame and Click-Lock are likely to excel as they both offer greater module flexibility within the context of existing construction techniques. Greater flexibility is not only seen to reduce waste and the need for specialist components at the time of construction but also as an important factor in ensuring the reuse of these materials. Further research is needed to expand this study from a closed analysis of the technical reuse potential of CAM construction solutions, to a study that measures if these materials are then adopted by builders and contractors on a frequent basis in new buildings. A range of other factors, such as the skill level of the labor, tools available, unique finishing and connection details, the integration of services as well as the integration of windows and larger structural elements also all affect the accuracy of the reported quantitative measures.

To validate these results in a wider context a larger range of non-CAM fabrication inclusive construction methods need to be examined in a comparative manner. This analysis may suggest that although CNC cut plywood construction methods are superior in a CE approach against conventional LTF, they are not the best CE solution. It is likely there are a range of 'low-tech' solutions, such as straw-bale and Hempcrete, which offer superior CE performance due to their material properties. The most successful CE construction manifestation may therefore be a hybrid incorporating both low-tech and CNC fabricated elements. Furthermore structural testing of the systems to determine if material can be removed from the configurations may improve their respective performance. A notable opportunity is to test X-Frame and Click-Lock with 12 mm plywood products. By-products of this change will be a decrease in the fabrication waste, faster cutting times and a lighter structural grid. For further validation a detailed investigation into the sawdust and solid waste produced at the time of material fabrication also needs to be undertaken. If it is found that the saw-dust waste produced during the fabrication of conventional timber lengths matches or is greater that of the sawdust waste produced during the manufacture of plywood, the respective performance of each system will shift.

97.7 Conclusions

Results indicate that the use of CAD/CAM technology to fabricate an alternative structural design can lead to a 67% reduction in the time necessary to recover building materials for reuse (versus the cost of reusing materials from traditional construction techniques) (Table 97.1). This finding is useful for researchers and practitioners alike as it indicates that CAD/CAM based construction systems are more economical to recover at the end of their useful life and therefore more appropriate for a CE. The increase in deconstruction speed is a result of the CNC fabricated building components inherent capability to be assembled, modulated and remain free of contaminating materials through use cycles. CAD/CAM in this sense enables the mass fabrication of detailed building components at competitive economic rates that are highly optimized for cyclic use. However, computer-aided manufacturing also introduces a range of challenging issues. Manufacturing waste produced during CNC routing is a key concern as it represents a new source of waste as well as adding additional costs to the building process. Similarly, computer-aided manufacturing's ability to create precise friction-only joints can become compromised due to inconsistencies in the raw material product.

In conclusion, this holistic study highlights the complex issues that arise when attempting to design for a Circular Economy in the building industry using CAD/CAM. Based on the metrics reported in this study researches and practitioners need to look beyond sophisticated manufacturing and product-based solutions if they are to ultimately deliver successful CE building solutions.

References

1. Environmental Protection Agency: Advancing Sustainable Materials Management: 2014 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States. United States of America (2016)
2. Environmental Protection Agency: Characterization of Building-related Construction and Demolition Debris in the United States. Franklin Associates Prairie Village, KS. United States of America (1998)
3. Inglis, M.: Construction and demolition waste—best practice and cost saving. In: Proceedings of the New Zealand Sustainable Building Conference. Ministry for the Environment. New Zealand (2007)
4. Resource Efficiency in the Building and Related Industries: Why REBRI? Building Research New Zealand. New Zealand. BRANZ Website, http://www.branz.co.nz/REBRI. Last accessed 18 Feb 2018
5. Forbes, N.: The Structural Reuse of Pinus Radiata in New Zealand. Thesis. Victoria University of Wellington, New Zealand (2018)
6. Braungart, M.: Cradle to cradle: remaking the way we make things. Farrar, Straus and Giroux, UK (2002)
7. SCION: Ligate™ bioadhesives from 100% renewable resources. Scion Crown Research Institute Website, https://www.scionresearch.com/science/bioproducts-for-sustainable-industries/bioadhesives. Last accessed 18 Feb 2018
8. Finch, G.: Defab: Prefabricated Architecture for a Circular Economy. Thesis. Victoria University of Wellington, New Zealand (2018)
9. Marriage, G.: Experimental construction in a timber house. In: Aurel-Schnabel, M. (ed.) 50th International Conference of the Architectural Science Association 2016, pp. 685–694. Australia (2016)
10. Moller, C.: CMA + U. Click-Raft Blog Website, http://click-raft.blogspot.co.nz/. Last accessed 25 Apr 2018

A Methodological Proposal for Risk Analysis in the Construction of Tunnels

98

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Abstract

Colombia is in the process of modernizing and changing its road infrastructure and, despite the fact that in this process the government entities request the contractors elements of risk analysis and assessment, this country has a precarious risk management for infrastructure projects. This research is intended to determine the project schedule affectation due to the materialization of risks and to stablish a risk assessment methodology considering the context of the project. The proposed methodology first takes into account the quantification of the probability of occurrence of the event or risk with the Bayesian analysis and their respective networks, in order to look at the interaction of their causes and their repercussion in the final event analyzed. Subsequently, the impact of the risk on the duration of the activity is found. Finally, the risk value (P $\times$ I) is calculated using a Monte Carlo Simulation technique, obtaining as a result a value in days of possible delay that must be compared with the value that details the initial programming. The methodology is realistic since it considers any type of risk that could be presented in a project, from engineering problems, to social events. Currently, the methodology is being implemented in a real project in order to evaluate it against the progress of the same, obtaining information so that later, organizations can propose the necessary contingency measures to deal with the risks presented.

Keywords

Risk analysis • Bayesian analysis • Monte Carlo simulation • Forecast value • Project scheduling • Underground excavation

98.1 Introduction

Road infrastructure is one of the main index for competitiveness in a country, thus, having in mind the competitiveness increase, Colombia is under a huge process to renew its roads, called fourth generation (4G) roads. The construction of new roads, bridges, and tunnels among other structures, highlights the need to set conditions that guarantee the quality, the cost, the execution time and the scope stablished. In Colombia, risk management related to infrastructure projects has been ignored by companies working with road infrastructure. In the 4G routes contracts, in which construction of tunnels is their base component, analysis and risk assessment are represented by a matrix. These requirements demanded by the government to the contractors show that there is an institutional effort to develop risk management in projects. Nonetheless, this effort remains insufficient to develop a complete quantification, subsequent implementation and monitoring. Matrix analyses based on qualitative data generate a bias since different interpretations can arise from the risk assessment.

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In the Colombian productive environment, the execution of engineering projects related with soil removal link with infrastructure, show that it exists a handicap in the planning, execution and monitoring of the activities that haven't had a correct schedule control. This fact is related to the process of recognition and assessment of risks in the construction tasks. This research is intended to determine, in percentage, how much will be affected the construction schedule of a project by the contractual milestones when introducing risk assessment in comparison with the initial one, which is the best method to assess the risk considering the context that involves the contractual situation for companies that work with public or private entities, and if the presented methodology effective to identify and quantify the risks that surround the subterranean terrain removal.

98.2 The State of the Art of Risk Management in Infrastructure Projects

Different methodologies of risk assessment have been published all around the world, a lot of them related to underground excavation and tunneling. Models can describe, with a great precision, the uncertainty that comes with the prediction of geotechnical conditions and the variations in the performance rate and unitary costs. Nevertheless, these models do not consider other factors such as unexpected events or social and organizational conditions related to local context, which can increase in a substantial way the uncertainty, the costs and the time length of the project. To build a realistic model, these factors must be considered.

Castillo [1] stablishes that the Bayesian analysis is related with a probability assignment to an event, or the probability distribution assignment to a random variable. This variable represents a relevant characteristic in the decision making that, in this research, corresponds to the causal relationship between previous events and risk probability. Bayesian analysis has been an effective tool to support the decision-making. Špačková and Straub [2], illustrate the implementation of Bayesian networks in tunneling processes.

Einstein and Souza [3], describe a technique that addresses to the geotechnical problems by specifying its risk, developing first a methodology that allows to identify the main risk origins in the geotechnical field in the specific context of a project. Then, a quantitative risk analysis must be done to identify the best construction strategies considering the best option the one with a minimum risk. Nowadays, there is no information to upgrade the exactitude of time length estimations in tunnel constructions. This information would be a useful tool to learn systematically from past experiences. Without the required information, this problem present in projects must be solved by the estimation from an expert in the field. Risk analysts must support their job with data bases containing information that improves the uncertainty quantification.

According to ISO 31000: 2011 [4], Risk Management is defined as the "*Systematic application of policies, procedures and management practices to the activities of communication, consultation, establishment of context, and identification, analysis, evaluation, treatment, monitoring and risk review*". The Impact "*is the consequence of the materialization of an event on the different objectives of the project*". The impact can then be measured in terms: monetary, time periods, injuries, deaths, environmental damage, and organizational reputation, among others. Risk in tunnel engineering refers to the adverse influence of events that occur during construction. Its effects may include economic loss, construction delays, casualties, environmental damage (to the natural environment, as well as the surrounding infrastructure), and social problems (including policy and safety impacts) [5]. To reduce the uncertainty during the construction of the project, the dynamic and systematic control of risks is applied in different phases of the life cycle within a project. Dynamic risk management is aimed at all stages of the project, from approval to completion. Effective control is based on dynamic feedback and real-time control [6]. This management also explains why risk efficiency is a key aspect of good project management practices, which provides a basis for future risk mitigation methods.

Bayesian statistics have formulated a coherent statistical theory that has allowed structuring and modeling subjective Probability in the context of a decision problem. This probability is understood as "*the degree of belief that an individual (an expert, a panel or interdisciplinary group) has about a random event taking place*" [1]. A Bayesian network is "*a compact and graphic representation of a joint distribution, based on some simplification of assumptions that some variables are conditionally independent of others*" [7]. As a result, the joint probability of a Bayesian network over the variables $U = \{X_1, \ldots, X_n\}$, represented by the chain rule can be simplified from Eq. (98.1):

$$P(U) = \prod_{i}^{n} P(X_i|x_1, \ldots, x_{i-1}) \tag{98.1}$$

where $P(U) = \prod_i^n P(X_i = x_i)$, the parents "(Xi)" is the set of parents of Xi. This property makes Bayesian networks powerful tools for the representation of domains in uncertainty conditions, which allows to calculate joint and marginal distributions more efficiently. The a priori probabilities must be taken into account, for this, an a priori probability distribution of a variable is taken, according to Eq. (98.2):

$$P(A) = \sum_{x_i} \ldots \sum_{x_k} P(X_1, \ldots, X_k, \boldsymbol{A}) \tag{98.2}$$

where A is the query variable, X_1 of X_K are the remaining variables of the network. This type of query can be used during the design phase of a tunnel, for example, to assess the probability of failure in design conditions (geology, hydrology, etc.). The posterior distribution of variables given the observations according to Eq. (98.3) must also be considered:

$$P(A|\boldsymbol{e}) = \frac{P(A, \boldsymbol{e})}{\sum X_i \ldots \sum X_k \sum A P(X_1, \ldots X_k, \boldsymbol{A}, \boldsymbol{e})} \tag{98.3}$$

where e is the vector of all the tests, and A is the query variable and X_1 to X_K are the remaining variables of the network. This type of query is used to update the knowledge of the state of a variable (or variables) based on the state of the other variables. It could be used, for example, to update the probability of a tunnel failure, after construction has begun, when new information about the geology is released.

In recent years, the Monte Carlo technique has been widely used to simulate risk events in different methodologies that analyze time, cost and scope variables related to the impact of each of them. Having this impact, the product with its respective probability of occurrence is calculated, resulting in the value of the risk according to a certain activity. This method includes the determination of a probability distribution of the variable to be treated to, then, obtain a sample of that distribution by random numbers. This series of random numbers generates a series of values that have the same distribution characteristics of the real experience that wants to be simulated. The outputs of the simulation show the possible duration values of the activities that have had a possible materialization of one or several risks represented in probability distributions [8].

The current planning and programming tools are based on deterministic models, such as the critical path method (CPM) which has been commonly used in practice due to its simplicity and has been adopted by most commercial software of project management. However, CPM has been widely criticized for its inadequate handling of the uncertainty inherent in construction projects [9]. Probabilistic methods, such as program evaluation and technical review (PERT) and Monte Carlo simulation (MCS) have been introduced as a supplement to the CPM to model the uncertainty inherent in construction projects. Both PERT and MCS assume durations of activities that are random variables and can be represented by probability distributions [9]. For this, it is necessary to generate probability density functions based on historical data, which makes the process cumbersome. For this, estimates of three points are taken (possibilities, optimistic and pessimistic). When these times are calculated, they tend to be optimistic, to remedy this trend the MCS is applied, providing more reliable estimates with probabilities that affect the critical path. Two objectives in the development of risk integration in programming are defined. First, is to increase the days of programming by explicitly incorporating the impact of the risks in the estimation of the duration of the activity, and second, to develop an effective programming and planning procedure that responds to risks [9].

The contingency is also modeled with the logic technique according to the activities affected by risks. The impact of the multiple risks in an activity can be determined, this makes it possible to make the comparison between the duration of the real project and the duration of the contract by reviewing the difference of both durations. The PERT method requires multiple estimates for task durations, considering the duration of tasks with random variables with a Triangular or Beta probability density function [10]. The concepts of the PERT model, detail that the tasks of the project are independent. This assumes that the estimates of the duration of the tasks should be executed independently of what may happen in other tasks in the project, which in turn may affect the availability of the resources provided for the task in question. PERT does not provide the probabilistic density function of all the tasks to the Project Managers, these are given by consensus of knowledge the 3 time parameters c, b, m. very similar to a triangular distribution with its 3 parameters (minimum, most probable and maximum duration).

98.3 A Methodological Proposal for Risk Analysis in the Construction of Tunnels

The proposed methodology for the risk assessment in excavation projects is developed in nine steps.

98.3.1 Risk Identification

The Risk identification is developed by an interdisciplinary group, which must be composed by professional and experienced workers capable to identify any type of risks. Then, a Risk Breakdown Structure (RBS) should be developed considering all the risks detected.

98.3.2 Qualitative Risk Assessment—Risk Nesting

The interdisciplinary group should create a matrix in which risk impact and risk probability must be rated in a qualitative way, for each risk considered in step 1. This is done in order to classify each risk depending on its impact and probability. The group defines the rating scale of the probability and the impact, stablishing an adequate number of scale levels. The impact is measured as time units in which the project is delayed and, to assign the scale levels for it, the group must consider percentages of the project length. To assign scale levels for the probability, the group must consider percentage ranks between 0 and 100% of occurrence of the risk event. After finding the value of the probability and the impact of each risk, the value of the risk should be calculated using the Eq. 98.4:

$$R = P \times I \tag{98.4}$$

This should be done with the qualitative values. This results in a classification of the risks that should be a priority for further quantitative analysis.

98.3.3 Risks/Activity Matrix

The analyzed risks and the project schedule activities are related. This is done to determine how the risks affect the critical activities of the project.

98.3.4 Quantitative Risk Assessment—Probability (Bayesian Networks)

Based on the model proposed by Špačková and Straub [2], in which they use Bayesian networks to model a tunnel construction process, particularly the time required for the excavation process under uncertain geotechnical conditions and varying time units, two processes should be taken into account:

- Definition of technical and geological specifications of the tunnel: Experts should collect all the geological information to classify the terrain, its dimensions, define excavation type and critical sections.
- Bayesian network development by tunnel sections: Considering the preliminary information, the Bayesian network should be structured to obtain the probability for each risk for each type of terrain defined in the previous process, taking into account the methodology proposed by Castillo [1], who builds the network in the following way:
  - Identification of relevant variables to explain the variables to be analyzed.
  - Build a network taking into account the causal relationships between the variables.
  - Verify the assumptions of conditional independence and the absence of circular relationships.
  - Define the conditions of the variables.
  - Estimate the probability of non-dependent variables (the concepts of the interdisciplinary group, historical concepts of other similar projects, among others, are used).
  - Estimate the conditional probability distribution of the dependent variables. To do so, an order of importance is stablished between the predecessor variables that are being analyzed.
  - Validate the consistency and structure of the networks by reviewing compliance with Bayesian network properties [7].
  - Evaluate the network through a specialized program.
  - Analyze the results and execute the adequate sensitivity analyzes for the important variables that relate the variables of interest.

After building the network, the data of the probability distribution of each analyzed variable is extracted in order to relate it to the respective risk. The results of the variable—risk are determined as a Bernoulli probability function, whose result is defined in 2 values (It occurs-It does not occur). This value will later provide information to the simulation and quantification matrix of the risk by activity.

98.3.5 Quantitative Risk Assessment—Impact

A probability function is defined which is determined as a time value that has affected each activity in days. For this application, a triangular function should be used considering the most optimistic, the most pessimistic and the most probable durations. These values are found considering the interdisciplinary group concepts; however, data from other projects can be obtained to observe the behavior of each duration.

98.3.6 Risk Value Calculation

The risk value should be calculated using Eq. (98.4) with the quantitative values. The entries for the simulation model are the following [8]:

- Estimation of the duration of the impact for each activity, without including any forecast or unforeseen.
- Scheduling of the project.
- Risks considered, including the risk classification in the qualitative analysis.
- Risk/Activity Matrix.

To obtain the results of the probable adjusted days and their respective probability of occurrence, the basic steps to simulate using the Monte Carlo method are the following:

- Risk events are characterized by their probability and Impact on the duration of the activity.
- Identify the activities that are affected by any of the determined risks.
- Considering the risk weighting for each activity, it is observed that an event may or may not occur, or a risk can be materialized. When the probability is 1 (100%), the event occurs all the times the model is run, however, when this value is lower, the event or risk occurs the percentage determined in each model run.
- Since the Impact has been quantified in three values (e.g.: 94% optimistic: 100% probable, 107% pessimistic), a probability density function must be assigned according to this data (e.g.: triangular distribution).
- In each subsequent iteration, the Monte Carlo model randomly chooses a multiplier according to the chosen probabilistic distribution. For these iterations, the factor that results from this operation multiplies the duration of the activities in which the risk materializes. Taking into account the probability of occurrence of the event, the multiplying factor in the Monte Carlo model should be related to the productivity of the affected day and its respective value.
- Obtain the respective graphs which must be evaluated to analyze the results.
- When the data of the model iterations are obtained, the project schedule is evaluated according to the critical route of the same.

The outputs of the simulation result in the possible duration values of the activities that have had a possible materialization of one or several risks represented in probability distributions. This can determine the probability of finishing the project and if the stablished deadlines can be reached, so a forecast value can be calculated in time with a more adjusted and real level. To define the forecast, a triangular probability function will be stipulated in the application for each activity related to its respective risk. For the assumption of the simulation, is necessary to define the rules as the risks occur, taking into account their probability of occurrence, which is an entry data. These rules were defined by the interdisciplinary group as follows:

- Criteria for obtaining maximum values when risks occur in parallel or when one occurs approximately in time with another as illustrated in Eq. 98.5:

$$Max(X_1, X_2, X_3, \ldots X_n) \tag{98.5}$$

- Value addition criteria when risks can occur in series, or when one occurs, then the other, as shown in Eq. 98.6:

$$\sum_{n}^{1} X_i \tag{98.6}$$

- Mixed criteria when the risks occur in parallel or series as a whole. In this case maximum values are taken within a sum of values according to their possible occurrence, as shown in Eq. 98.7:

$$\sum (X_1, X_2, \ldots X_n \ \max(Y_1, Y_2, \ldots Y_n)) \tag{98.7}$$

The foregoing depends exclusively on the position that the Contractor adopts against the risk. There are 3 options: Prone to risk (Add the values of the risks, minimum values or their combination), Neutral risk (Average risk values) and Risk aversion (Add the values of the risks, maximum values or their combination).

When the probability of occurrence is found by the Bayesian network method, it is being determined how the risks can be materialized. For the purposes of the proposed methodology, the Interdisciplinary Group should define the criterion to be taken regarding the interaction of each risk with each activity. Subsequently, the project schedule should be analyzed and its relationship with the occurrence of the activities. This analysis must be carried out by activity, by sub-milestone, milestone and total time of project duration in a staggered manner.

98.3.7 Data Review and Adjustment to Entry Project Data

When the values have been determined in days of the materialization of the risk for each activity, a data review and adjustment to entry project data must be done. The congruence of the data should be checked against the durations of each one, respectively. If they are right, the time buffers are added to the schedule and, if they are not, it is necessary to review the Bayesian networks.

98.3.8 Scheduling Adjustment with Time Buffers

The respective adjustment to the schedule should be done. This is done taking into account the values of time addition by milestone. It is not executed by activity considering that it would be very cumbersome and not practical for the programmer to add extra times for each activity. By milestone, a better versatility is reached since the buffer can be visualized in a more explicit and clear way. In addition, a better planning of the prevention, correction and contingency plans to be applied in the project can be projected.

98.3.9 Results Revision

To verify the results, is very important to observe the coherence of these against the duration by milestones and total of the project. The percentage margin of the total extra days that could be incurred in the schedule is determined. This percentage depends on the position that the organization took before the adoption of the risk. The organization review, according to their experience, the establishment of control measures, prevention against the materialization of the risks previously found.

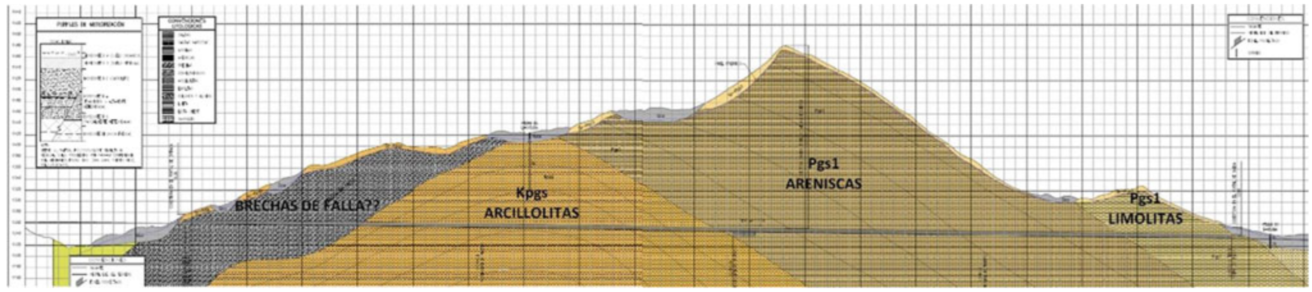

Fig. 98.1 Cut plane of one of the tunnels showing the excavation terrains

98.4 Application of the Proposed Methodology

The proposed methodology is currently being tested in the construction of two tunnels which belong to one of the 4G roads located in a town named Guaduas. The cut plane of one of the tunnels is shown in Fig. 98.1.

An interdisciplinary group of geologists, civil and environmental engineers, maintenance, equipment, safety, scheduling and management professionals, was formed to identify risks related to the project. Then, the RBS, the qualitative risk assessment and the Risk/Activity Matrix was done. The Bayesian networks were formed and developed using the program *Hugin Lite 8*. The most probable risks found were "Excavation profile collapse due to soil failure" in sandstone and claystone soils, and "Community social strike". The interdisciplinary group defined, in the quantitative risk assessment, the most probable, optimistic and pessimistic durations for every risk. Considering the Probability and Impact for every risk, the risk value calculation was done using the Monte Carlo simulation developed in an Excel workbook using the application *Crystal ball*. The results of the simulation show that the mean value for Tunnel 1 was 133 delay days (with Beta function adjustment) and 183 delay days for Tunnel 2 (with Weibull function adjustment). Since the project is being currently developed, the results of the validation of the methodology are proposed for future research.

98.5 Conclusions

- The proposed model shows that it is possible to relate the time variable (total duration of programming) with the risks detected in the process of risk identification, linked to the planning of projects.
- It is recommended, in order to determine a more detailed assessment of each risk and in each activity, a more exact formulation could be set up to have the possibility of simulating it, thus the model would not depend too much in the concepts of the interdisciplinary groups.
- In the future, the information should be extracted from projects historical data, in order to form databases to work with more closed and less biased reliability margins.
- Management must have a deeper decision making process to choose its risk treatment, either by preventing, mitigating or transferring it according to its policy and risk appetite for the execution of its projects.
- This methodology could be extended for another type of project such as roads, bridges, industrial assemblies. It is necessary to review the steps and, in particular, the determination of the Bayesian analysis since here it is stablished by geographically affected section, in other projects the standardization and homologous behavior of some activities could be visualized in order to define the rules of interaction of the risks and your activities on the critical route.

References

1. Castillo, M.: Toma de decisiones en las empresas: entre el arte y la técnica: metodologías, modelos y herramientas. Ediciones Uniandes, Bogotá D.C. (2006)
2. Špačková, O., Straub, D.: Probabilistic risk assessment of excavation performance in tunnel projects using Bayesian networks: a case study. In: Proceedings of the 3rd International Symposium on Geotechnical Safety and Risk, pp. 651–660 (2011)

3. Sousa, R.L., Einstein, H.H.: Risk analysis during tunnel construction using Bayesian networks: Porto Metro case study. Tunn. Undergr. Sp. Technol. **27**(1), 86–100 (2012)
4. ISO, "ISO 31000." (2008)
5. Bai, Y., Dai, Z., Zhu, W.: Multiphase risk-management method and its application in tunnel engineering. Nat. Hazards Rev. **15**(2), 140–149 (2014)
6. Hwang, S.: A Bayesian approach for forecasting errors of budget cost estimates. J. Civ. Eng. Manag. 178–186 (2015)
7. Neapolitan, R.: Learning Bayesian Networks (2003)
8. López, M.A.: Diseño de una metodología de análisis de decisión para la cuantificación de las reservas de contingencia de tiempo y costo para la planeación y control en proyecto de construcción de obras de infraestructura. Universidad de los Andes (2011)
9. Pawan, P., Lorterapong, P.: A fuzzy-based integrated framework for assessing time contingency in construction projects. J. Constr. Eng. Manag. **142**(3), 4015083 (2016)
10. Chrysafis, K.A., Papadopoulos, B.K.: Possibilistic moments for the task duration in fuzzy PERT. J. Manag. Eng. **31**(5), 1–10 (2015)

Technology Alternatives for Workplace Safety Risk Mitigation in Construction: Exploratory Study

Ali Karakhan, Yiye Xu, Chukwuma Nnaji, and Ola Alsaffar

Abstract

Safety performance in the construction industry has reached alarming levels and continues to be a primary source of concern to industry stakeholders. The construction industry is considered more hazardous than other major industries such as manufacturing. In the other industries, safety performance has been substantially improved and generally falls within acceptable levels. One noticeable difference between construction and other industries is that the rate of technology implementation in the other industries is significantly higher than in construction. High rates of technology implementation are expected to lead to improved safety and non-safety performance. The primary objective of the present study is to summarize the use of technology alternatives in the application of the hierarchy of controls using a preliminary, unstructured review of literature. The hierarchy of controls is a systematic method to reduce worker exposure to workplace hazards and mitigate potential safety risks on jobsites. The result of the study indicated that there are several technological controls used to mitigate workplace safety hazards during construction. Although virtual reality and building information modelling (BIM) are more effective than others in mitigating workplace safety hazards, the other technologies such as wearable sensing devices, warning systems, drones, and robotics can play significant role in protecting and/or alerting workers from potential workplace safety hazards. It is expected that the present study will help industry practitioners improve their understanding of technological controls used to mitigate workplace hazards and motivate higher levels of technology adoption in construction.

Keywords

Hierarchy of controls • Occupational safety • Technology • Building information modeling • Virtual reality
Wearable safety devices

99.1 Introduction

Safety performance in the construction industry remains a primary concern and continues to frustrate industry stakeholders. Annual fatality and injury statistics from the Bureau of Labor Statistics (BLS) indicate that construction is one of the most hazardous industries in the US [1]. In 2016, 991 fatal work injuries were recorded in construction [1], which accounts for almost 20% of all US fatal injuries in that year. Given that the construction workforce comprises no more than 5% of the overall US workforce [2], safety performance in construction is considered poor especially compared with other major industries. In the other industries (e.g., manufacturing), technology implementation is maximized to prevent or reduce

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worker exposure to potential workplace hazards, thus improving work conditions and safety performance. High levels of technology implementation usually lead to improved safety performance [3]. Unfortunately, in the construction industry, the rate of technology implementation is still limited, although upward trends have been observed recently. Previous studies have concluded that technology implementation in the built environment can bring numerous advantages with respect to safety, schedule, cost, and quality throughout the facility life-cycle [4]. In particular, high levels of technology implementation found to particularly improve safety performance outcomes [5, 6]. The challenge is that technology implementation in construction is still relatively low.

Fortunately, there are abundant safety technologies that project teams can implement throughout the facility life-cycle to improve workplace conditions, mitigate potential jobsite hazards, and enhance safety performance outcomes. However, the application of technology as it relates to safety management and risk mitigation plans has not been adequately studied and explained. The present study attempts to bridge this gap in knowledge by reviewing previous studies on the use of technology in safety management and risk mitigation plans.

99.2 Study Objective

The specific objective of the present study is to identify and summarize technologies that can be used to mitigate safety risks on the jobsite and improve workplace conditions as they relate to the hierarchy of safety controls. The research method adopted to identify safety technologies is a preliminary, unstructured review of literature on the topics of safety and technology, as used by Gent et al. [7]. The unstructured literature review conducted has limitations but is considered acceptable for a preliminary investigation. For future research on the topic, a more systematic review of literature supported by industry insight is recommended.

99.3 Hierarchy of Controls

The hierarchy of controls is a safety management system used in many industries to minimize or eliminate workplace safety risks. It is an effective means of determining what safety measures to implement and how to implement them effectively. Manuele defines the hierarchy of controls as "a systematic way of thinking and acting, considering steps in a ranked and sequential order, to choose the most effective means of eliminating or reducing hazards and the risk that derive from hazards" [8]. The hierarchy of controls is divided into five levels of safety controls—personal protective equipment (PPE), administrative controls, engineering controls, substitution, and elimination—as shown in Fig. 99.1. The rationale behind the hierarchy is that some levels of safety control are more effective in mitigating workplace risks than others. Typically, high order levels at the top of the hierarchy, such as hazard elimination and substitution, are perceived as the most effective and reliable measures of safety control as opposed to levels that are low in the hierarchy such as PPE. Safety measures that are low in the hierarchy are considered reactive; reactive safety measures are usually less reliable and more expensive to implement onsite than proactive safety measures. Reactive safety measures typically require worker involvement in the

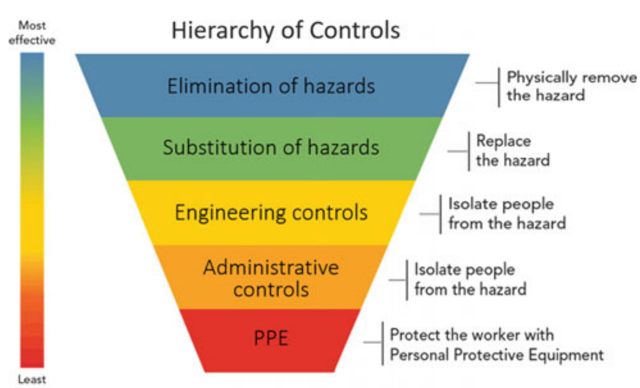

Fig. 99.1 Hierarchy of controls, adapted from [10]

activation of the system [9]. Accordingly, they are perceived as less effective at mitigating workplace risks than proactive measures. The five levels of safety control are described below in more detail.

99.3.1 Personal Protective Equipment (PPE)

PPE is the least effective level of safety control although its presence is indispensable in any safety management plan. PPEs are considered reactive safety measures and can be ineffective in some circumstances (e.g., workers may not use them or use them improperly). They are used to reduce severity of the injury if an accident occurs, as opposed to mitigating safety hazards on the jobsite. PPEs do not decrease worker exposure to hazard nor reduce severity of hazard on the jobsite. Accordingly, this type of safety control should not be used independently, and it is more effective when used in conjunction with other safety measures, such as engineering and administrative controls. Moreover, PPEs can be sometimes uncomfortable and may place physical burden on workers. All of the aforementioned reasons make PPEs the least effective level of safety control. Examples of PPEs include safety goggles, gloves, hard hats, high-visibility clothing, safety footwear, and ear plugs.

99.3.2 Administrative Controls

Administrative safety controls are changes in work procedures and policies including written safety program, job rotation policy, safety rules and supervision, safety training and education, safety and health planning, and warning systems with the intent to improve employee awareness of potential workplace hazards and reduce potential severity of injuries if an accident occurs. Administrative controls are reactive measures and typically require worker involvement in the activation of the system [9]. A fall arrest system (a combination of PPE and administrative control) can be used during construction and maintenance of a roof to prevent roofers from falling to the ground level. However, if roofers do not use the system, or use it improperly, they can fall and be seriously injured. Moreover, even if the roofers use the system properly, they can still fall and be injured although the fall-protection gear will catch the roofers and prevent them from falling to the ground level. Administrative controls do not aim to remove hazards from the jobsite or isolate workers from the hazards; instead, the goal of their usage is either to improve risk perception of employees or to reduce severity of injuries when accidents occur. Typical examples of administrative controls are equipment safety standards, material safety data sheet (MSDS), frequent housekeeping, safety hazard warning signs and symbols, personal hygiene practices, pre-task planning, job hazard analysis, safety checklist, and OSHA 10-hour training.

99.3.3 Engineering Controls

Engineering controls are methods and practices integrated into the design of a product, or a process, to isolate workers from potential workplace hazards. They are considered reliable measures to prevent worker exposure to hazards if adequately designed, implemented, and maintained [11]. Even though engineering controls do not eliminate hazards from the jobsite, they can eliminate exposure to the hazards. That is, by isolating workers from potential workplace hazards, the risk of injuries will be substantially reduced or even eliminated in some cases. Building a temporary guardrail system around the entire perimeter of a building's rooftop is a form of engineering control that an employer can implement to protect workers from the risk of falling over the roof edges. Other common examples of engineering controls are safety nets and machine guarding.

99.3.4 Substitution of Hazards

Substitution of hazards is considered the second most effective method of safety control after hazard elimination. Substitution of hazards involves replacing a material, machine or a process, with an alternative that is either non-hazardous or less hazardous than the original material intended for use. Substitution of hazards is a reliable method to mitigate workplace hazards and oftentimes inexpensive to implement especially if considered early in the design process [10]. Specifying the use of non-toxic and low chemical-emitting materials [e.g., zero volatile organic compound (VOC) materials] for caulks, paints, carpets, sealants, adhesives, and other building materials is a typical example of hazard substitution.

99.3.5 Elimination of Hazards

Elimination of hazards is a proactive method and widely recognized as the most effective means of preventing workplace injuries, illnesses, and fatalities. This method aims at removing the hazards physically from the jobsite, thus eliminating safety risks associated with a particular operation. Risk is the product of both frequency of exposure to hazard and severity of hazard [12], and, therefore, elimination of the hazards from the jobsite will likely result in minimal safety risks during work operation. The design of underfloor heating, ventilation, and air conditioning (HVAC) systems instead of typical overhead systems is one way to eliminate the risk of working at height. Eliminating the risk of working at height can minimize fall hazards during construction and maintenance operations, the leading cause of fatal work injuries in the US [1]. Nevertheless, the implementation of hazard elimination in construction is challenging, and several barriers that may inhibit construction stakeholders from implementing this method have been recognized. For more details about potential barriers, prospective readers are advised to review the SmartMarket Report [5].

99.4 Technological Controls for Workplace Safety Risk

99.4.1 Smart Personal Protective Equipment (PPE)

PPEs, which are considered reactive safety measures, are the least effective method to mitigate workplace safety hazards, as mentioned previously. However, they can become more effective, or even proactive in some cases, when wearable sensing devices (WSDs) and sensors are embedded in them. Physiological sensors such as temperature and heart rate detectors can be equipped in hard hats and safety vests to provide real-time health conditions of workers, and alert both workers and supervisors of potential safety risks such as fatigue and physical complaints. Locating techniques such as global position systems (GPS) and radio frequency identification (RFID) can also make PPEs more effective in mitigating workplace safety risks. Besides locating and tracking workers on the jobsite, RFID tags attached to PPEs can be used to detect unsafe worker behaviors such as the improper use of PPEs [13]. Furthermore, by incorporating GPS, RFID, and inertial measurement units (IMU) into some PPEs (e.g., smart boots and smart vests), employee location and motion can be tracked [14, 15]. Tracking employee location and motion can detect situations when workers lose balance and fall, for example, thus providing immediate help to those workers. In all cases, the severity of hazard in the workplace is not reduced by using WSDs and other sensors. However, the integration of these technologies into PPEs improves awareness among workers and enhances interactive communication between workers and managers/supervisors. Improved awareness and enhanced interactive communication can maximize the usability and effectiveness of PPEs, thus improving worker safety on the jobsite. It should be mentioned that these technologies can be also considered administrative controls, but they are primarily categorized into this level of control in this study because they are encased into PPEs. That is, these WSDs and sensors integrated into PPEs may be used to serve a different function (e.g., sending real-time locations and warning signals) than the primary function of traditional PPEs.

99.4.2 Administrative Controls Through Technology

As mentioned previously, administrative controls are typically used to improve employee awareness of potential workplace hazards and reduce potential severity of injuries if an accident occurs. Recently, the incorporation of technology to enhance administrative safety controls has received substantial attention. With respect to training, technology has been utilized in multiple ways to enhance safety training programs. Teizer et al. developed interactive training methods using three-dimensional immersive data visualization tool to train workers on performing steel erection tasks safely in a virtual, indoor environment [16]. In addition, technology is frequently used to create real-time digital safety signage on construction jobsites. Digital safety signage is an effective method to warn workers of potential workplace hazards and remind them of necessary safety protection and precautions required in order to perform a task safely [17]. Moreover, safety warning systems can be applied to alert workers from potential workplace hazards. For example, heavy construction equipment can be linked into a proximity warning system to alert workers when they are in-close proximity to equipment by releasing visual and audible alarms. Work zone intrusion alert technology is another form of warning systems used on highway construction projects to alert workers from potential hazards resulting from a vehicle intrusion into the work zone [18]. Such alert can provide additional reaction time for construction workers to protect themselves and avoid potential risks. Quick response (QR) codes, also referred to as two-dimensional barcodes or matrix barcodes, are, in turn, used to improve worker safety through providing precaution information pertinent to a specific location on the construction jobsite. Smartphones or tablets enabled with a QR code reader are used to access information stored in a database using a designated URL. QR codes could be used to check if a worker obtained the required training to perform work at a specific location, list out the work operational procedures and safety issues associated with a specific task, and provide schematics of temporary structures to facilitate hazard identification [19].

99.4.3 Engineering Controls Through Technology

Engineering controls aim to isolate workers from potential workplace hazards, thus reducing the risk of injuries. Advanced technologies have been increasingly adopted in the construction industry as effective engineering controls to mitigate workplace safety risks. Unmanned aerial vehicles (UAVs), also known as drones, are proven to improve monitoring and safety inspection processes on the jobsite [5, 20, 21]. High-resolution images and videos captured by UAVs can provide accurate information of jobsite conditions, as well as detailed reports about onsite compliance with safety procedures. Moreover, the use of UAVs in structural inspection and condition assessment can eliminate the need for ironworkers to work in high risk situations or locations (e.g., bottom of a bridge), thus reducing worker exposure to potential workplace hazards, such as fall hazards. Similarly, robotic technology is another method used to provide effective engineering safety controls. Previous studies have also evaluated the effectiveness of automated flagger assistance devices (AFADs) as a potential technology to provide engineering safety controls in highway work zones [22]. The AFAD automates the traffic control flagging process—enabling a worker to remotely control the flag—thereby eliminating the need for a construction worker to work in close proximity to moving traffic. Furthermore, positive protection systems such as truck mounted attenuators (TMAs) and mobile barriers are utilized in highway work zones to reduce worker exposure to hazards and isolate them from potential risks resulting from moving traffic passing by.

99.4.4 Hazard Substitution and Elimination Through Technology

Substitution and elimination of hazards are considered the most effective methods of safety control. These methods are oftentimes feasible only if implemented early in the design process. Clash detection and spatial collision are two potential sources of jobsite hazards that can be detected and eliminated during the design process. However, identifying and eliminating such kinds of collisions using traditional, two-dimensional (2D) drawings is challenging. To overcome potential challenges, technology, such as building information modelling (BIM), can be utilized using a simulation approach to visualize the physical characteristics of a workplace and identify potential collisions and other jobsite hazards [23]. The visualizing of design can assist project teams to identify potential safety hazards early in the project lifecycle, before start of construction, especially those hazards that are not readily detectable in 2D drawings [24]. Shen and Marks conducted real-life experiment and concluded that even experienced practitioners with many years of experience may not be able to detect a high percentage of jobsite hazards unless they use visualization tools such as 4D-BIM [25]. Likewise, virtual reality models can be used to reduce jobsite hazards and improve workplace conditions. Both BIM and virtual reality models are versatile and can be shared with different project entities to enhance team interaction and communication [26]. Enhanced team interaction and communication are critical factors to maintain high levels of jobsite safety.

Figure 99.2 illustrates technology alternatives organized in a hierarchy based on their level of risk mitigation effectiveness. Technologies at the top of the pyramid are more effective than those at the bottom in terms of mitigating workplace safety risks.

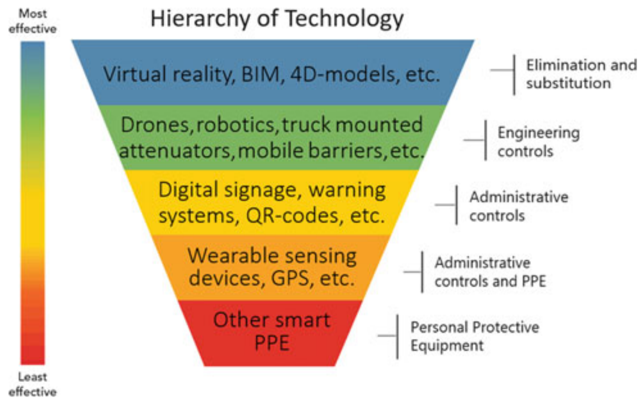

Fig. 99.2 Technology alternative organized in a hierarchy based on level of risk mitigation effectiveness

99.5 Summary and Conclusions

Current statistics indicate that safety performance in construction is poor and that safety management in the industry lags considerably behind other major industries. Previous studies suggest that introducing innovative technology into safety management practices provides substantial potential for improving construction safety performance. One way that technology implementation could improve safety management in construction is through utilizing technologies as a safety control in phases that hold high impacts on performance outcomes—that is, applying technology as part of the risk mitigation plan to improve safety. The present study explored the potential alignment between safety technology and effective safety management protocols using the hierarchy of controls. Findings from this study suggest that although PPEs could be digitalized using technologies such as sensors and their effectiveness could be improved, the most effective technological controls for eliminating workplace safety hazards in construction are virtual reality and BIM. Results from this study provide valuable information to industry practitioners about existing technological controls used in practice to improve workplace conditions and safety performance. Future research should conduct a systematic review of existing literature on the topic to identify other potential technologies used for safety management and determine their level of effectiveness using the hierarchy of controls. Such research can be facilitated using a panel of experts with industry insight.

References

1. BLS (Bureau of Labor Statistics): National census of fatal occupational injuries in 2016. U.S. Dept. of Labor, Washington, DC. Retrieved from https://www.bls.gov/news.release/pdf/cfoi.pdf on 14 Feb 2018
2. Abdelhamid, T.S., Everett, J.G.: Identifying root causes of construction accidents. J. Constr. Eng. Manag. **126**(1), 52–60 (2000)
3. Azeez, M., Gambatese, J.: Using the risk target concept to investigate construction workers' potential biases in assigning/assuming safety risk. Construction Research Congress (CRC): Safety and Disaster Management, pp. 324–333. New Orleans (2018)
4. Ozorhon, B., Oral, K.: Drivers of innovation in construction projects. J. Constr. Eng. Manag. **143**(4), 04016118 (2016)
5. SmartMarket Report: Safety Management in the Construction Industry 2017. Dodge Data and Analytics, Bedford (2017)
6. Zhou, Z., Irizarry, J., Li, Q.: Applying advanced technology to improve safety management in the construction industry: a literature review. Constr. Manag. Econ. **31**(6), 606–622 (2013)
7. Gent, I.P., Jefferson, C., Miguel, I., Moore, N.C., Nightingale, P., Prosser, P., Unsworth, C.: A preliminary review of literature on parallel constraint solving. In: Proceedings PMCS 2011: Workshop on Parallel Methods for Constraint Solving, pp. 499–504 (2011)
8. Manuele, F.A.: Prevention through design addressing occupational risks in the design and redesign processes. Prof. Saf. **53**(10), 28–40 (2008)
9. OSHAcademy (Occupational Safety and Health Academy): Course 700—Introduction to Safety Management: Reactive and Proactive Safety Programs. Retrieved from https://www.oshatrain.org/courses/pages/700approaches.html on 22 Mar 2018
10. CDC (Centers for Disease Control and Prevention): The National Institute for Occupational Safety and Health (NIOSH): Hierarchy of Controls. Retrieved from https://www.cdc.gov/niosh/topics/hierarchy/ on 22 Mar 2018
11. CCOHS (Canadian Centre of Occupational Health and Safety): OSH Answers Fact Sheets. Retrieved from http://www.ccohs.ca/oshanswers/hsprograms/hazard_control.html on 23 Mar 2018
12. Manuele, F.A.: Risk assessment and hierarchies of control. Prof. Saf. **50**(5), 33–39 (2014)
13. Kelm, A., Laußat, L., Meins-Becker, A., Platz, D., Khazaee, M.J., Costin, A., Teizer, J.: Mobile passive radio frequency identification (RFID) portal for automated and rapid control of personal protective equipment (PPE) on construction sites. Autom. Constr. **36**, 38–52 (2013)

14. Jones, K.: Wearables are Helping Make Construction Sites Safer. Retrieved from https://www.constructconnect.com/blog/construction-technology/wearables-helping-make-construction-sites-safer/ on 21 July 2017
15. Awolusi, I., Marks, E., Hallowell, M.: Wearable technology for personalized construction safety monitoring and trending: review of applicable devices. Autom. Constr. **85**, 96–106 (2018)
16. Teizer, J., Cheng, T., Fang, Y.: Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity. Autom. Constr. **35**, 53–68 (2013)
17. Ng, A.W., Chan, A.H.: Mental models of construction workers for safety-sign representation. J. Constr. Eng. Manag. **143**(2), 04016091 (2016)
18. Gambatese, J., Lee, H., Nnaji, C.: Work Zone Intrusion Alert Technologies: Assessment and Practical Guidance. No. FHWA-OR-RD-17-14, Oregon Department of Transportation, Salem (2017)
19. Lorenzo, T.M., Benedetta, B., Manuele, C., Davide, T.: BIM and QR-code: a synergic application in construction site management. Procedia Eng. **85**, 520–528
20. De Melo, R., Costa, D., Álvares, J., Irizarry, J.: Applicability of unmanned aerial system (UAS) for safety inspection on construction sites. Saf. Sci. **98**, 174–185 (2017)
21. Irizarry, J., Gheisari, M., Walker, B.: Usability assessment of drone technology as safety inspection tools. J. Inform. Technol. Constr. (ITcon) **17**(12), 194–212 (2012)
22. Finley, M.: Field evaluation of automated flagger assistance devices in work zones on two-lane roads. J. Transp. Res. Board **2337**, 1–8 (2013)
23. Zhang, S., Teizer, J., Lee, J., Eastman, C., Venugopal, M.: Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules. Autom. Constr. **29**, 183–195 (2013)
24. Shen, X., Marks, E.: Near-miss information visualization tool in BIM for construction safety. J. Constr. Eng. Manag. **142**(4), 04015100 (2015)
25. Perlman, A., Sacks, R., Barak, R.: Hazard recognition and risk perception in construction. Saf. Sci. **64**, 22–31 (2014)
26. Ganah, A., John, G.: Integrating building information modeling and health and safety for onsite construction. Saf. Health Work. https://doi.org/10.1016/j.shaw.2014.10.002 (2015)

Part VII

Education, Training, and Learning with Technologies

BIM4VET, Towards BIM Training Recommendation for AEC Professionals

100

Annie Guerriero, Sylvain Kubicki, V. Maquil, N. Mack, Yacine Rezgui, H. Li, S. Lamb, A. Bradley, and J.-P. Poli

Abstract

The rapid development and use of BIM in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry requires an adequate understanding of the roles and competencies that professionals should develop and maintain. Besides, as the specific processes associated with BIM remain closely linked to the nature of the activities and teams involved in each project, one can consider that the definition of roles and competencies requires a project-level discussion and alignment. This article presents the main results achieved through the BIM4VET research project. It focuses first on the matrix of responsibilities defined for BIM profiles, and presents the global approach for assessing competency maturity and further recommends training courses, thanks to a benchmark carried out by the project partners. Second, the paper describes the BIM4VET toolset developed, and its associated repository of training modules, the management of users and their maturity assessment, and further the collective decision-making system intending to help practitioners collaboratively elaborating project-level responsibilities and registering for training sessions. The assessment of results is presented, through both (1) a Delphi questionnaire for achieving a sector-wide validation of roles and responsibilities, and (2) an experimental protocol involving observation of professionals using the tools.

Keywords

BIM (building information modeling) • Competence matrix • Training courses recommendation

100.1 Introduction

The article presents the results of the BIM4VET project (a project funded by Erasmus + programme, carried out from Sept. 2015 to Feb. 2018, http://bim4vet.eu). This project addressed the issue of BIM skills and the alignment of the training offer based on a EU transparent and harmonized BIM actor competence matrix.

Building Information Modelling (BIM) is in the process of rapidly changing the way in which construction projects are obtained, designed, constructed and managed throughout the lifecycle of a building. While new skills are necessary, the project Standardized Vocational Education and Training for BIM in EU (BIM4VET) addresses the urgent need to devise a skills matrix, which is transparent and unified for BIM actors throughout Europe, to standardize BIM tasks and processes within the European Union, taking existing international developments into account, and to classify and standardize BIM training programme and certification schemes.

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The BIM4VET objectives are to contribute towards the European Area of Skills and Qualifications by focusing upon the issue of BIM actor's qualifications transparency and BIM training in Europe. It is also a first step towards a convergence roadmap for European training curriculums.

Moreover, the partners have developed the BIM4VET application dedicated to BIM maturity assessment as well as BIM training course recommendation according to the professionals' needs. A tangible interface has been implemented in order to reinforce the collaborative aspects of training courses selection. This enables BIM skills to be assessed collectively and individually for the actors that work together on a digital model project using BIM processes.

100.2 Background

Since before the 20th Century, research has been undertaken documenting the issues linked with the management of within construction projects. A number of industry papers and academic research has been undertaken [1] identifying the effects of poor information management and highlighting key causes such as incomplete and uncoordinated information and work-flows. To improve the quality of construction information, much work has been developed within the industry around the drawing and specification production and the coordination of information [2, 3]. Recently, good practice around information management has been updated to suit the exchange of information attributed to graphical models; this process is referred to as 'Building Information Modeling' (BIM).

International progress has been undertaken around BIM, with the UK cited as the highest rating in BIM maturity [4] through the development of a number of BIM standards and processes. These standards, in particular BS1192 [5] and PAS1192-2 [6] are being incorporated into the BIM international standard ISO19650 [7]. Within PAS1192-2 BIM is defined as the "process of designing, constructing or operating a building or infrastructure asset using electronic object-oriented information".

While the UK has lead the way in the development of standards around satisfying BIM at a project level, little work has been done around the skills and capability of an individual. Continuing with the work done within the UK, a Learning Outcome Framework (LOF) has been developed outlining the knowledge required of a BIM professional [8, 9]. However this falls short of outlining the specific competencies required, despite industry research identifying a gap in BIM related skills [10].

Comprehensive research has been undertaken by BIM excellence around a framework for BIM competencies, defining them as "a specialized type of Competency representing the ability of an individual or team to generate pre-defined BIM Deliverables" [11]. However, this definition does not take into account other non-deliverable based activities such as the need to validate and verify data within deliverables once they are produced. Therefore, there is a need to utilize a broader definition.

ISO 17024 defines competency as: "ability to apply knowledge and skills to achieve intended results". This definition is more suitable to capture competencies, which are not directly associated to the production of deliverables. Otherwise, little research has been conducted on this topic.

A comparison of skills for project managers and BIM managers was undertaken through a study involving social media analysis [12]. This research identified a cluster of core BIM skills related to both project managers and BIM managers, but with skillsets used in different ways for each role. The findings of this research have highlighted some BIM competencies but only in relation to a BIM manager role.

In addition, a similar schedule of competency topics were also collected through an analysis of job advertisements [13], and identified mainly software proficiency competencies. There is therefore, an opportunity to produce a schedule of BIM competency items that individuals could utilize to assess their training and development requirements, as well as structure role profiles within organizations to suit the competencies required.

100.3 Methodology

The BIM4VET project methodology were developed through 8 major steps (see Fig. 100.1):

1. A phase of literature review that allowed to scope the problem and defining a first BIM competence matrix focusing on 4 BIM roles: BIM author, Senior BIM author, BIM coordinator, BIM manager.
2. The BIM competence matrix was adapted based on a DSM (Delphi Survey Method). Two rounds were necessary for obtaining the final BIM competence matrix.

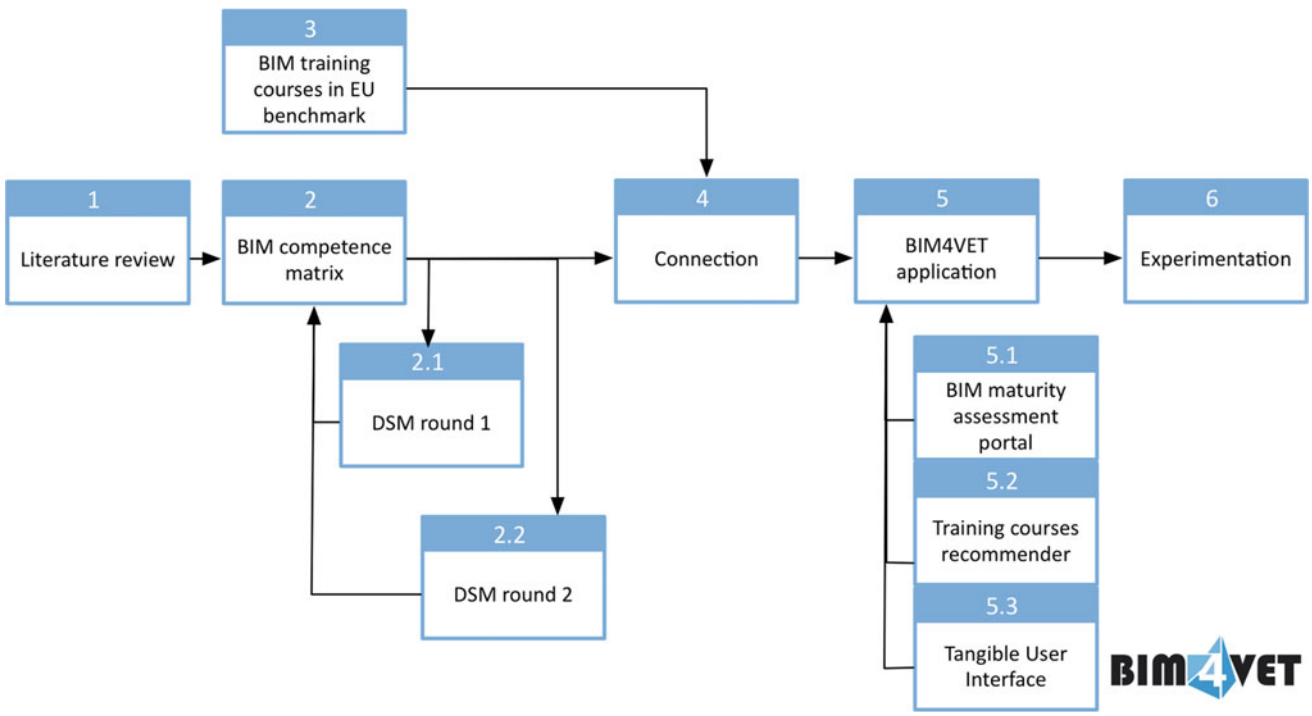

Fig. 100.1 BIM4VET project methodology

3. A BIM training courses benchmark were made in order to have an overview of the current BIM training offer in EU.
4. The connection between the BIM training courses data and the final BIM competence.
5. Based on the previous data centralized in a unique database, the BIM4VET application for collaborative selection of BIM training courses according predefined needs and users' preferences. The application contains a BIM maturity assessment portal, a training course recommender, and a tangible user interface.
6. Finally, the proposal was tested with professionals for validation of the results.

100.4 BIM4VET Proposal

100.4.1 BIM Profiles and Competence Matrix

The BIM profiles that were identified are presented below:

1. **BIM Manager** who is responsible for leading the project coordination and standards compliance at the project level.
2. **BIM Coordinator** who is a senior staff and is responsible for the coordination and standards compliance at the team level.
3. **Senior BIM Author** who is a senior staff member who produces design outputs such as models, drawings, schedules and reports for his team.
4. **BIM Author** is a staff member who produces design outputs such as models, schedules and reports for his team.

These four BIM profiles result from the literature review and job offer analysis.

These roles have been developed from PAS1192-2 and the responsibilities associated with information management within roles of a task team. Guidance has also been derived from the CIC BIM Protocol [14] which states 'an Employer is required to appoint an information manager as a wider set of duties under a Design Lead or Project Lead appointment'. For the purposes of the assessment this role is entitled 'BIM Manager' and is at the Project Level.

Table 100.1 Extract of the profile A: BIM author

Role	Responsibility	Competency
BIM author	A2. Develop and maintain graphical and non-graphical models against project standards	T04: Modelling T07: Model management T06: Presentation and animation O01: General modelling O02: Capturing and representing

From PAS1192-2, Information Delivery, the specification requires roles to be embedded into contracts, either through a specific schedule of services or more general obligations. Therefore, PAS1192-2 identifies the types of roles that should be considered. The specification also notes that on projects led with the CIC BIM Protocol a key role is the Information Manager or 'BIM Manager'.

Kymmell [15] surmises the three primary BIM-related roles that emerge from a team selection process are the BIM Manager, the BIM Operator, and the BIM Facilitator. Further research using UK BIM advertised roles as a primary source of information [16] identified the spread of responsibilities relating to job descriptions and also identified that three core roles are likely to be found in BIM project teams which align themselves with Kymmell's three BIM Specialist Roles.

The Building Information Council (BIR) is based in the Netherlands and forms a partnership between various stakeholders in the Dutch construction and infrastructure industry. BIR has identified the benefits to business through the uptake of BIM and has published a knowledge leaflet entitled 'BIR Leaflet Number 3—BIM Roles and Competences' [17]. Here, the most common BIM roles in the Dutch construction sector have been identified and expanded to include roles and competencies for individuals and organisations. BIR No 3 includes four main roles of a BIM Project Manager, BIM Coordinator, BIM Team Manager and BIM Modeller with a number of key competencies aligned to each role.

In a review of BIM job vacancy advertisements undertaken by Barison and Santos [13] the competencies and roles identified for a BIM Modeller required attributes to develop and extract 2D documentation from BIM models. Similar attributes to the BIM Modeller where also identified by Kymmell [15] who described the role as a BIM Operator. Similar descriptions also can be found in "BIM Demystified" book [18]. For this research project the term BIM Author has been adopted as it aligns itself with PAS1192-2 Task Team Role.

After this step of state of the art, the responsibilities have been developed (see Table 100.1 for an example).

Then, the responsibilities identified for each roles have been linked to the competencies defined by Succar [19].

The 201in Competency Table developed by the BIMe Initiative [19] has 8 Competency sets with an accompany 55 Competency Topics, each defined within a BIM Dictionary. The 201in Competency Table B is organised within four primary sets of Managerial, Functional, Technical and Supportive headings. There are also four secondary competency sets of Administration, Operation, Implementation and Research and Development.

Finally, after two DSM consensus rounds, four BIM profiles were compiled that each contained a repository of BIM related responsibilities, and competencies levels. The results of the round 2 questionnaires provided an aggregated opinion from a diverse set of SMEs' and were used to inform each of the BIM-related profiles. The aggregated BIM skills repository profiles would be used as benchmark for the maturity assessment being developed in the wider project deliverables (Table 100.2).

100.4.2 BIM Training Benchmark and Connection with the BIM Competence Matrix

In order to make the training courses "recommendable" by the system, BIM4VET researchers proceeded to a benchmarking exercise, aiming at describing BIM training courses by using the 25 BIM responsibilities. For each training course, the contribution to acquiring competency related to these BIM responsibilities is evaluated by using the Dreyfus scale (i.e. from novice to expert) to qualify the training course prerequisites and the learning outcome. The level "novice" is associated to the value 1 until the value 5 for the level "expert". The level 0 means that the BIM responsibility is not treated by the training course considered. During the course of the project, 100+ training modules have been benchmarked.

100.4.3 BIM4VET Application

The BIM4VET application (see Fig. 100.2) is composed of a centralized database containing (1) the data related to the BIM training offer (modules benchmarked, see Sect. 100.4.2), and (2) the data related to the users and their BIM maturity. Then,

Table 100.2 BIM profiles and BIM responsibility matrix (extract of the BIM competence matrix)

BIM4VET responsibility matrix

	BIM Profiles	BIM author	Senior BIM author	BIM coordinator	BIM manager
1	Refer to the work done by other project team members	X			
2	Develop & maintain Graphical and Non-graphical models against Project Standards	X	X		
3	Prepare model for sharing with internal and external stakeholders	X	X		
4	Produce project outputs from graphical and non-graphical models	X	X		
5	Revise outputs to incorporate clash resolution: - Maintain a continuous interface with the BIM Coordinator - Participate in coordination and BIM technology meetings	X			
6	Reference of other shared models to ensure design coordination and clash avoidance	X	X		
7	Assist in Maintaining Project Standards		X	X	
8	Address immediate software issues and support the upskilling of staff		X	X	
9	Remain fully UP TO DATE with Industry good practice around the production and exchange of Information		X		X
10	Help maintain internal CAD standards and workflow by providing feedback to BIM coordinator		X		
11	Revise Outputs regarding QA/QC protocols		X		
12	Supervise BIM Authors		X		
13	Ensure compliance to project standards			X	
14	Ensure compliance to corporate standards			X	
15	Ensure compliance to relevant national and international standards			X	
16	Coordinate the different BIM authors junior/senior outputs to ensure the good quality and compliance of the model according to the BIM Project Execution Plan / BIM Protocol/client's requirements			X	
17	Supervise Clash detection, reporting and resolution			X	
18	Ensure implementation of BIM software			X	
19	Define & maintain project standards				X
20	Agree software solutions to be implemented				X
21	Define project outputs, according to the client's requirement				X
22	Create & maintain a coordination programme for delivery				X
23	Ensure the implementation of a system to share project information				X
24	Lead BIM activities at project level				X
25	Assess project team capabilities to comply with project standards				X

the application is composed of recommender allowing to rank the training courses according to the users' preferences. The rules' base can be summarized as one rule: the more the user's profile matches the prerequisites and the outcomes match with the goal, the more the training is recommended. Finally, a tangible user interface allows the users to determine their preferences, and then to collaboratively select the most adapted BIM training courses in accordance with the users' needs.

The Fig. 100.3 illustrates the tangible interface. On the left, each round element represents a training, and the thickness of the outline associated to the color allows to visualize how much a training module (=round) is recommended to a user (=color). On the right, a token is placed on the tangible table in order to configure the expected level of expertise for each of the 25 BIM responsibilities represented by a colored segment.

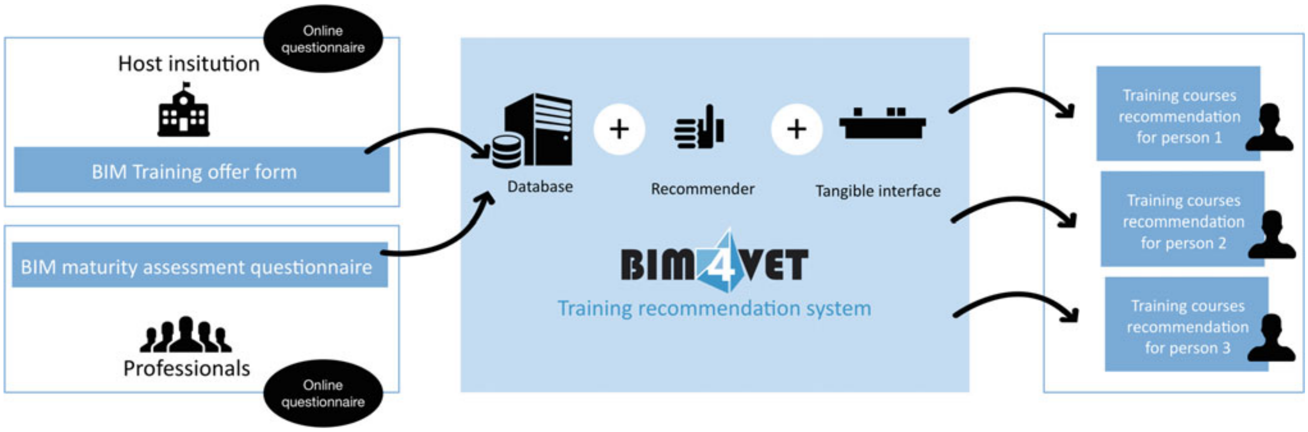

Fig. 100.2 Principle of the BIM4VET application

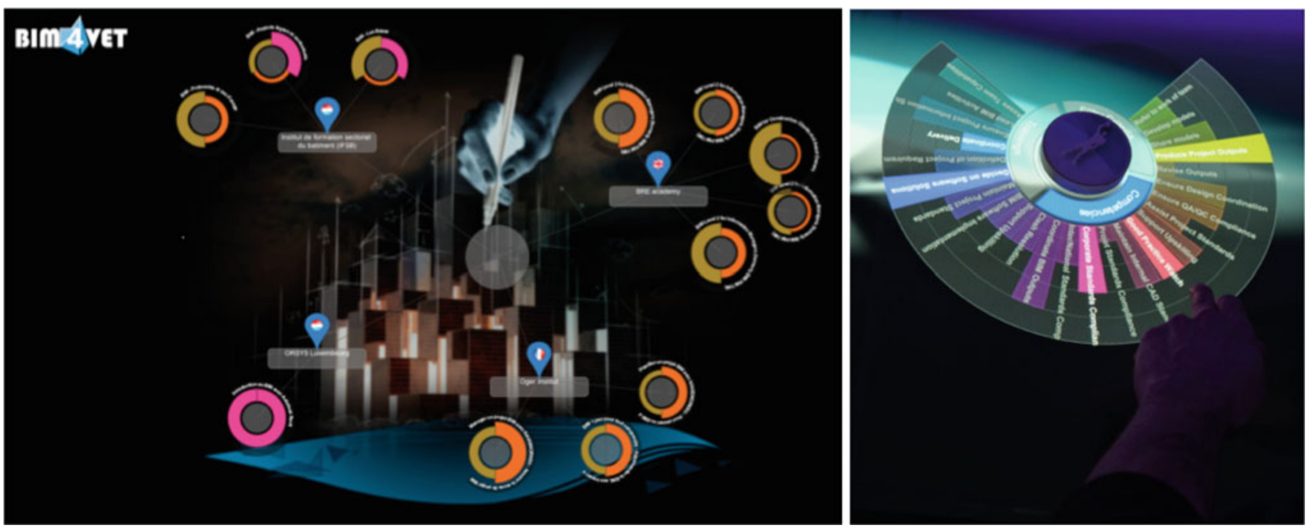

Fig. 100.3 Tangible user interface of the BIM4VET application

100.4.4 BIM4VET Application Assessment

An experimental protocol was prepared in order to evaluate the utility and the usability of the BIM4VET application. This protocol based notably on the TAM3 questionnaire (Technology Acceptance Model [20]) was deployed on the three partners sites at LIST (Luxembourg), Cardiff University (UK) and CEA (France).

The BIM4VET application was deployed on three MultiTaction MT555UTB devices installed at the center of the experiments' rooms. The tangible objects were placed on the border of the table embedding the tangible tabletop. An additional screen was setup in front of the table to provide a series of tasks to the participants.

At total 7 groups of three professionals were invited to participate to the experimentation of the BIM4VET application. The protocol was based on 4 steps:

(1) The protocol started with an introduction of the BIM competence matrix and the general principles of the BIM4VET application.
(2) The participants were asked for choosing a persona (i.e. BIM manager, BIM coordinator and BIM author).
(3) The participants had to accomplish a series of tasks and played the role that they selected in step 2.
(4) After using application, participants filled out a questionnaire based on the TAM3 questionnaire and allowing to assess elements such as perceived ease of use, perceived enjoyment, objective usability, perceived usefulness job relevance, etc.

The analysis of the collected data shows an above average rating for all categories, with a slightly higher rating for the "perceived ease of use" as compared to the "perceived usefulness". This first feedback is very encouraging, showing the acceptance of the BIM4VET application. In the meantime, some of the small problems detected during the experiments let place to minor improvements and a new version of the BIM4VET application.

100.5 Conclusion and Prospects

The paper intends to provide the main results achieved within BIM4VET project. It consists of a definition of four BIM profiles, associated with 25 BIM responsibilities, which identify the main business tasks associated with the deployment of BIM in projects and organizations. Further, competency items have been linked to these responsibilities. These competency items are taken from the BIMExcellence initiative. A continuous validation, based on the application of a two-round Delphi methodology, enabled a convergence amongst 18 international industry experts.

Besides, a set of computer-based tools has been developed. The whole BIM4VET toolset addresses the issue of recommending training to BIM professionals. A database of training modules, benchmarked against the BIM4VET responsibility/competency matrix, has been developed and fed by the researchers. A platform for users' management and competency assessment has been designed and developed. Finally, a collaborative decision-making system, allowing people involved in a project and helping to collectively assess their competencies and register to training has been proposed. Assessment of the system has been carried out, showing its benefits and limits.

During the duration of BIM4VET project, the market offer in terms of training modules has grown very rapidly. It definitely demonstrates the need for a common knowledge on the responsibilities and competencies associated with BIM, as well as their understanding in local/regional markets across Europe, which differ from a country to another. The BIM4VET matrix of responsibilities is flexible enough to allow for different applications, from organization-scale strategy towards skills development to project-level implementation of teams or sector-wide development of training offer. At the moment of publishing this article, Luxembourg is progressing towards a unified training offer, intended for designers, contractors and facility managers, relying on BIM4VET framework.

Moreover, the tools developed demonstrated their usefulness. Further developments are expected, and their use by professionals could help the development of BIM a sector level in the future. In the meantime, demonstrations and dissemination of these prototypes, available in Luxembourg, Cardiff (UK) and Paris (France), is definitely a mean to help the EU practitioners to progress towards the generalization of BIM in their practice and projects.

The results of BIM4VET are further re-used and improved in the framework of BIMEET project, a Coordination and Support Action funded by H2020 (grant number 753994). BIMEET addresses the BIM competencies in relation with the design, construction and operation of energy-efficient buildings, and aims at producing responsibilities and competencies for further specialized training offers in this area.

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References

1. Group SC: A Report for the Government Construction Client Group, BIM working strategy Client Group (2011)
2. CPIC Production Information: A Code of Procedure for the Construction Industry, 1st edn. Construction Project Information Committee, UK (2003)
3. DTI: The Construction Research Programme, Project Showcase (2007)
4. Kassem, M., Succar, B.: Macro BIM adoption: comparative market analysis. Autom. Constr. **81**, 286–299 (2017). https://doi.org/10.1016/j.autcon.2017.04.005
5. British Standards Institute: BS 1192-2007+A2: Collaborative Production of Architectural, Engineering and Construction Information, UK (2016)
6. BSI Standards Limited: PAS 1192-2:2013 Incorporating Corrigendum No. 1—Specification for Information Management for the Capital/Delivery Phase of Construction Projects Using Building Information Modelling, UK (2013)
7. ISO/DIS 19650-1(en) Organization of Information About Construction Works—Information Management Using Building Information Modelling—Part 1: Concepts and Principles. https://www.iso.org/standard/68078.html
8. Platts, T.: Embedding Building Information Modelling (BIM) within the Taught Curriculum (2013)
9. BIM Taskgroup: BIM Learning outcomes Framework (online), 2–3 (2016)

10. BRE Academy: Boardroom to Building Site—Skills Gap Survey (2016)
11. Succar, B., Sher, W., Williams, A.: An integrated approach to BIM competency assessment, acquisition and application. Autom. Constr. **35**, 174–189 (2013). https://doi.org/10.1016/j.autcon.2013.05.016
12. Rahman, R.A., Alsafouri. S., Tang, P., Ayer, S.K.: Comparing building information modeling skills of project managers and BIM managers based on social media analysis. In: Procedia Eng. 812–819 (2016)
13. Barison, M.B., Santos, E.T.: The competencies of BIM specialists: a comparative analysis of the literature review and job ad descriptions. In: Zhu, Y., Issa, R.R. (eds.). International Workshop on Computing in Civil Engineering 2011, pp. 594–602. https://doi.org/10.1061/41182(416)94 (2011)
14. Construction Industry Council: Building Information CIC/BIM Protocol (2013)
15. Kymmell, W.: Building Information Modeling: Planning and Managing Construction Projects with 4D CAD and Simulations. McGraw Hill Professional (2007)
16. Gathercole, M., Thurairajah, N.: The influence of BIM on the responsibilities and skills of a project delivery team. International Conference on Construction in a Changing World, Heritance Kandalama, Sri Lanka (2014)
17. Bouw Informatiie Raad: BIR Leaflet Number 3: BIM Roles and Competences (2015)
18. Race, S.: BIM Demystified. RIBA Publishing (2013)
19. Succar, B.: BIMe Initiative—201in BIM Competency Table. http://bimexcellence.org/resources/200series/201in/ (2017)
20. Venkatesh, V., Bala, H.: Technology acceptance model 3 and a research agenda on interventions. Decis. Sci. **39**, 273–315 (2008). https://doi.org/10.1111/j.1540-5915.2008.00192.x

Teaching Effective Collaborative Information Delivery and Management

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Dragana Nikolic and Robert M. Leicht

Abstract

This paper explores a pedagogical approach to teaching construction students how to plan, execute and monitor an efficient collaborative information delivery plan from the perspective of managing scope of work, time, resources and communication. This study extends the work of similar studies that tasked students with developing BIM process maps to gauge any shift in the students' perception on their ability to map the process. In this context, students in the final year of an undergraduate construction management program participate in a team-based project to plan, execute, update and evaluate the efficiency of their collaborative information delivery plan. To plan this process, the students use references including both UK-based BIM Level 2 standards and US-based CIC BIM Project Execution Planning Guide. Through a semester-long sequence of modeling and planning activities, the students specifically aim to address the following learning objectives: (i) define and allocate project- and information delivery responsibilities; (ii) identify information workflows and respective tasks with estimated durations, and (iii) execute and update their plan to record actual tasks, durations and outcomes. Comparing the initial and executed plan would provide the students with the basis to reflect on the influence of formal planning guides on their understanding of efficient collaborative information management and delivery. In this aspect, the study contributes to the knowledge of how to pedagogically deploy industry-oriented process planning approaches for effectively teaching roles and responsibilities for engaging in interdisciplinary teams.

Keywords

Problem-based learning • BIM • Collaborative process • Management

101.1 Introduction

The construction industry in the UK, as well as globally, is currently pressed to improve the efficiency of project delivery and generate value with a recent shift in emphasis on the structured data set at every project stage. The design and construction industry in the UK tendering for publicly procured work is currently faced with a government mandate to deliver projects compliant with building information modeling (BIM) standards, methods and protocols, published as a number of BIM documents. Furthermore, the goal of the UK mandate and other similar global developments is to reduce the effects of uncertainty and offer guidance to increase the accuracy, completeness and usability of the generated information down the activity stream. In terms of teaching students how this mandate translates in practice, the challenge is the reality that these published standards and processes have been slow to adopt among other due to an overwhelming need to up-skill the

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existing workforce in how to properly apply them on the projects. This in turn presents educators with the challenge to adequately prepare the graduates with relevant knowledge and collaborative, problem-solving and teamwork skills [1, 2].

Though construction engineering and management students tend to master software-related skills, strong communication and teamwork skills have been deemed essential to apply knowledge in practice [3–5]. At the same time, the increase in project complexity necessitates more efficient construction processes and cost-effective management of available resources. Thus, the students are expected to develop skills to leverage their technical knowledge as part of an integrated design and construction team beyond the simple capability to use the software. It is this knowledge and epistemological development in students that is significantly more challenging to embed and assess using traditional approaches. To address some of the challenges, a growing body of research suggests that providing students with an experiential learning environment advances problem-solving and decision-making skills. The development and adoption of BIM can be viewed as an opportunity to engage students in more practicable problems and projects that allow the development and assessment of the integrated process design skills that are much needed.

101.2 Background

101.2.1 Approaches to BIM Process Planning

Broad body of literature discusses a range of building information modeling and management (BIM) aspects seen to offer solutions to ailing inefficiencies in how information is authored, shared and used in design, construction and operations. A series of UK government funded reports produced between the 1970s and late 1990s (e.g. [6–8]) gave way to the government strategy [9], that defined BIM maturity levels with the mandate to use BIM (level 2) on all publicly procured projects starting in April 2016. Though there is much debate on the reality of its implementation [10], the mandate involves a number of required and voluntary measures in an effort to decrease industry fragmentation through a more structured approach to information exchange and project management. What BIM Level 2 in essence mandates is a file-based collaboration and library management within a centrally coordinated data environment.

In this context, the implications for teaching BIM are found in a gradual shift from an emphasis on the digital model as a source of knowledge [11] towards “value creating collaboration” [12] and “collaborative way of working, underpinned by the digital technologies” [13]. While the claimed benefits of BIM approaches span across disciplines and scopes of implementation, from a collaboration standpoint, BIM is still regarded as a facilitator of concurrent rather than sequential information workflows and more integrated tasks through a shared (3D) model [14]. This approach in turn, requires careful planning of information management and team coordination activities, typically documented in what is known as a BIM execution plan (also BEP). BIM execution plan documents client and stakeholders’ goals and requirements for the project, as well as standards, methods and procedures the teams adhere to for authoring, sharing, coordinating and delivering requested information. In the UK a set of formal standards such as BS1192:2007 and specifications such as PAS1192 series prescribe the methods for structuring the common data environment (CDE). The purpose of the CDE as a single source of information and the file naming convention is to prevent mistakes from duplication, incorrect file versioning, or use of information for purposes other than indicated. Through explicit file and task management strategies the intent is to encourage the conversation among the team members early and continuously throughout the project.

In the US similar objectives through a slightly different approach have been addressed in the BIM Project Execution Planning guide [15], which offers a structured procedure for planning the collaborative process and communication on a project. The guide has already been implemented in teaching undergraduate and postgraduate students process-mapping activities and inter-disciplinary collaboration [16–18]. Still, approaches to teaching BIM remain as diverse as the topic itself. While a large number of studies have explored the necessary skills relative to the new computing tools as well as the dynamics of sharing files and collaborating, there has been little work to explore how learning related to integrated processes can best engage the students to advance their metacognitive and epistemological development.

101.2.2 Pedagogy Around Teaching BIM-Enabled Collaboration

The ability to identify a problem, evaluate options and make decisions in a collaborative setting are all necessary skills for students in the construction and architectural engineering disciplines. The design and construction fields are dynamic and dominated by complex, ill-defined problems with many possible solutions. Planning a collaborative project delivery in a

BIM context is a complex and interdependent process that typically includes a number of considerations such as the project context, scope, goals, information requirements, information exchanges, needed and available resources, technologies and other contingencies for delivering the requested information on time. Planning how to do this process efficiently, as the BIM mandate implies, leaves little room for oversight and plenty of managerial issues for students lacking professional experience to absorb and apply. Studies have been tackling these types of pedagogical challenges by considering questions of soft skills such as leadership, interdependence, social communication and teamwork skills in both collocated and remote settings [19, 20] as well as supporting information technology needs.

At the same time, rapid developments in BIM technologies and shifting focus in the BIM discourse have broadened the scope for educators to effectively tackle what needs to taught, when or how [14, 21]. However, the growing consensus to move beyond teaching technology decoupled from the practical interdisciplinary and collaborative context emphasizes the need for self-directed learning and epistemological development in problem-based settings. Epistemological development, or epistemic cognition, relates to the ability to understand the nature of the problem and deciding what types of problem-solving strategies are appropriate [22]. This level of cognition builds upon the abilities associated with performing a task, and metacognition, which allows one to choose among cognitive strategies. Perry [23] describes this as a way a person makes sense of knowledge as they are challenged with meaning in both philosophical and technical areas. As Salner [24] points out in her framing of systems thinking in epistemological development, few students move from multiplicity to contextual relativism. Salner further asserts that this development is associated with placing students in a position or environment that pressures them to generate their own syntheses and reflect upon their own cognitive patterns. This type of 'pressure' aligns with the common employment of project-based learning in construction management curricula.

101.3 Method: Course Overview and Objectives

Current employability rates of our graduates from the School of Construction Management and Engineering are in the upper ninetieth percentiles[1] and this reflects the School's ongoing strategy to identify and equip students with employable and necessary skills while working closely with industry. Collaboration and communication skills are those always raised as worth improving and strengthening, which has incited current discussions about introducing project-based work as early as in the first year.

To illustrate some of these pedagogical challenges, the authors describe their experience from a senior level undergraduate construction management and engineering elective course that introduces students to advanced concepts and topics on how digital technologies affect collaborative practices. The course applies the techniques of self-directed, research-driven and reflective learning experience through a problem-based group project and a series of small practical assignments where students learn new software through online tutorials. Specifically, the goal of the module is to raise practical questions of how to work and collaborate with different disciplines when technology, information formats, exchanges and management issues start to bring tension into this practice. The course enrolled 25 students with background in quantity surveying, construction management, building surveying and mechanical engineering. The lecture-based approach caused challenges in the past when guest lecturers from industry and academia revealed often conflicting views of the existing practices and concept definitions. For students who are accustomed to well-structured problems, this can become challenging if there is no understanding of the reasons for differing views. Thus, specific learning objectives in the module were for the students to: (1) identify goals, tasks and methods for effective collaboration using existing guidelines, standards and specifications; (2) build collaborative and communication skills through student-to-student interactions for negotiating and allocating roles, responsibilities and milestones; (3) identify and use technologies deemed appropriate for respective tasks; and (4) evaluate and reflect on the applied strategies and team performance to draw relevant lessons about usability of BIM approaches and their understanding of effective collaboration needs.

Educational research in engineering reports that ill-defined problems can be effectively addressed through project-based or problem-based work [25]. Project-based or problem-based learning, are both similar in that they present students with an open-ended or a "messy" real-world problem with no singular solution and which they try to solve by working in small groups, and subsequently reflecting on their experience [26, 27]. The project assignment asked student teams to deliver specific project information (well-defined product) by following their own developed BIM-compliant collaboration practice (ill-defined process) to manage time, tasks, roles and resources.

[1]https://www.reading.ac.uk/ready-to-study/study/subject-area/surveying-and-construction-ug/bsc-construction-management-and-surveying.aspx.

Setting the scene. The students self-enrolled into 6 teams which were introduced to the semester-long course project. The project asked the students to plan, execute and evaluate their collaborative approach to producing a structured set of completed hospital design project information. The teams received the initial set of exchange files in IFC and Revit format, which included architectural, structural, mechanical, plumbing, electrical, fire and sprinkler system models of a large hospital project, with one floor wing remaining to be completed. In order to get the students started planning their collaborative approach, the first three weeks introduced students to the UK and international BIM initiatives, published documents, standards and protocols. The first step for the student teams was to understand the goal of the mandate—eliminate waste and create near zero-defect information. The second part of the problem was challenging—how to actually plan this process, apply these documents and standards in a project, and how will the process work? Both the industry and students face the same challenge of delivering a project using a large number of published documents that predominantly outline *what* needs to be done, but not necessarily *how*. The complexity of this problem is that there is no single solution. Thus, students were expected to establish goals, review published documentation, prioritize it, understand tradeoffs, and negotiate the approach with other team members, ultimately documenting decisions in their BIM plan to produce a coordinated set of project information. Thus, solving the problem had to engage student teams in planning and executing the work by searching for resources, discussing the problem, allocating responsibilities and addressing any questions with the instructors through two planned "client-team" meetings. The teams were also given a general timeline for agreeing on the project roles and responsibilities; familiarizing with the project information and its quality through initial clash detection; producing initial and updated plans to consult with the client, and final delivery.

How students work. Planning for group work is always challenging due to known issues of possible uneven workload or otherwise specific group dynamics. Drawing upon previous research into group work [28–30] several strategies were employed as an attempt to improve the group experience. These included: (1) an option for students to self-select given that in their final year they have fair knowledge of each other and thus can choose team members based on mutual expectations, work ethics and performance goals; (2) suggest project roles to help plan the workload, but let the students negotiate the division of work and responsibilities based on their skills and other commitments as a way to exercise communication and negotiation skills; (3) have planned progress check meetings with each group and act as a mediator and facilitator, and lastly, (4) use peer-evaluation to alleviate any discontent with members who do not contribute. The first meeting with the teams took place in week 4 to discuss their initial plan and address any questions, followed by the second progress meeting in week 8 to discuss their updated plan. During the progress check meetings, an informal survey was distributed to all teams asking each team member to, among other state their level of confidence in understanding the type and amount of work required to do, as well as their ability to do the work and deliver it on time. This revealed a range of instances where some members did not read the assignment, or understood it differently, or had varying sense of ability to do it at that stage. As a result, in addition to the instructors' feedback and steering, the set of questions prompted internal discussion among the team members. Still, at this stage the prevalent questions were quite general, indicating confusion and frustration over not knowing where to start and focused on clarifying the expectations of the assignment, as they seemed uncomfortable with the perceived latitude offered in how they approach it. Ultimately, while groups were tutored in the same way, there was a possibility that some groups moved in a different direction, but reaching equally informative results and conclusions. This became evident in week 8, in the second progress check meeting, where teams began to discuss specific approaches to how they were implementing the collaborative process. The instructors primarily raised reflective questions (e.g. "Why did you decide to do it that way?", "What information did you use in the process?" or "How did you agree on this procedure?"). In this manner, the objective was to help students arrive at answers by articulating the decisions they may have made as they were running into numerous practical problems (e.g. what file-sharing platform they need to exchange files, how to reference each other's files without duplicating, or who is responsible for the file checking) and why they deemed certain options more viable than others.

Assessing the learning. Project-based learning emphasizes self-directed learning supported by small group work [27]. The group work helps each of the team members to contribute in gathering information and discuss questions. The assessment in this course was structured around the collaborative considerations documented in the final BIM strategy report the teams presented at the last day of class, along with lessons learned subsequently captured in the individual reflective reports as a critical component of the learning experience. The group report structure and formatting was open to team's decision and the extent to which they considered existing guidelines and templates. Still, the report had to include the record of initial and any subsequently updated plans with tasks, milestones, deadlines, and responsible parties as a minimum. The goal was to capture the evolution in the team's approach to delivering the project and any change in the team's definition of work scope and internal project targets.

Though formative feedback to stimulate team reflection has been integral part of the process throughout the term, the individual reflective report following the group work intended to help students articulate their collaborative experience and knowledge gained through identifying problems, discussing options, managing their own and other member's input in exploring solutions and delivering information. The primary goal of a written reflective report is to encourage the transfer of learning to the workplace by analyzing and reflecting on the decisions made during the group work, evaluation of how well they worked and what they would do differently next time in the form of broader recommendations. This metacognitive approach is an extension of the guided reflection in experiential learning concepts [31, 32].

101.4 Findings and Lessons Learned

Students' confusion about the project deliverables and scope of work marked the initial stages of the group work, though towards the end, all teams met the learning objectives to (i) define and allocate project- and information delivery responsibilities; (ii) identify information workflows and respective tasks with estimated durations, and (iii) execute and update their plan to record actual tasks, durations and outcomes. The quality of the final group BIM plans was consistent, though the reflective accounts gave a wide range of valuable insights into the learning and decision making process, and the way students considered addressing the challenges should they repeat the process (Table 101.1).

All teams initially defined discipline-specific roles based on systems knowledge, software skills and interests within the team. There was a learning curve until the teams understood their individual members' skill levels before they began adjusting their model management. The initial plans showed tasks and roles that were mostly focused on model authoring, and general milestones broadly set to durations in weeks rather than deliverable or handover dates. It was a common point of discussion amongst teams in meetings that the roles and responsibilities often appeared vaguely defined. For example, the responsibilities for managing information sharing were quite different where one group created a role specifically for this purpose, while another group identified this as a key area that no one was managing, but only after missing a deadline. Responsibilities for doing the clash detection, setting up the common data environment, coordinating the team file exchanges and scheduling meetings were gradually recognized as the work progressed, after the discussions with the instructors and consulting the BIM standards and guidelines.

Students also applied and adapted existing standards and guidelines in different ways, often creating a hybrid. They noted the straightforwardness of the US BIMex approach to defining goals, uses and priorities, while the UK's BS1192 and PAS1192 offered more specific guidelines for managing file exchanges through CDE and file naming. Some groups used a process modeling approach, others used Gantt charts to plan and communicate the process and handoffs, while others used tables that documented deliverables and deadlines. File naming structure though recognized as part of the mandate was inconsistently applied—some groups had an agreed file naming convention, but did not use it, while other groups started without one, but quickly realized the need for it when the number of files started to increase rapidly.

Students generally appreciated the unexpected nature of the project that required skills to manage time that was often underestimated ("*Time estimates were based on meeting the deadline, rather than actual amount of time needed to successfully carry them out*") or work scope that was unaccounted for. None of the teams considered the time and skills needed to produce IFC and COBie files even though they had no experience with either, which resulted in files that were missing data or misaligned. Management challenges were raised in the lack of specifically assigned responsibilities, which caused quality problems: "*Updating the BEP, like many other tasks, was open to everybody, whoever had the chance to do so. Hence its mediocrity.*" Communicating and monitoring the team members' work progress and lag resolution tended to be loosely structured, missing, or otherwise challenging. Some of the teams experienced consistent delays because members were not sharing work by their internally set deadlines, but also did not communicate the reasons for delays and there were

Table 101.1 Students' reflection: considerations for effective collaboration

Skills needed	Improvement strategies	Challenges
Time management	Team's workloads and schedule	Guidelines complexity
Accountability	Meeting strategy	Technology issues
Positive attitude	Adequate task allocation	Logistics
Commitment	Task prioritization	Enforcing team deadlines
Technical confidence	Task time estimates	
Knowing own strengths	Time allocation for brainstorming	

no mitigation strategies put in place. It was observed that developing and agreeing to a plan did not necessarily guarantee adhering to it. The necessity to hold members accountable, motivated and engaged were identified as considerations for effective collaboration. Other students raised the need to more carefully consider each other's skills, workloads and schedules and have more strategic, rather than ad hoc meetings to properly tackle problems that were deemed complex.

101.5 Conclusions

Overall, some of the students welcomed the opportunity to tackle the problem type this course project presented, which was also viewed as different from other projects they typically do. The expectation to master additional software skills become secondary to tangible challenges in managing expectations and work ethics among team members towards effective collaboration. The overall experience of this year's module is that it has in part successfully introduced and reinforced the iterative and complex nature of the collaborative process planning and management. Initial and updated plans demonstrated a gradual increase in task considerations and timelines, though still leaving much room for added clarity and detail. At the same time, the limited time of one term and the learning curve to internalize, apply and evaluate BIM strategies poses challenges to effectively balance multifaceted nature of the collaborative project delivery. The course project focused on supporting and evaluating the learning process where students' understanding of the possible reasons for the given outcomes is more informative than the final product. This problem-based approach carries broader implications to similar initiatives around teaching collaborative BIM. The process demonstrated the value and the need for formative feedback and careful coaching on the productive team discussions. Working with student groups is time-intensive and thus effective for smaller enrollment, but the reality of larger classes will necessitate adequate approaches to problem-based learning. The assessment of problem-based learning warrants further investigation into more creative methods to both scaffold and assess the learning process. This suggests focusing specifically on skills usually not part of a standard assessment, such as communication, work planning and collaborative team-work skills.

References

1. Koutsabasis, P., Vosinakis, S., Malisova, K., Paparounas, N.: On the value of virtual worlds for collaborative design. Des. Stud. **33**, 357–390 (2012). https://doi.org/10.1016/j.destud.2011.11.004
2. Kronholm, M.M.: The impact of developmental instruction on reflective judgement. Rev. High. Educ. **19**, 199–225 (1996)
3. Fruchter, R.: Dimensions of teamwork education. Int. J. Eng. Educ. **17**, 426–430 (2001)
4. Kalay, Y.E.: Enhancing multi-disciplinary collaboration through semantically rich representation. Autom. Constr. **10**, 741–755 (2001). https://doi.org/10.1016/S0926-5805(00)00091-1
5. O'Brien, W., Soibelman, L., Elvin, G.: Collaborative design processes: an active-and reflective-learning course in multidisciplinary collaboration. J. Constr. Educ. **8**, 78–93 (2003)
6. Crawshaw, D.T.: Coordinating working drawings., Building Research Establishment, Current Paper CP 60/76, Watford, UK (1976)
7. Latham, M.: Constructing the team. HM Stationery Office, London (1994)
8. Egan, J.: Rethinking construction. Department of the Environment, Transport and the Regions, London (1998)
9. Cabinet Office: Government Construction Strategy. Cabinet-Office London (2011)
10. Dainty, A., Leiringer, R., Fernie, S., Harty, C.: Don't believe the (BIM) hype: the unexpected corollaries of the UK'BIM revolution'. In: Engineering Project Organizations Conference, The University of Edinburgh, Scotland, UK (2015)
11. National Institute of Building Sciences: National Building Information Model (BIM) Standard-United States, http://www.buildingsmartalliance.org/index.php/nbims/ (2008)
12. U.K. BIM taskgroup: U.K. BIM taskgroup. http://www.bimtaskgroup.org (2014)
13. HMGovernment: Industrial strategy: government and industry in partnership. www.bis.gov.uk. 22 (2012)
14. Becerik-Gerber, B., Ku, K., Jazizadeh, F.: BIM-enabled virtual and collaborative construction engineering and management. J. Prof. Issues Eng. Educ. Pract. **138**, 234–245 (2012). https://doi.org/10.1061/(ASCE)EI.1943-5541.0000098
15. Computer Integrated Construction Research Program: BIM Project Execution Planning Guide—Version 2.1. The Pennsylvania State University, University Park, PA, USA (2011)
16. Poerschke, U., Holland, R., Messner, J., Pihlak, M.: BIM collaboration across six disciplines. In: Proceedings of the International Conference on Computing in Civil and Building Engineering 2010, p. 6, Nottingham, UK (2010)
17. Holland, R., Messner, J., Parfitt, K., Poerschke, U., Pihlak, M., Solnosky, R.: Integrated design courses using BIM as the technology platform. In: Education Thread, p. 12, Washington, DC, USA (2010)
18. Ayer, S.K., Cribbs, J., Hailer, J.D., Chasey, A.D.: Best practices and lessons learned in BIM project execution planning in construction education. In: Proceedings of 9th BIM Academic Symposium and Job Task Analysis Review, pp. 167–174, Washington, DC (2015)
19. Sancho-Thomas, P., Fuentes-Fernández, R., Fernández-Manjón, B.: Learning teamwork skills in university programming courses. Comput. Educ. **53**, 517–531 (2009). https://doi.org/10.1016/j.compedu.2009.03.010

20. Fruchter, R.: Innovation in engaging learning and global teamwork experiences. In: Information Technology 2003. pp. 1–13, Nashville, Tennessee, USA (2003)
21. Sacks, R., Pikas, E.: Building information modeling education for construction engineering and management. I: industry requirements, state of the art, and gap analysis. J. Constr. Eng. Manag. **139**, 04013016 (2013). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000759
22. Kitchner, K.S.: Cognition, metacognition, and epistemic cognition. HDE **26**, 222–232 (1983). https://doi.org/10.1159/000272885
23. Perry, W.G.: Forms of Intellectual and Ethical Development in the College Years: A Scheme. Jossey-Bass Higher and Adult Education Series. Jossey-Bass Publishers, 350 Sansome St (1999)
24. Salner, M.: Adult cognitive and epistemological development in systems education. Syst. Res. **3**, 225–232 (2011). https://doi.org/10.1002/sres.3850030406
25. Perrenet, J.C., Bouhuijs, P.A.J., Smits, J.G.M.M.: The suitability of problem-based learning for engineering education: theory and practice. Teach. High. Educ. **5**, 345–358 (2000). https://doi.org/10.1080/713699144
26. Hmelo-Silver, C.E.: Problem-based learning: what and how do students learn? Educ. Psychol. Rev. **16**, 235–266 (2004). https://doi.org/10.1023/B:EDPR.0000034022.16470.f3
27. Walker, A., Leary, H., Hmelo-Silver, C.E.: Essential Readings in Problem-Based Learning. Purdue University Press, West Lafayette, Indiana, USA (2015)
28. Boud, D., Cohen, R., Sampson, J.: Peer learning and assessment. Assess. Eval. High. Educ. **24**, 413–426 (1999). https://doi.org/10.1080/0260293990240405
29. Dochy, F., Segers, M., Sluijsmans, D.: The use of self-, peer and co-assessment in higher education: a review. Stud. High. Educ. **24**, 331–350 (1999). https://doi.org/10.1080/03075079912331379935
30. Kriflik, L., Mullan, J.: Strategies to improve student reaction to group work. J. Univ. Teach. Learn. Pract. **4**, 13–27 (2007)
31. Schön, D.A.: Educating the reflective practitioner: toward a new design for teaching and learning in the professions. Aust. J. Adult Learn. **50**, 448–451 (2010)
32. Rosier, G.: Using reflective reports to improve the case method. J. Manag. Dev. **21**, 589–597 (2002). https://doi.org/10.1108/02621710210437563

A Story of Online Construction Masters' Project: Is an Active Online Independent Study Course Possible?

102

Gulbin Ozcan-Deniz

Abstract
With the availability of online teaching tools, educators got the opportunity to create learning environments for students that are flexible and user-friendly. Though being exciting and intuitive, this opportunity comes with great responsibility, as students may be lost in online education without any face-to-face (FTF) contact. Engaging online students becomes even harder in an independent research study course, where students are expected to perform a high level of self-directed work. It is a challenge to promote an online independent study, as students need to be active, engaged, motivated, and prepared in the virtual environment. Additionally, the non-traditional nature of online students requires flexibility and interactive teaching methods to sustain collaborative and connected learning. The Construction Management (CM) Masters' Project at Jefferson is an independent research study that serves as the culminating experience in the program, where students choose their own project to produce a comprehensive Project Manual with an oral defense presented at the end of the semester. This paper identifies best practices for delivering an online Masters' Project course, which is engaged, collaborative, real world-based, and grounded in the liberal arts and sciences. The methodology will include creation of online learning models, assessing principles of online independent study development, and evaluating the new online Masters' Project delivery model with a pilot group of students. Results will be used to create guidelines and assessment methods for faculty, who teach online independent study courses and who are willing to embrace the emerging online education phenomenon in construction.

Keywords
Construction management • Online independent study • Best practices for online teaching

102.1 Introduction

With the growth of internet, web-supported education has taken its place in today's higher education institutions [1]. Many researchers have been in favor of implementing technology-based services in higher education and believe that technology has the capability of increasing student participation and comprehension [2]. Online education has been an opportunity for educators to utilize technology in offering flexibility to students in terms of location and time. This has been particularly appealing to adult learners and students with non-traditional life styles (i.e. who are working part-time or full time) [3].

While opponents of online education emphasize the lack of face-to-face (FTF) contact, proponents argue that FTF interaction can be substituted by online discussions in bulletin board systems or online video conferences [4]. Being very different from FTF instruction, online courses need a unique delivery method to make sure the connected learning is achieved between the instructor and students [5]. Engaging online students becomes even harder in an independent research study course, where students are expected to perform a high level of self-directed work. Therefore, it is very important to set guidelines to design and assess the online environment [6]. This paper identifies best practices for delivering an online

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independent study course through evaluating the new online Masters' Project delivery model with a pilot group of students. Best practices presented in this study are created around VOCAL [7] and Jefferson' Nexus Learning Principles [8], i.e. engaged, collaborative, real world-based, and grounded in the liberal arts and sciences.

102.2 Background

Despite the opponents, online education was found to improve students' critical thinking, problem-solving and collaborative learning skills [9]. Some of the innovative online teaching techniques were mentioned as emails, video conferencing, static and dynamic Web pages, case studies, audiovisual presentation, assignments/quizzes, and project works [3, 10]. Two common ways of online teaching are defined as asynchronous and synchronous. Asynchronous teaching is achieved through recorded video lectures and assignments that can be viewed anytime/anywhere, whereas synchronous teaching involved in live/real-time video lectures, where students should log into an online portal on a pre-set date and time.

Different guidelines have been proposed for online education. Penn State University in association with other two universities developed a set of guidelines and benchmarks for distance education [11]. Recommendations include:

- Create and prepare instructional materials for delivery via distance education
- Use specific instructional activities that are beyond direct instruction to meet the goals and objectives of the course
- Ask learners to design an "Action Plan" to demonstrate they understand and accept responsibility for achieving the learning goals
- Provide effective learning environments to enhance interactions among students and the instructor
- Allow students to self-monitor progress by providing feedback.

Ten (10) principles of effective online teaching was set in a Magna Distance Education Report as [12]: show up and teach, practice proactive course management strategies, establish patterns of course activities, plan for the unplanned, response requested and expected, think before you write, help maintain forward progress, safe and secure, quality counts, and (double) click a mile on my connection.

Another approach to online education is set as VOCAL principles [7]. Online educators are called to be VOCAL, where the acronym identifies the characteristics of an effective online instructor as one who is: **V**isible, **O**rganized, **C**ompassionate, **A**nalytical, and a **L**eader-by-example. The study claims that each component of VOCAL contributes to a positive teaching experience for both educators and students.

With this abundance of online education research and strategies to make online education effective, still there are no guidelines set for online independent study courses. As mentioned before, online independent study courses include self-direction and a higher level of autonomy than lecture courses. This unique situation causes not only the students to get confused, but also the educators to need extra help and clear directions on the course design, organization, and assessment. The framework of this study employs the practices of VOCAL in exploring the best practices of online Masters' Project delivery. While VOCAL principles support a positive learning environment, Nexus Learning Principles will be used to obtain effective and engaged online teaching in independent study courses.

102.3 Methodology

The motivation of this study is to answer the question: *How to deliver online independent study courses effectively?* Primary goals include creating effective online teaching modules and best practices for faculty who teach online independent study courses using VOCAL and Nexus Learning principles. In order to fulfill these goals, the flowchart in Fig. 102.1 is created. The details of each step will be covered in the following sections.

102.3.1 Principles of Online Independent Study Development

VOCAL guidelines were re-interpreted to fit into the asynchronous online independent studies and the principles below were created to be tested in the new online Masters' Project delivery model.

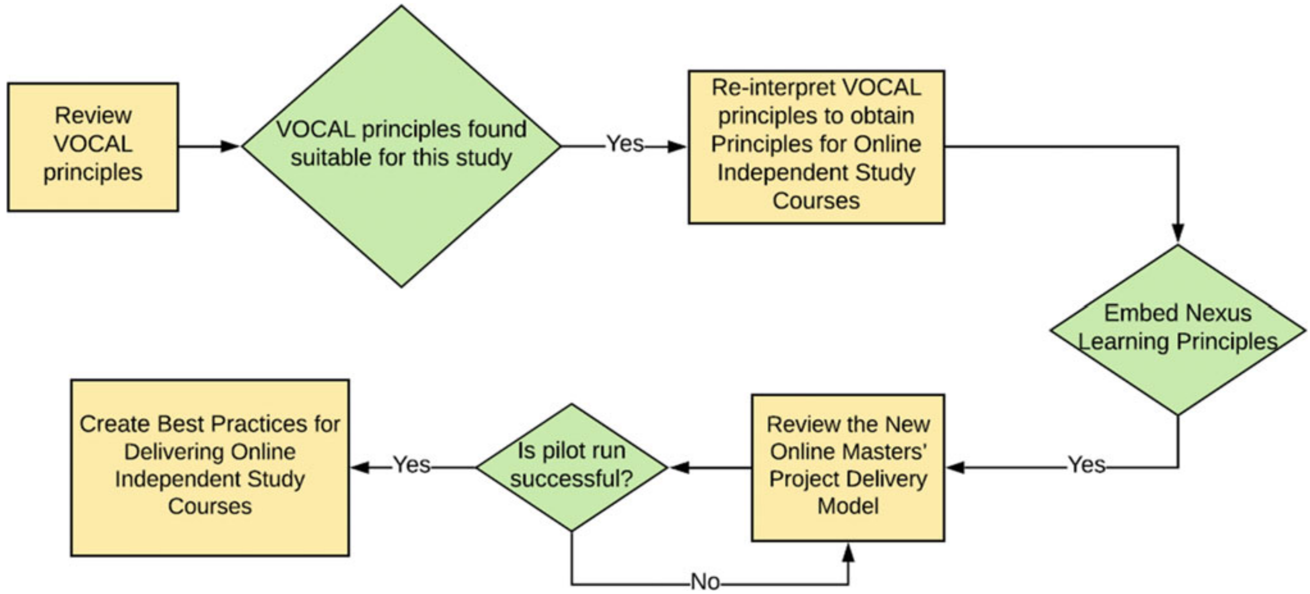

Fig. 102.1 Effective online independent study flowchart

Visible means being virtually available to students. Online learners, especially new students, may not know the extent of the Learning Management System (LMS) used. Therefore, it is very important to encourage students to check their university emails and LMS frequently for 'visible' to work successfully. Students should be clearly informed about the virtual attendance policy and on how to connect to the instructor.

Organized includes providing a structured learning environment. This is a must for all online courses, however the addition of the last bullet point above is unique to independent study courses. Independent study courses give students' autonomy to control their own organization and schedule. Therefore, they will be asked to create a dynamic timeline for their preliminary deliverables and final project binder in the Masters' Project course.

Compassionate is about providing a welcoming learning environment. There are set basics to warm online students up to the learning environment and their peers, such as encouraging students to communicate with the professor and with one another. In the online version, being compassionate has to be performed all virtually, which requires the educator to be active in LMS as well as in any other online systems used.

Analytical is usually achieved by using low-stakes assessment activities. Although independent study assignments do not require fixed answers, students are very much in need of feedback and checkpoints throughout the process. Low-stakes assignments allow both parties to track student's progress over time. Meanwhile students learn the 'acceptable' content and format of submissions.

The main point in being **L**eader-by-example is to set an example online persona in the virtual class and keeping your word related to course activities. All educators on campus or online set the example for their students. In an online setting, leadership has to be set by written approaches and following due dates and meeting times as promised. As students are expected to follow due dates and have an organized calendar, it is very important that the educator to show strong skills in this area.

102.3.2 The New Online Masters' Project Delivery Model

This section includes how Nexus Learning Principles have been embedded into the Masters' Project Course. As the background information, Masters' Project is the last course Masters of CM (MCM) students are taking at Jefferson. This course is equivalent of a Masters' Thesis, where students choose an actual construction project and prepare an extensive bid package with the following sections: Executive Summary, Company Information, Project Information, Revit Model, WBS, Estimates, Schedules, Cash Flow, Site Logistics Plans, Means and Methods, Risk Management, Safety Plan, Environmental Plan, QC/QA Plan, and LEED.

Fig. 102.2 Masters' project activities around nexus learning principles

As each project is unique, students go through a unique critical thinking process to solve specific issues related to the actual construction process. They frequently meet with the professor and an advisor, who is a professor or a construction expert from outside. The end-product, as the comprehensive bid package, is submitted as a written report and is presented to CM faculty and outside evaluators from the construction industry. Due to its setup, this course is a best fit for applying all four Nexus Learning Principles of Jefferson as:

- Engaged/Active Learning
- Collaborative and Connected Learning
- Understanding the Real World
- Grounded in the Liberal Arts (Fig. 102.2).

In an online independent study, engaged/active learning can be achieved by creating online learning modules that gives room for interactivity. Using interactive course material with video lectures and various sources such as Open Electronic Resources (OERs) will help in this case. There are software applications that can be used with MS PowerPoint presentations [13] or other applications that can convert any video into interactive lessons by adding video and questions to the content [14]. In the new Masters' Project, online students are asked to set comprehensive objectives and create a dynamic timeline. This timeline was created with the scheduling software MS Project and has to include milestones and preliminary and final submission dates, as well as the duration of each section mentioned above. As an example, students are asked to mark dates of when to start the estimating process, when to meet with the professor and advisor, and when to finalize their detailed estimate. They listen to video lectures related to the topics in the bid package and submit weekly progress updates to Blackboard. The updates include written submissions as well as presentations to increase student engagement.

The collaborative learning portion is achieved by setting up online meetings with the professor and advisor. Blackboard has room for collaboration through the setup of online discussion boards. In the pilot setup of the Masters' Project, OneNote Class Notebook [15] was used to improve connectivity among the professor and students. Class Notebook has a course setup that allows a collaborative area and one-to-one shared pages with each student. Feedback to students' preliminary submissions and notes about their progress were shared through this platform in addition to Blackboard.

Understanding the real world is achieved though working in actual construction projects with selective standards based on the project location and requirements of the specifications. A high level of proficiency in research and professional presentations in terms of oral and written submissions were used to support grounded in liberal arts principle.

102.3.3 The Pilot Run of the Online Masters' Project

The new model with VOCAL and Nexus Learning principles were practiced within a hybrid setting. Students were informed about the definition and requirements of the Masters' Project before the semester starts, so that they can find a suitable project and create the dynamic timeline on time. Students were welcomed on the first week of the semester, where the digital tools to be used were explained. All students were familiar with Blackboard, but only one student was familiar with OneNote. OneNote signup process was explained to students by using the institution's Office 365 license. There were some technical issues, where students could not log into their accounts. This problem was resolved by the IT Department. However, outside advisor could not get access to the OneNote Class Notebook due to not having institution's email accounts.

Students were provided video lectures to review course topics including course overview, project information, Revit, estimate, schedule, cash flow, risk, quality, safety, and environmental management plans, site logistics plan, means and methods, and Leadership in Energy and Design (LEED) sections. Each week, students were required to review the lecture

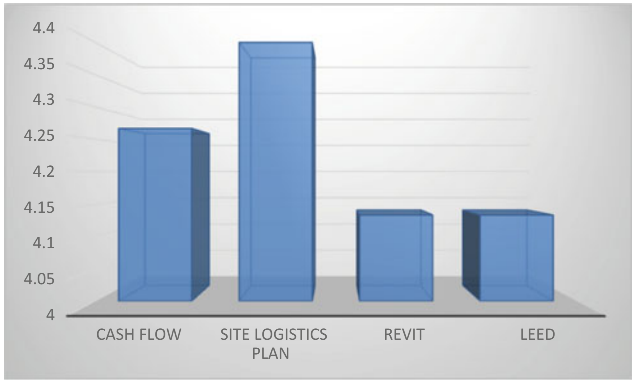

Fig. 102.3 Masters' project low-stakes assignment survey results on a 1–5 scale

notes with supplementary reading and fill in the provided templates to have draft versions of these sections. Students submitted twelve (12) progress presentations within fifteen (15) weeks of the semester durations to prove their progress and earn partial grades. This process is not very common for an independent study, however the low-stakes assignments were used to help students to be more engaged and organized. Students were surveyed to collect data about the effectiveness of low-stakes assignments on a 1–5 scale. In total, 165 data points were collected. Four topics of the average results are presented in Fig. 102.3. The preliminary evaluation of the results showed that students were satisfied to highly satisfied (4–5 scale) with the video lectures and their related assignments. Among the categories evaluated, only means and methods and safety templates were found on a 3–4 scale corresponding to neutral to satisfied ranges. These two topics were re-evaluated for improvement and it was found that students needed clearer direction on how to use the provided MS Excel templates. The improvement was decided to record video lectures specifically on filling out templates for the next offering of the class.

Students were also asked about their meetings with the professor and their specific advisors. While the meetings with the professor were rated as satisfied or highly satisfied, the scores of advisors meeting had a range of 2–5, meaning dissatisfied to highly satisfied. This range of results were due to having different advisors. In this pilot offering, there were 2 full time CM professors and 5 outside CM professionals as advisors.

Another aspect of the survey was to evaluate OneNote as a tool to improve connection between students, professor and advisors (Fig. 102.4). Around 50% of the class found OneNote very or extremely helpful, while a small portion found it not helpful at all. Written feedback was collected from students related to their use of OneNote. One of the cons was the login issues students' experiences. Although this was solved by IT, it created a barrier between students and educators. Another issue was the inability to have outside advisors on this platform. On the next offering of the class, outside advisors would be added to the institutions system to be able to give them access to OneNote. A repeated comment from students included having too many online systems running at the same time. Students were looking to a single platform to include all information, assignment submissions, and feedback. Unfortunately, Blackboard was not flexible for this purpose. Although OneNote was found user-friendly, students had a hard time tracking information on various platforms.

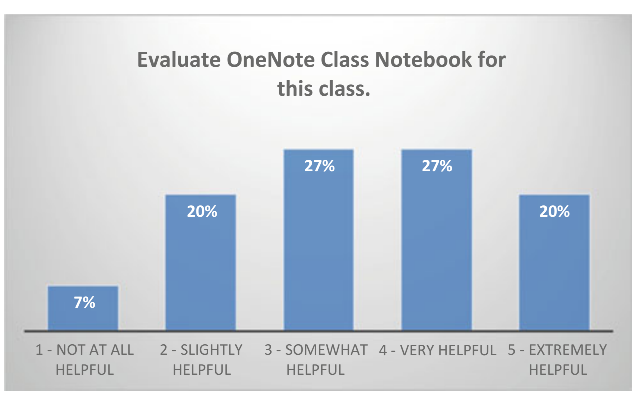

Fig. 102.4 Evaluation of onenote class notebook

102.4 Best Practices for Delivering Online Independent Study Courses

The results of this study were used to set the following best practices as a combination of the re-interpreted VOCAL and Nexus Learning:

- **V**isible
  - Sent Welcome to the Week Emails every week on the first day of the week to show that the professor is virtually there reminding them the agenda of the week.
  - Reply to emails within 24 h.
  - Show students that you can track their virtual attendance through the LMS or other platform as used (e.g. Blackboard has a retention center to track students' activities).
  - Hold live meetings via Adobe Connect, Zoom, etc. to improve connection among students and the professor. This will improve collaborative and connected learning.
  - Use live meetings as opportunities to collect formative feedback (i.e. this was used to collect feedback on OneNote and to solve IT related issues on the pilot run).

As it can be observed from above, 'visible' requirements are not very different from any online courses for online independent studies. The key part is to set the visibility platform and the frequency of activities. When an additional software like OneNote is used, students should be told on the log in credential and the specific use of the software. OneNote was found effective on giving one-to-one feedback to student files in various formats such as PDF, word, or excel.

- **O**rganized
  - Tell them what is expected of them clearly (e.g. when to report, which templates to use and how to use them).
  - Give them a Weekly Schedule with assignments and due dates, including required meeting times and frequency. As online independent study will have online meetings, student should know how to attend virtual meetings and how to use the virtual platform. Technical issues are inevitable in this case, so it is suggested to have IT support ready.
  - Allow self-organization (e.g. dynamic timeline). Independent study students need autonomy to achieve the overall goal of the study. It is required to give online independent study students a controlled autonomy through tracking their dynamic timeline. This will help students to be active learners.
- **C**ompassionate
  - Use an online ice-breaker to know your students and to motivate students to know one another.
  - Encourage students to communicate with you via email or other preferred method. In the online setting, you will not hear issues as they happen, so it is required to have a virtual open-door policy to invite students to connect. This will also increase students' professional communication skills and support infusion of liberal arts.
  - Use personalized reminders (e.g. course progress concern alerts). These alerts can be created on Blackboard for each student while tracking their virtual attendance and can be emailed them separately.
  - Allow time for students to process. Students need time to understand the online independent study setting and online platforms used for engagement. Demo submissions and discussion boards will help to ease this process.
  - Make sure they understand what an online independent study means (i.e. *set expectations*). It should be clarified that this is not a lecture setup and there are no fixed correct answers. The uniqueness of this situation should be emphasized in written feedback provided to low-stakes assignments to remind this to students over time.
- **A**nalytical
  - Use smaller and more frequent assessments. Students can be asked to upload their draft submissions as low-stakes assignments. As mentioned before, in the pilot run, students uploaded 12 sections over 15 weeks to receive feedback and show their progress over time.
  - Allow room for feedback. Students need detailed feedback on their independent study. A flexible and user-friendly environment like OneNote is helpful for this purpose. OneNote allows figures and different file formats to be included in each student's page/journal. Emails can be sent from Outlook to OneNote to keep track of all communications with each student and make sure they receive feedback virtually. As an additional advantage, having OneNote app on their phones will allow students to access data frequently and easily.
  - *Determine 'acceptable'* (i.e. a threshold for research and other activities). Although it is very hard to set a threshold in an independent study, students frequently ask what is accepted as 'enough.' It is good to show previous examples and highlight their ups and downs to help students decide on the 'acceptable.'
  - Provide mid-semester and end-of-semester surveys for students to evaluate the online course.

- **L**eader-by-example
  - Follow through with promises.
  - Give timely feedback.
  - Model the way to behave in an online environment. When the professor follows the rules and pre-set due dates, students will tend to mimic this behavior.
  - *Remind learning outcomes* and connection to other courses in the curriculum. Students are motivated to learn when they know why they are learning a certain topic and how they will benefit from that in real-world. Therefore, it is needed to help them connect the dots in-between different courses they have taken and to remind them what they will gain at the end of the class through learning outcomes.

102.5 Conclusions

This study focused on identifying best practices on online independent study delivery through combining VOCAL and Nexus Learning principles. Jefferson's Masters' Project course was used to assess the preliminary principles and obtain the finalized best practices presented. The assessment was performed by using a pilot run of this class with MCM students. Students were asked to evaluate all low-stakes assignments, their meeting with the professor and advisors, as well as the OneNote software setup. The results showed a need in best practices to involve student autonomy and better technical guidance on OneNote. Based on student feedback, OneNote Class Notebook has great potential to improve collaboration and connection among parties, if the technical and advising issues are fixed.

Faculty, who teach online independent study courses and who are willing to embrace the emerging online education phenomenon in construction, can use the best practices and the new online Masters' Project delivery model presented to develop and improve online independent study courses like Jefferson's Masters' Project course. Future studies will include expanding the use of OneNote for fully online settings and testing its effectiveness.

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References

1. Lindner, J., Dooley, K., Murphy, T.: Differences in competencies between doctoral students on campus and at a distance. Am. J. Distance Educ. **15**(2), 2540 (2001)
2. Wu, J., Wang, S.: What drives mobile commerce? An empirical evaluation of the revised technology acceptance model. Comput. Educ. **42**(5), 719–729 (2005)
3. Schott, M., Chernish, W., Dooley, K., Lindar, J.: Innovations in distance learning program development and delivery. Online J. Distance Learn. Adm. **5**(2) (2003)
4. Blake, N.: Tutors and students without faces or places. J. Philos. Educ. **34**(1), 183–199 (2000)
5. Liang, X., Creasy, K.: Classroom assessment in web-based instructional environments: instructors' experience. Pract. Assess., Res. Eval. **9**(7) (2004)
6. McLoughlin, C., Luca, J.: Quality in online delivery: what does it mean for assessment in e-learning environment. In: Australasian Society for Computers in Learning in Tertiary Education (ASCILITE), pp. 417–426. Brisbane, Australia (2001)
7. Savery, J.: BE VOCAL: characteristics of successful online instructors. J. Interact. Online Learn. **4**(2), 141–152 (2005)
8. NexusLearning, Nexus Learning, The Jefferson "X" Factor. Retrieved 19 Apr 2018, from http://philau.edu/nexuslearning/ (2018)
9. Rosie, A.: Online pedagogies and the promotion of "deep learning". Inf. Serv. Use **20**(2/3), 109–116 (2002)
10. Natarajan, M.: Innovative teaching techniques for distance education. Commun. IIMA **5**(4), 73–80 (2005)
11. IDE.: An Emerging Set of Guiding Principles and Practices for the Design and Development of Distance Education. Penn State University. University Park, PA: Innovations in Distance Education. Retrieved 01 2017, from http://colfinder.net/materials/Supporting_Distance_Education_Through_Policy_Development/resources/web1/innovation.pdf (1998)
12. Magn.: 10 Principles of Effective Online Teaching: Best Practices in Distance Education. Magna Publications, Inc., Madison, WI (n.d.)
13. OfficeMix. Office Mix Preview. (MS Office) Retrieved 23 Apr 2018, from https://mix.office.com/en-us/Home (2018)
14. EdPuzzle, (EDpuzzle Inc.) Retrieved 23 Apr 2018, from https://edpuzzle.com/ (2018)
15. OneNote, OneNote Class Notebook. (MS Office) Retrieved 23 Apr 2018, from https://www.onenote.com/classnotebook (2018)

Lessons Learned from a Multi-year Initiative to Integrate Data-Driven Design Using BIM into Undergraduate Architectural Education

103 Lessons Learned from a Multi-year Initiative to Integrate Data-Driven Design Using BIM into Undergraduate Architectural Education

J. Benner and J. J. McArthur

Abstract

The question of how to best integrate BIM into the curriculum is one of significant debate, especially at the university level. This paper presents the ongoing development of a third-year BIM integration curriculum within an Architectural Science undergraduate program, with a specific focus on a project designed to introduce students to data-driven design. This project has students create a series of massing models in Autodesk Revit, which are analyzed for both initial cost and life-cycle energy performance and these iterations guide studio project development. This paper presents the pedagogical approach developed to introduce students to advanced BIM use cases such as cost analysis and energy simulation and evaluates the first three years of integration of these topics into an architectural curriculum. From 2015 to 2017, over 300 students participated in this project, creating and evaluating over 1000 model iterations. Student feedback obtained through surveys and course evaluations demonstrates that this project is effective not only to provide students with increased BIM capabilities, but also encourage them to synthesize a broad range of data generated through simulation to refine and develop their designs.

Keywords

Pedagogy • Energy simulation • BIM • Data-driven design

103.1 Introduction

The last few years have seen an increasing interest by the architectural profession in the integration of simulation into the design process, frequently referred to as "data-driven design". Within a pedagogical context, there is similarly significant debate regarding the best way to integrate BIM into curricula, particularly in the design disciplines (architecture and engineering) at the university level.

Several educators have developed approaches for integrating into the architectural curriculum, through studio/design courses [1, 2], construction applications [3], or capstone projects [4]. The systematic review by Abdirad and Dossick [7] provides an excellent summary of BIM pedagogical approaches through March 2015 and provides a comprehensive reference for readers, while Poirier et al [6]. provide further insight and a summary of recent industry-academic workshops on this topic. Of particular interest to this work was the application of Bloom's taxonomy to BIM education outcomes by Sacks and Pikas [5], who recommended that Levels 1–3 (Knowledge, Comprehension, and Application) be the objectives of undergraduate education and that Level 4 (Analyze) constitutes best practice at the graduate level.

This paper presents the ongoing development of a third-year BIM integration curriculum within an architectural science program, with a specific focus on a project designed to introduce students to data-driven design, particularly the use of BIM-based building performance simulation and cost analysis as an iterative design tool. This mirrors increasing industry adoption of similar practices, whereby BIM is increasingly integrated with energy simulation and other analysis tools, allowing designers to more comprehensively consider building performance as a part of the design process. The objective of

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the research presented in this paper is to develop a pedagogical approach to introducing students to advanced BIM use cases such as cost analysis and energy simulation, and to evaluate the first three years of integration of these topics into an architectural curriculum. This pedagogical research was undertaken in parallel with a technical study investigating the relative accuracy of BIM-based energy simulation with industry standard tools at the schematic design stage [8].

103.2 BIM Integration Toolkit

The BIM Integration Toolkit was initially developed in 2015 to introduce third-year undergraduate students to intermediate and advanced BIM concepts and forms an integral part of Ryerson's digital curriculum integration strategy, building on first-year virtual reality (VR) use in studio, second-year introductory BIM tutorials focused on design authoring and the use of augmented reality to engage with real site conditions, and supporting fourth-year advanced digital design and fabrication activities. This approach follows experiential learning principles, and is described in detail by Hui et al. [9].

Rather than focusing on *how* to use the software, which was introduced in the first half of the undergraduate program, the BIM Integration toolkit focuses on *why*, discussing the impact of BIM on lifecycle project delivery and how it can be used to integrate simulation and analysis to improve building design, construction, and operations. This focus on practice implications and holistic understanding aligns well with the recommendations made by Sacks and Pikas [5]. The objectives of this toolkit are to:

1. Prompt reflection and critical thinking on the fundamental shift in how buildings are designed and visualized between CAD and BIM design paradigms.
2. Explore how multi-disciplinary coordination can be facilitated or hindered by the use of BIM.
3. Understand how BIM is used by various parties for analysis, cost estimating and scheduling, and operations management, and what the key requirements are for architectural BIM models to facilitate this use.
4. Understand how building systems are integrated by exploring a complete, multi-disciplinary BIM model of a campus building and comparing it to as-built conditions.
5. Gain experience in simple BIM-based energy simulation and cost analysis and apply this knowledge to refine a design.

The toolkit consists of a set of elements designed to supplement project management and design studio courses, including real project case studies, question and answer interviews with both practicing architects and general contractors, video tutorials guiding students through BIM techniques such as energy modeling and cost estimation, and a comprehensive multi-media literature review including peer-reviewed literature, online lectures, relevant industry blogs, and technical resources. This toolkit is supported by an instructional guide for professors, including recommended in-class and assigned activities. A key element of this toolkit—and the focus of this paper—is a project linking the integrated design studio building form development (massing) activity with the Project Economics course and using simulation to test design alternatives. This toolkit was rolled out in the fall of 2015/16 and adopted in the Project Economics (project management) course, and Integrated Design Studio I and II, and repeated in 2016/17 and 2017/18. This project was refined over this period based on lessons learned.

103.3 Case Study Methodology

A total of 310 students participated in the data-driven design project between 2015 and 2017, creating and evaluating over 1200 model iterations. In each year, these students completed this project as part of a third year mandatory core course.

The data-driven design project was initially introduced in 2015 and was completed by 101 students. In this first iteration, students undertook a 2 × 2 factorial study considering two potential building shapes ("massings"), each tested with two different building envelope approaches. In the first year, these envelope approaches were prescribed as one of: (1) two dramatically different envelope types, noting that opaque facades must include a reasonable amount of glazing for daylighting and views; (2) the same cladding material but dramatically different window-to-wall ratios (WWRs), with WWR consistent on each facade; or (3) consistent WWR but comparing even distribution (e.g. 40% glazing on each façade) to a distribution with the majority of glazing on the south facade and limited glazing on the east and west. Figure 103.1 shows a sample set of massing and envelope combinations generated in this initial project using the third option described above. Once these four models had been created, students undertook two investigations. First, a simplified capital cost estimate was created

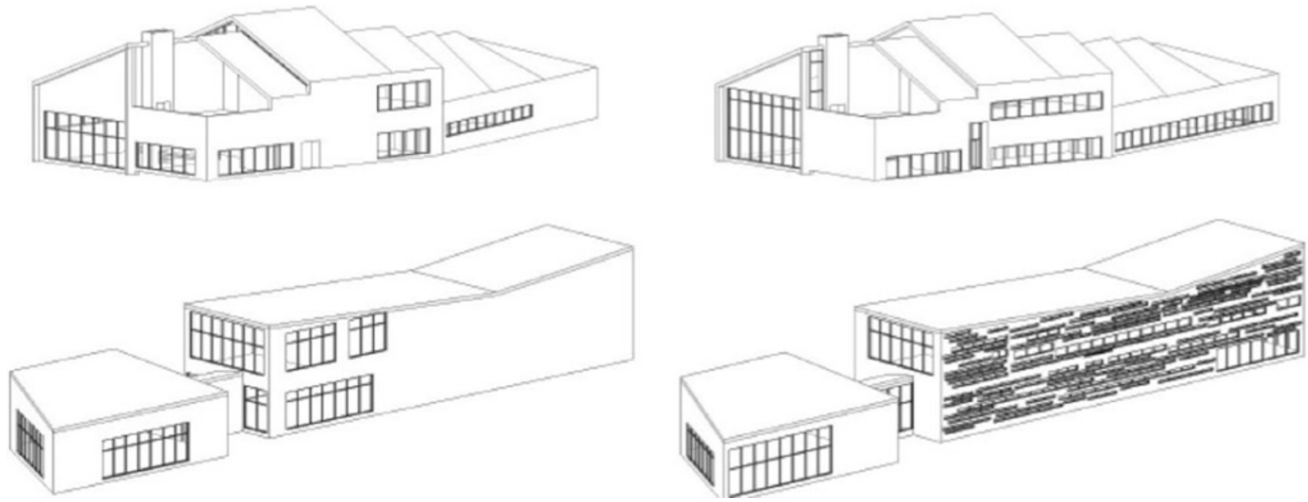

Fig. 103.1 Sample massing and envelope concept combinations (Fall 2015) (used with permission)

considering only building envelope quantity take-offs; due to the level of development of this project in the studio (conceptual massing) only the form had been developed and more detailed costing was not feasible as was discovered early in the first year of implementation. The second analysis was that of building lifecycle energy. Using Green Building Studio, each student performed an energy simulation using energy settings provided in the project brief. Students synthesized their results into a memo summarizing their justification for each envelope and massing considered, the results of the cost and energy analysis and their recommendations for the most cost-effective design. This pushed the students to achieve Level 4 (Analysis) and begin to achieves Level 5 and 6 (Synthesize and Evaluate) of Bloom's taxonomy as defined for BIM education [5].

Based on the best results from these two years, the 2017 project was revised to guide students to engage more fully with data-driven design concepts. In this new iteration, students analyzed their studio project massing and investigated design iterations to try to improve energy performance. Having performed this preliminary evaluation alone, they teamed with a second student to compare results from these initial explorations. Students then worked together to create a fifth iteration to further reduce the life-cycle cost of the better-performing massing and documented their findings in a poster.

Autodesk Revit [10] was used for quantity take-offs, while Green Building Studio (GBS) [11] was used for building energy modeling. A comprehensive set of tutorials was created to guide students through the mechanics of this process.

Model results from both 2016 (representing the first iteration) and 2017 (second iteration) were reviewed by a Professional Engineer with energy simulation expertise, who reviewed relative end use ratios, simulated energy use intensities (EUIs in ekWh/m^2/yr), and the energy end-use breakdown to identify modeling errors and evaluate design refinements. Note that in Years 1 and 2, students were primarily using Revit 2015 or 2016, whose GBS plug-in provided detailed heating and cooling load breakdowns, for example *window conduction* and *infiltration*, as standard outputs. In Year 3, many students used Revit 2017, which no longer provided these breakdowns, making specific modeling issues more difficult to diagnose. Instead, students were able to export end-use breakdowns, for example *space heating*, which was used for model result checks to inform the statistical analysis presented.

Learning outcomes were evaluated primarily through qualitative evaluation of the student projects. In iteration 1, the grading rubric equally weighted the correct execution and documentation of quantity take-offs and energy simulation (25% each) with the students' analysis and discussion of the results obtained (50%), which was focused on whether these results were realistic and the appropriateness and value of using the GBS plug-in for energy simulation at this stage of design. In iteration 2, the rubric equally valued four elements: energy analysis and cost estimates (individual mark), the refined design (group), and presentation (group). Within each category, comprehensive and correct execution as well as depth of critical analysis formed the basis for the grade assigned. The complete rubric is provided as supplemental material to this paper.

103.4 Case Study Results

Over the first two years, 206 students completed this project, resulting in 824 models. In the third year, the pairing of students resulted in the creation of only 231 models.

103.4.1 First Iteration (Years 1 and 2)

In Year 1, a BIM knowledge benchmark was established using a start-of-term survey and an evaluation survey was conducted at the end of term to both quantify learning outcomes and inform toolkit refinement and use in future years. 14 questions were asked on this quiz, covering both professional practice and technical aspects. Results showed improvement on all but one question (which had 98% correct responses initially), with four showing statistically significant differences (95% confidence). The most helpful element was from the students' perspective were the data-driven design project (33%), followed by the tutorials for GBS (26%) and quantity take-offs (16%), respectively. When asked which element was most valuable and why, representative student comments are: "*The video tutorials we received for project 1* (were the most valuable)*, simply because I continue to find myself using them for other projects, especially the Revit design ones.*" and "*For the individual project, we had tutorials, 3 of them were very important for the project to do energy analysis, but also the other tutorials were really good too. I never knew that BIM could give all the light, energy, analysis, in a very short amount of time.*"

Starting in Year 2, the iteration savings were analyzed statistically alongside error rates and the frequency of design insights arising from this work. On average, students were able to achieve a 26% reduction (interquartile range (IQR):15–34%) in the building performance using GBS defaults for 12/7 occupancy. Of these models, 94% provided expected results, while 25 (5.9%) provided simulation results inconsistent with the expected building performance. An investigation into these models classified these issues as excessively high underground losses likely due to incorrect ground plane definition (16),

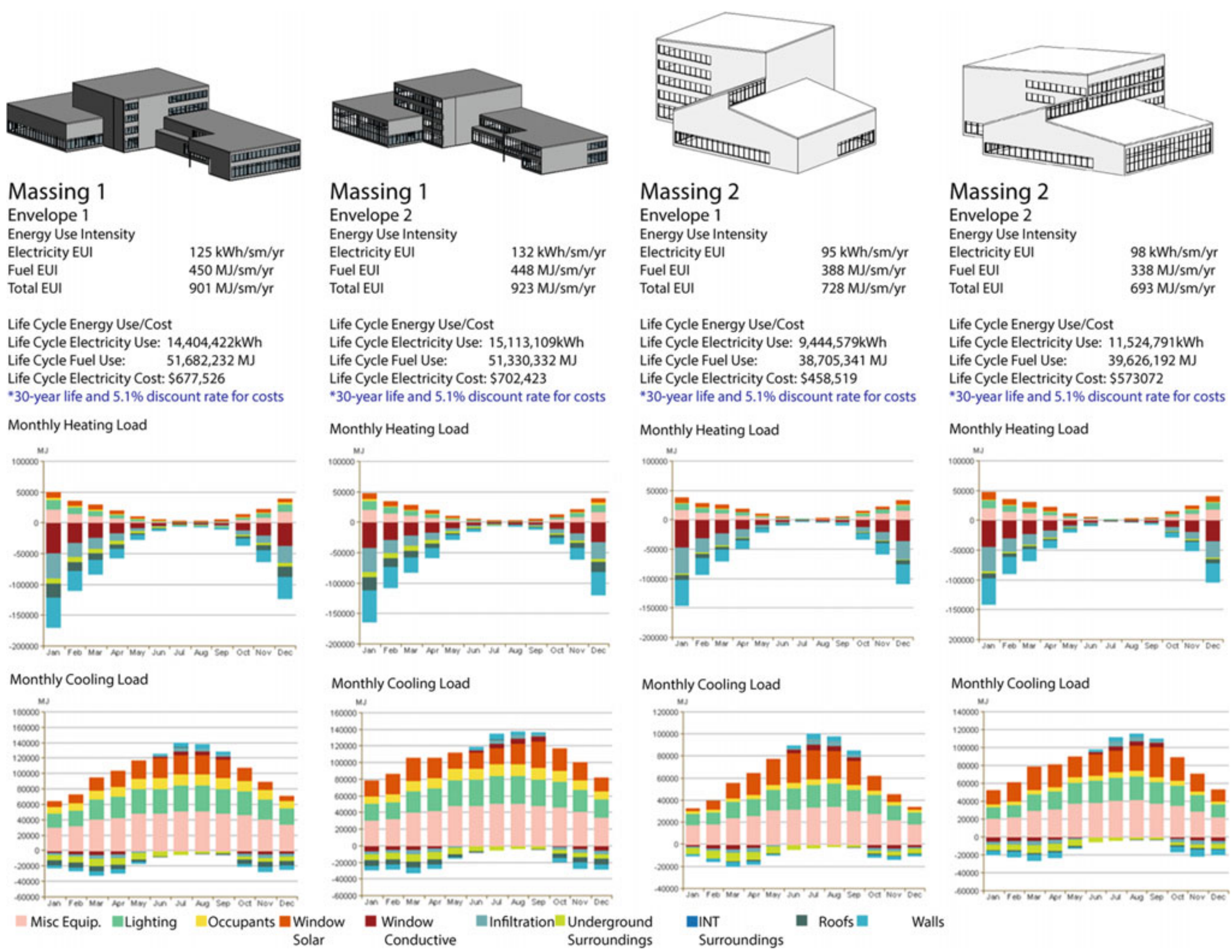

Fig. 103.2 Factorial investigation—case study #2 (used with permission)

zero window solar or conduction gains due to incorrect window family definitions (5), highly variable occupant densities due to inconsistent energy settings (2), and extremely high roof losses due to inconsistent material assignments (2).

Three student investigations have been selected to demonstrate student engagement. The first student tested variations in the WWR as well as overall building compactness. Describing the first investigation, they noted: "*This exploration showed how slight adjustments to the components of a facade could produce great savings on a project. It also showed the ability to more easily make comfortable spaces, putting less strain on mechanical systems to make up for the heat exchange.*" Investigating this in conjunction with a more compact form, they noted that as-predicted, this was the most efficient massing. This student continued to use their model to guide design beyond this course and through to the end of the design project the following term.

A second student project (Fig. 103.2) investigates the impact of a tighter envelope with the same overall floor area, along with dramatically reduced glazing for each, and shows the student's response to the building performance simulation at each iteration. They concluded that "… *although amount of glazing plays an important role in determining the energy consumption of a building, the mass form is also a large determining factor in its performance. A more condensed mass will reduce energy loads significantly, and appears to be more effective at doing so than glazing reconfigurations*."

In the third case study, the student was clearly proactive in using GBS as a data-driven design tool. Figure 103.3 shows the massing development in response to the results and includes the student's narrative on how they were used to shape the final design.

This example clearly illustrates the stepwise iteration of design with constant feedback offered to designers through the use of GBS for early-stage building performance simulation. These case studies are representative of the student experiences as a whole; 96% of students noted the daylight-heating/cooling load trade-off of high amounts of glazing and were able to improve building performance through adjusting both the window-wall ratio (96%) and/or specific glazing orientation (44%). In addition, 53% of students used this exercise to quantify the energy savings associated with increasing the compactness of the built form, and were able to use this insight to further refine their schematic design.

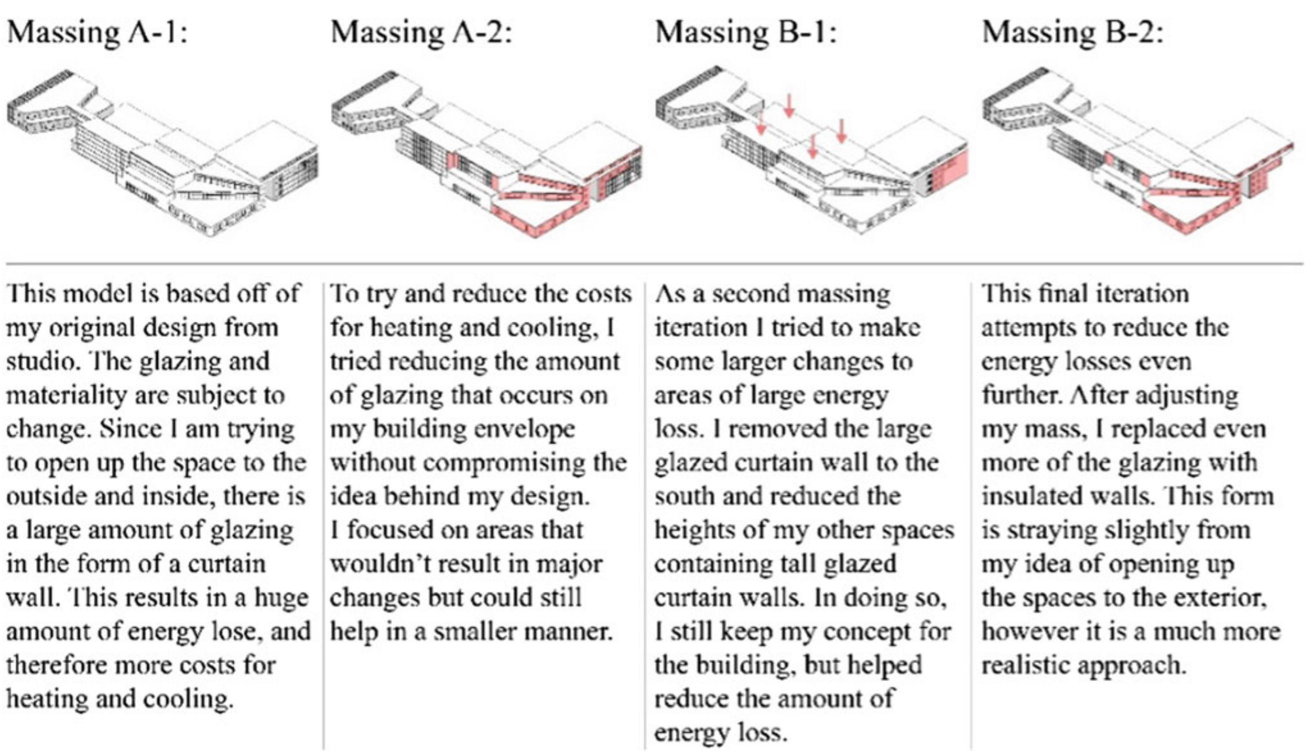

Fig. 103.3 Factorial investigation—case study #3 (used with permission)

103.5 Second Iteration (Year 3)

In the third year, the data-driven design project was refined to guide students through a process similar to that illustrated in Fig. 103.3. This refined project was completed in pairs to provide students with peer-learning and teaching opportunities. Through their massing study, students generated a total of 238 models, a selection of which are illustrated in Fig. 103.1. In the individual portion of the project, 75% of students achieved EUI savings on their first design iteration. On average, individual students were able to achieve a 14% reduction (IQR: 5–18%) in building performance using GBS defaults for 12/7 office occupancy. Of the models developed, 89% provided reasonable results, based on evaluation of EUI, end-use breakdowns, and fuel use ratios. Because the final design optimization was based on cost, rather than just energy, only 27% of the final proposed massings resulted in an improved EUI, though 76% decreased their lifecycle costs. On average, the lifecycle cost reduction achieved was 5% (IQR: 1–16%).

Three student investigations have been selected to demonstrate student engagement with the refined project in contrast to the previous iteration. In the first, the students noted that the greatest benefits occurred when the building compactness was increased, the east-west axis was elongated to permit significant glazing on the south façade, and minimize glazing to the north. Applying these strategies to refine the initial massings resulted in approximately 12% life cycle cost savings compared to all previous iterations. In the second case study, one student started with a central glass atrium feature, but determined that this was a significant source of solar gains during the cooling season and winter losses. This was removed in their second iteration, resulting in a 13% energy (EUI) savings. Their partner similarly noted the effect of high glazing percentages on the southeast and southwest facades, and reduced the window wall ratio to achieve 12.5% energy savings. The final design was determined after multiple glazing iterations and combined the desired architectural features of both approaches.

In the third case study, the student maintained the overall form of the massing, and manipulated the window to wall ratio to assess the difference in breakdown of the electrical loads. Figure 103.4 demonstrates this exploration in the massings. From this analysis, the student was able to identify and understand the correlation between electrical lighting loads and mechanical loads in regards to the percentage of glazing. This understanding was able to be applied to the student's final model massing model that showed a 6% decrease in the building's total EUI from the previously most-efficient massing. The logic that brought the students to this final design is expressed in their own words as-follows: "*… The massing was further developed to increase its efficiency by ensuring that the window to wall ratio is within the ideal range … The curtain wall area and the number of windows was decreased to avoid excessive heat loss during the winter seasons (…) floor area was also decreased by combining programs to create a more compact building to lessen energy usage. (…) Better materials were*

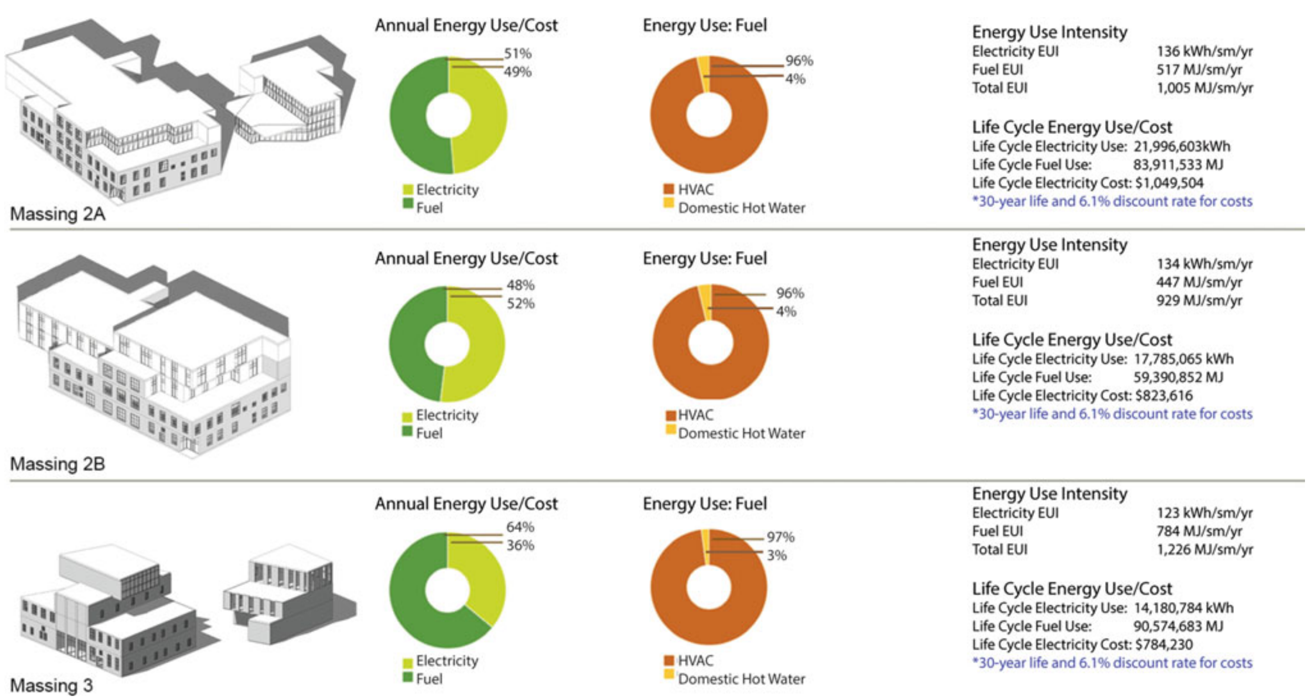

Fig. 103.4 Year 3 example [used with permission of students (names withheld)]

invested to the exterior cladding to increase efficiency for the long run. This investment contributed to the reduction of energy use in the building … wind is mostly coming from West Southwest direction; the windows allocated west of the building were decreased to minimize wind infiltration. Certain volumes were also oriented in an East-West direction to allow an even distribution of natural light thus increasing efficiency throughout the building."

Once again, the majority (76%) of students noted the daylight-heating/cooling load trade-off and were able to improve building performance through adjusting the window-wall ratio (95%) and/or increasing envelope R-Values (41%). In addition, 69% of students used this exercise to quantify the energy savings associated with increasing the compactness of the built form, and were able to use this insight to further refine their schematic design, in addition to the finalized form.

103.6 Discussion

It is apparent from student work that in the first iteration of the project, students consistently achieved Levels 3 (Apply) and 4 (Analyze) of Bloom's taxonomy as applied to BIM [7], with some progressing into Levels 5 (Synthesize) and 6 (Evaluate). When the project was restructured to specifically guide students to use the BIM-bases analysis as a design tool, students intrinsically synthesized and evaluated their results to generate new and improved design iterations, thus consistently engaging them at higher levels. While a minority of students (<10% overall) had modelling issues, the tutorials provided adequate support to resolve issues. A very small number of students (<5 per year) sought support from the professor or teaching assistant to resolve model issues. Student feedback obtained through surveys and course evaluations demonstrated that this project is effective not only to provide students with increased BIM capabilities, but also encouraged them to synthesize a broad range of data generated through simulation to refine and develop their designs.

The learning outcomes of the project were significant. Beyond demonstrating an increased degree of comfort using BIM software and specific BIM uses, this project guided students to engage with the broader curriculum. For example, many expressed surprise at discovering the heating and cooling penalty associated with glazing far outweighs daylighting savings due to Toronto's extreme climate (+31 °C summer/−22 °C winter design conditions). Students engaged with previous building science course material to address this issue as they worked to refine their design. Because this formed part of a project economics course, the students also gained insight on the relative cost of construction (25%) versus operation (75%) and the necessity of energy-efficient design.

103.7 Conclusions

The results of this study demonstrate how an experiential approach to BIM focused on iterative design-analysis-synthesis cycles permit students—even at an undergraduate level—to engage in a sophisticated manner with BIM. As demonstrated in the selected examples and statistical analysis presented, students consistently demonstrated an increased understanding of building physics as well as project economics through their engagement with this project, effectively using BIM to undertake simple analysis and evaluate this analysis to make informed decisions to refine their designs. While the incremental refinements demonstrated by the students were modest, on the order of 10–15%, they demonstrated the use of BIM for analysis, synthesis, and evaluation, thus beginning to achieve the ambitious recommended by Sacks and Pikas [5]. Based on the success of this project, the use of GBS for design analysis and refinement have been regularly integrated into the design student course in the winter term, providing students with additional opportunity to engage with simulation to evaluate design alternatives and achieve improved building performance.

The key student learning outcomes were: (1) a better understanding of how particular design decisions—particularly the impact of glazing and overhangs—affected building performance, and (2) significantly increased confidence with BIM as an interactive design evaluation, rather than simply design authoring, tool. As noted, some students had poor modeling skills, resulting in erroneous results; the majority of those students were further unable to determine that their results were incorrect. A one week BIM bootcamp for 2nd year students has been developed to help address the former issue while the latter is unsurprising as energy simulation is a specialized skill taught primarily in 4th year or graduate courses. To address this issue, a document highlighting the key GBS outputs and the pattern of expected results was provided to help students interpret these results.

While the approaches presented have been tested over multiple years, the single-program context limits generalization. However, this approach aligns well with recognized best practice and pedagogical recommendations. Future research to test this approach in other contexts would be valuable to better gauge the results; the corresponding author would be pleased to actively support such work. An additional line of inquiry is the potential application of parametric design tools to enable rapid refinement and testing. This was tested as part of a competition entry [12] to achieve a net-zero building design. Finally, it would be valuable to track how increasing BIM execution (software) knowledge obtained prior to university will change student engagement with the curriculum. Given the focus on the *impact* and *appropriate use* of BIM, this increase in skill level is unlikely to dramatically change the content delivery, though it will ease the software learning curve for these students.

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References

1. Ambrose, M.: Agent Provocateur–BIM in the academic design studio. Int. J. Archit. Comput. **10**(1), 53–66 (2012)
2. Duarte, J., Celani, G.P.R.: Inserting computational technologies in architectural curricula. In: Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education, pp. 390–411 (2012)
3. Cory, C., Schmelter-Morret, S.: Applying BIM in design curriculum. In: Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education, pp. 122–138 (2012)
4. Solnosky, R., Parfitt, M., Holland, R.: IPD and BIM–focused capstone course based on AEC industry needs and involvement. J. Prof. Issues Eng. Educ. Pract. **140**(4), A4013001 (2013)
5. Abdirad, H., Dossick, C.: BIM curriculum design in architecture, engineering, and construction education: a systematic review. J. Inf. Technol. Constr. (ITcon) **21**(17), 250–271 (2016)
6. Poirier, E., Forgues, D., Staub-French, S., Newton, L.: BIM in Canadian research and education. In: 11th BIM Academic Symposium, Boston (2017)
7. Sacks, R., Pikas, E.: Building information modeling education for construction engineering and management. I: Industry requirements, state of the art, and gap analysis. J. Constr. Eng. Manage. **139**(11), 04013016 (2013)
8. McArthur, J., Sun, X.: Disrupting the status quo with early-stage BIM-based energy modeling. Technol. Archit. Des. **1**(2), 231–239 (2017)
9. Hui, V., McArthur, J., Lelay, P.: Digital Integration: Synthesizing Poetic Possibilities and Pragmatic Production. Proceedings Building Technology Educator's Society, Des Moines (2017)
10. Autodesk Revit: https://www.autodesk.com/products/revit-family/overview. Last accessed 15 Apr 2018
11. Autodesk Green Building Studio: https://gbs.autodesk.com/GBS/. Last accessed 15 Apr 2018
12. Benner, J.: The Data-Driven-Design Environmental Learning Centre (2017)

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Integrated and Collaborative Architectural Design: 10 Years of Experience Teaching BIM

104

João Alberto da Motta Gaspar, Regina Coeli Ruschel, and Evandro Ziggiatti Monteiro

Abstract

In Brazil, undergraduate courses in architecture and urbanism under promote technologically mediated collaboration in design studio classes. The industry is incorporating BIM and has been looking for collaborative skilled employees. Teaching BIM should take into account issues related to student integration through collaborative methods. This paper presents the summary of a study to evaluate the collaborative process mediated by BIM over the past ten years in its capstone course, contemplating learning and educational strategies. Therefore, the following questions ought to be asked: Were design exercises appropriate? Was the adopted dynamics of collaboration coherent? Did the collaborative tools and standards serve the mediating function? Was collaborative training fostered? Action research is the methodology used to conduct this study. Each year, the evaluation process of the previous sequence is carried out, followed by the planning of the current one. Through the historical comparison between the course curriculum and collaboration strategies adopted over the years, there have been changes in the understanding of how to use BIM in a collaborative process for educational purposes. The two-axes collaborative integration method developed over the years of the course, where students are tested to collaborate, at the same time, in a design process and in a research process that assists the design, is an innovation that results from the evaluation cycles based on the research-action method. It was possible to conclude that the essence of teaching collaboration mediated by BIM follows the same precepts of the current BIM definition. To teach BIM, one must comprehend how the processes, policies, and technologies are related to the design teaching goals.

Keywords

BIM • Collaborative design • Education • Technology dissemination

104.1 Introduction

Brazilian undergraduate courses in architecture and urbanism underpin technologically mediated collaboration in design studio classes. Therefore, they are at odds with the industry, which is incorporating BIM and has been looking for collaborative skilled employees to achieve the benefits of this digitally integrated methodology. In the same manner, the

Electronic supplementary material
The online version of this chapter (https://doi.org/10.1007/978-3-030-00220-6_104) contains supplementary material, which is available to authorized users.

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intensive use of collaborative processes mediated by BIM favors students' understanding that BIM learning goes beyond technological topics. BIM teaching should take into account issues related to student integration through collaborative methods; otherwise, as Solnosky et al. [1] point out, companies end up hiring technology-savvy graduates and designate them as BIM Managers without them having project management skills. Recent research on teaching methods in technology applied to design indicates there is a change in the way BIM is taught [2]: there is less emphasis on technological issues and a greater focus on stimulating skills in design process and management.

The integration of informatics applied to design aiming at encouraging collaboration has always been one of the leading concerns of the School of Architecture and Urban Design at University of Campinas since its inception, in 1999 [3]. This paper presents the summary of a study that intends to evaluate the collaborative process mediated by BIM over the past ten years in its capstone course, "Design Theory X: Integrated and Collaborative Design Studio," contemplating learning and educational strategies.

104.2 Background

104.2.1 About the "Design Theory X: Integrated and Collaborative Design Studio" Course

The "Design Theory X: Integrated and Collaborative Design Studio" course is the 10th in the design studios sequence. It offers 4 h per week in the studio and 2 h per week in the computer lab. In the studio, there are design classes and assisting sessions to support design development by groups of students. In the lab, there are classes of fundamentals in integrated and collaborative design and principles of BIM. Whenever necessary, the lab holds workshops on software. Sometimes, the theoretical foundation is also developed through lectures or seminars in the studio. Every year teachers propose a different design exercise and indicate a bibliography related to BIM and design. The Results section in this article present more information about course features, as well as the research results regarding the evolution of the course.

104.2.2 Teaching Applied Informatics to Architecture in Brazil in the Years 2000

Unicamp's School of Architecture and Urban Design introduced the Integrated and Collaborative Design Studio in 2007. Its purpose is to provide learning and experience of a digital, integrated and collaborative architectural design practice. It follows the school's principles that guide the use of applied computing since its foundation, as presented by Kowaltoswki et al. [3]. Informatics is not only instrumental but also an integral part of the creative process that influences the solutions.

Despite the disagreements as to how to incorporate digital technology into design studios, it was common sense that education innovation and renovation depend mainly on faculty actions and planning [4, 5]. Vincent and Nardelli [6] pointed out that trying to fit the digital design tools into a traditional studio approach proved to be ineffective, as applied computing favors more immersive design development, which imposes faster training-assessment cycles that students cannot reproduce or fully explain when presenting their work in the studio. Romano and Scarabotto [7] observe that technological evolution necessarily implies a re-evaluation of educational methodologies and re-evaluation of teacher-student relationships. Thus, it seems clear that Brazilian researchers who studied this subject were aware of the challenges, as well as their peers in other parts of the world.

104.2.3 Evolution of Teaching BIM and Its Influence in This Course

Over time, there have been many efforts to adopt applied computing to Architecture and Engineering, and consequently BIM, in the curriculum of some Brazilian and other countries universities. Barison [8] described how the teaching of BIM evolved in universities and what the market expected of it between 2000 and 2010. At that time, companies were interested in BIM competencies associated to cost estimation, simulation, interference detection, and quality control, while Civil Engineering and Architecture courses were teaching BIM focused modeling and 3D visualization. Wu and Issa [9] surveyed educators and professionals on BIM education status and career development. They found out that leading approaches to integrating BIM in undergraduate AEC programs aimed at the development of a full BIM class curriculum or included BIM contents in traditional courses; Barison [8] thought as well that priorities on BIM curricula were BIM modeling, analysis, and configuration. However, Solnosky et al. [1] realized that educating future engineers in BIM technology required the integrated project delivery (IPD) collaboration and design approach with industry involvement. An educational strategy consistent with IPD is observed [1] when comparing the pedagogical approach proposed by the School of Architecture faculty for its courses in informatics [3]; therefore, at the moment, we address the following questions for the Integrated and Collaborative Design Studio: Were design exercises appropriate? Was the adopted dynamics of collaboration coherent? Did the collaborative tools and standards serve the mediating function? Was collaborative training fostered?

104.3 Research Method

The methodology for this study is action research. Each year, before the beginning of each course, the evaluation process of the previous sequence is carried out, followed by the planning of the current one; during the course implementation, the teachers maintain a monitoring process to make appropriate changes if necessary. Systematic evaluations were applied throughout the years, to understand how students were learning: course portfolio reflections, content analysis, secondary analysis and observational research [5]. The data from the collaborative environment logs were the subject of the secondary analysis. Team-based learning has always been part of the teaching strategy in this course; however, from 2015 on, it is possible to observe that the methodology becomes the axis that structures all the course contents.

104.4 Results

104.4.1 Results of the Research on the Evolution of the Course

All previous course programs have undergone a documentary analysis, to see if and how planning a new sequence has taken advantage of the experiences and lessons learned from previous ones (Online Resource 01). From these documents, it was possible to gather and catalog information on how teachers conducted the course each year, and which BIM-mediated activities were most encouraged. The tables with the data and formulas analyzed in the results reported here are in Online Resource 02. The totals presented in the ten years course evaluation matrix indicate that the years 2017, 2013, 2012 and 2007, in this order, were those in which integration and collaboration, as well as activities mediated by BIM, occurred more intensively. The settle of an Electronic Document Management System/Common Data Environment (EDMS/CDE) by the teachers is an important policy, as well as the emphasis on interoperability. 4D Planning teaching was more intense in the first six years of the course, and Digital Markup and Cost Analysis activities were fostered more in recent years. Energy Analysis has been fairly well distributed over the years.

From an analysis over the recommended bibliography (Online Resource 03), it was possible to verify an increase in the number of bibliographic indications on BIM when comparing the first five years of the course with the following five years. Figure 104.1 presents overall results.

The publications indicated with more recurrence, that is, more than three times in these ten years, are: The BIM Handbook [10], 9 nominations; AECbytes blog [11], Autodesk BIM Workshop webpage [12], Autodesk Revit 2011 Tutorials webpage [13], and Autodesk Revit Architecture 2012 book [14], with 5 references each; and a Rivka Oxman's journal article [15], 3 nominations.

104.4.2 Specific Characteristics of the 2017 Course

A senior professor conducted the 2017 course with the assistance of a Ph.D. student. The proposed challenge was the design of a light rail system with six stations in the city of Santos, which is located on the coast of the state of São Paulo, Brazil. In

Years	Book	Book Chap.	Implem. Guide	Journal Article	Scientific Event	Soft. Guide	Whitepaper	Magazine	Tutorial	Mag. Article	Total
07-11	15			6	2		3			3	29
12-17	7	1	5	4		13		5	12	5	52
Total	22	1	5	10	2	13	3	5	12	8	81

Fig. 104.1 The five-year period comparison of quantities and types of indicated bibliographic references

Table 104.1 Amount of different software used by students, by category

Software category	0 (%)	1 (%)	2 (%)	3 (%)	4 (%)
Design	0	0	40	43	17
Desktop publishing	34	66	0	0	0
GIS	94	3	3	0	0
Illustration	11	89	0	0	0
Image processing	14	86	0	0	0
Programming	91	6	0	3	0
Rendering	69	29	3	0	0
Visual programming	89	6	6	0	0

the first phase, six teams were in charge of studying visual identity design, technical standards and legislation on rail transport systems, geomorphological and socioeconomic aspects, and mobility issues of the city. Such information formed the foundation used in the second phase. At this stage, the previous groups were rearranged, and the six new ones had to design the stations and surroundings; within each one, pairs or trios of students formed new groups to act according to the disciplines of Architectural Design, Landscape and Urban Design and Interiors and Signage Design. In some moments, as in Exam 03, the students were reunited among disciplines to carry out task proposed by the teachers. The Online Resource 04 provides complete information about the 2017 course program, as well as the different versions developed during the semester.

BIM action plan diagnosis. Teachers decided to adopt the BIM Competencies strategy proposed by Succar [16] to develop the BIM action plan. The laboratory's hardware and software were evaluated from the technology point of view (Online Resource 05). The equipment was not able to handle sophisticated 3D modeling, but it was suited for collaboration and communication, practical exercises on interoperability, IFC fundamentals, clash detection, among others. Regarding process and policies, it was decided how the groups would be structured and the theoretical approach to the object of study. Students' skills were taken into consideration. There was a poll with 35 of the 41 enrolled (Table 104.1 and Online Resource 06) with the purpose of learning more about which category of programs they had sufficient knowledge.

83% of the students declared they dominate 2 or 3 different design software: AutoCAD (100%), SketchUp (77%), Revit (60%), Rhino (26%), among others. 12% claimed to know how to use a visual programming tool (Grasshopper or Dynamo) and 9%, programming languages like C, C # or Python. The results of the survey grounded the decision to let students choose to use whatever programs they wanted.

The BIM action plan. The goal of the BIM action plan for the course was to facilitate communication and exchange of design information amongst students and between students and teachers, with minimal interference regarding the use of digital tools, but with a very incisive interfering in the process of information and communications management. The course develops design authoring and 3D coordination using BIM.

Collaborative platform. Trimble Connect, a solution pointed out by Preidel et al. [17] as a mature approach for a CDE, was adopted as the collaborative platform for communication between teachers and students, as well as to perform 3D coordination, clash detection and create quantity reports from model data. It has a system for synchronizing files on personal computers, facilitating data exchange; allows creation and management of tasks (BCFs), offers a Revit add-on for exporting models, and generates reports in Excel format from data in IFC, SketchUp Pro, and Revit models.

Design models geolocation. Geolocation of the team design model files as an essential, non-negotiable premise, was adopted at the beginning of the course, as it deals with the development of several projects in a simultaneous and coordinated fashion in the urban site.

Use of IFC as the predominant means of information exchange. Students had classes to learn how to produce quality IFC files from the programs they used, which was vital to perform the integrated visualization of projects in Trimble Connect or in any other software they wanted (Fig. 104.2). A collection of videos and images with samples of student deliveries in Exams 01, 02 and 04 is gathered in Online Resources 07 through 12.

Fig. 104.2 Geolocalized projects of the teams in the city of Santos

104.4.3 Evaluation of Performance Based on Model Data Extraction

The content analysis occurred on automated readings of BIM models delivered by the teams on exam dates. The analyzes encompassed: Clash detection in Exams 01, 02, and 04, and quality audit of the information extracted from the models, in Exam 04. Mapping of the BIM process, related to the flow of design files, delivery dates of exams, and teams, can be checked in Online Resource 13. Table 104.2 and Online Resource 14 show results obtained by clash detection tests on the models delivered in Exams 01, 02, and 04.

It is possible to notice a reduction in the clashes per object rate in almost all the cases, with three exceptions. The increase in team C and F rates is due to the lack of knowledge on how to export a quality IFC file at the time of the first exam. The almost constant value presented by team D is due to the high level of geometric complexity of its design proposal.

Defining Objects, Parameters, and Values. Exam 03 was a collaborative work proposed to develop an object classification system (Online Resource 15). Students had to create parameters and fill out related values for six object types chosen in a previous exercise: Doors, Windows, Toilets, Signage Boards, Trees, and Landscape Benches. For objects of type Door, the following parameters applied: Brazilian BIM Standard Code, Cost, Model, Manufacturer, Supplier, Shipping Weight, Noise Reduction Coefficient, Thermal Conductivity Coefficient, Panel Finishes, and Material Type. The other objects

Table 104.2 Clash checks on the models delivered

Cl. per obj.	Arch. design			Int. and sign. design		Land. and urb. design	
Teams	EX 01	EX 02	EX 04	EX 02	EX 04	EX 02	EX 04
A	1.25	0.00	–	–	–	0.45	–
B	0.32	0.30	0.21	–	0.00	–	0.30
C	0.13	0.27	–	–	–	–	–
D	1.57	1.50	1.57	0.35	0.00	0.43	0.10
E	0.65	0.53	–	–	–	–	–
F	0.00	0.80	0.00	–	0.00	–	0.49

Table 104.3 Results of data audition from the models delivered in exam 04

Parameters in object types	Corr. (%)	Inc. (%)	Corr. (abs)	Inc. (abs)	Total
ALL	72	28	5659	1293	6952
Various	61	39	1090	328	1418
DOR and WIN	67	33	230	120	350
LBE and SBO	60	40	238	44	282
TOI	100	0	114	0	114
TRE	89	11	1543	317	1860
SBO	58	42	112	22	134
LBE	55	45	346	88	434
Total	73	27	9332	2212	11544

received the same treatment. The evaluation of Exam 04 consisted of verifying whether the elements were in the correct IFC classification; if they had the proper prefix; if there were ten properties previously defined in each object in each model; if values were correctly filled out. Results of the data audition are summarized by parameters' category, in Table 104.3. Other results are in Online Resources 16.

73% of the 11,544 values were correctly filled out by the students. The highest hit rate is in Toilets category, but the chances are that this happened because students used Toilet objects with parameters already filled out. The high accuracy rate in Trees category (89%) confirms that the students learned well how to create and fill out parameters, as no team used tree libraries with pre-filled parameters and values.

Table 104.4 The average rate of added files: comparison between 2007, 2008, and 2017

Categories	2007	2008	2017
CAD drawing	1.13	3.15	2.68
Document or presentation sheet	0.74	3.85	6.34
Image	5.04	10.00	12.24
Model—deliverable (IFC)			1.66
Model—design			4.41
Modeling support			0.46
Other	0.78	2.08	4.41
Total	7.70	19.08	32.22

Table 104.5 Types and quantities of activities in collaborative platforms in 2008 and 2017

2008—Autodesk Buzzsaw		2017—Trimble connect	
Activity group	Count	Activity group	Count
Similar activities	1049	Similar activities	10006
Comment	0	Comment	12
File	1049	File	5678
Folder	0	Folder	4267
Project administration	0	Project administration	49
Other activities	5	Other activities	8596
Markup	0	ToDo	115
Note	0	View2D	12
Publish	5	Clash	368
Link	0	Sync	8101
All activities	1054	All activities	18602

104.4.4 Comparisons Between the Course of 2017 and Previous Ones

A statistical comparison was performed only among course offerings that registered log uses, that is, through secondary analysis, to verify the evolution of the use of collaborative platforms. Table 104.4 shows the average rate of added files by category. There is a constant increase in the average number of shared files; there is also a reduction in the average number of CAD files created and added to the collaborative platform, per student. Other related results are in Online Resources 17.

Table 104.5 shows the number of activities performed by students in 2008 and 2017, which are grouped and summed by type. Similar operations and other ones (i.e., those that do not exist in the other platform) form a hierarchical top-level grouping for ease of comparison. There is a significant increase in students' adherence to the collaborative platform in all categories. The number of activities divided by the students per year is also a good indicator: there were 81 activities per student in 2008 versus 453.7 in 2017, an increase of 560%. Other findings are in Online Resources 18.

104.5 Discussion

In 2017, statistical analysis shows that the efficient sharing of information reduced the rework of the teams. There was an optimization of the workflow through centralized management of information models, and an increased understanding of the value and function of mandates to regulate collaboration and integration. Collaborative platform improved teacher-student communication regarding questions about design, which was answered directly in the BIM models and supported an efficient evaluation of student work. Through the historical comparison between the course curriculum and collaboration strategies adopted in classes over the years, it was possible to perceive changes in the understanding of how to use BIM in a collaborative process with educational purposes.

104.6 Conclusion

The results of the analyzes presented in Sect. 104.4 and discussed in Sect. 104.5 are the basis for the answers to the questions raised in Sect. 104.2.3, and support some of the conclusions presented in this section. The evolution of teaching practices contributed to the improvement of teachers as mediators. Technologies also changed from Computer-Aided Architectural Design (CAAD) and EDMS to BIM and CDE. There was an evolution of the process of understanding the course, the methods of collaboration and communication and currently available technologies. The intense exchange between teachers and students and analysis by teachers between cycles resulted in this transformation, which gave the course the character of educational research. Sophisticated design exercises, with the inclusion of environmental requisites, cost analysis, clash detection and other BIM related activities are appropriated for this type of course and require a team effort. The two-axes collaborative integration method developed over the years of the course, where students are tested to collaborate at the same time in a design process and in a research process that assists the design, is an innovation that results from the evaluation cycles based on the research-action method. Such dynamics foster efficient collaboration and can also be promoted involving external teams. The collaborative tools can be better harnessed, and standards development mediates integration understanding. The fostered collaboration training is the knowledge of the efforts and consequences of the conciliatory decision-making process. It is possible to conclude that the essence of collaboration teaching mediated by BIM follows the same precepts of the current BIM definition, taking as reference the academic meaning that is more often attributed to the term [18]. To teach BIM, one must comprehend how the processes, policies, and technologies are related to the design teaching goals.

References

1. Solnosky, R., Parfitt, M.K., Holland, R.J.: IPD and BIM–focused capstone course based on AEC industry needs and involvement. J. Prof. Issues Eng. Educ. Pract. **140**(4), A4013001 (2013)
2. Zhang, J., Wu, W., Li, H.: Enhancing building information modeling competency among civil engineering and management students with team-based learning. J. Prof. Issues Eng. Educ. Pract. **144**(2), 05018001 (2018)
3. Kowaltowski, D.C.C.K., Da Silva, V.G., Gouveia, A.P.S., Pina, S.A.M.G., Ruschel, R.C., Borges Filho, F., Fávero, E.A.: Ensino de Projeto com Inserção da Informática Aplicada: O Curso de Arquitetura e Urbanismo da UNICAMP. IV Seminário Ibero-americano de Gráfica Digital —SIGraDi'2000, pp. 352–354. SIGraDI, Rio de Janeiro, BR (2000)

4. Oreta, A.W.C.: Engineering Educators must evolve, too! J. Prof. Issues Eng. Educ. Pract. **142**(1), 02515002 (2015)
5. Streveler, R.A., Smith, K.A., Pilotte, M.: Aligning Course Content, Assessment, and Delivery: Creating a Context for Outcome-Based Education. Outcome-Based Science, Technology, Engineering, and Mathematics Education: Innovative Practices, pp. 1–26. IGI Global, Pennsylvania (2012)
6. Vincent, C.C., Nardelli, E.S.: Estado da arte em projeto digital: quanto tempo até logo ali. III Fórum de Pesquisa. FAU/Mackenzie, São Paulo (2007)
7. Romano, E., Scarabotto, H.: CAD Criativo—Uma Experiência Didática. Informática Pública **11**(1), 13 (2009)
8. Barison, M.B.: Introdução de Modelagem da Informação da Construção (BIM) no currículo—uma contribuição para a formação do projetista [São Paulo]: Universidade de São Paulo, p. 387 (2015)
9. Wu, W., Issa, R.R.A.: BIM education and recruiting: survey-based comparative analysis of issues, perceptions, and collaboration opportunities. J. Prof. Issues Eng. Educ. Pract. **140**(2), 04013014 (2014)
10. Eastman, C., Teicholz, P., Sacks, R., Liston, K., Handbook, B.: A Guide to Building Information Modeling for Owners, Managers, Architects, Engineers, Contractors, and Fabricators. Wiley, Hoboken, NJ (2008)
11. Khemlani, L.: AECbytes [Internet]. AECbytes. Available from: http://www.aecbytes.com/info/about.html
12. Autodesk: BIM Workshop [Internet]. Available from: http://bimcurriculum.autodesk.com/
13. Autodesk: Autodesk Revit Architecture 2011 English Tutorials [Internet] Autodesk. Available from: http://students.autodesk.com/?nd=revit2011_english
14. Read, P., Krygiel, E., Vandezande, J.: Autodesk Revit Architecture 2012: Essencial. Bookman, Porto Alegre (2012)
15. Oxman, R.: Theory and design in the first digital age. Des. Stud. **27**(3), 229–265 (2006)
16. Succar, B.: The five components of BIM performance measurement. In: Barrett, P., Amaratunga, D., Haigh, R., Keraminiyage, K., Pathirage, C. (eds.) CIB World Congress 2010—Building a Better World, p. 14. CIB, Salford, UK (2010)
17. Preidel, C., Borrmann, A., Oberender, C., Tretheway, M.: Seamless integration of common data environment access into BIM authoring applications: The BIM integration framework. eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2016. In: Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016), Limassol, Cyprus, CRC Press, p. 119, 7–9 September 2016, 2017
18. Gaspar, J., Ruschel, R.C.: A evolução do significado atribuído ao acrônimo BIM: uma perspectiva no tempo, p. 8. XIX SIGraDI, Concepción, CL (2017)

Toward a Roadmap for BIM Adoption and Implementation by Small-Sized Construction Companies

105

Wylie Ferron and Yelda Turkan

Abstract

Building Information Modeling (BIM) offers a variety of tools to help a wide range of stakeholders in the construction industry. There has been substantial research on the advantages and challenges of implementing BIM for large-scale construction projects; however, there is a dearth of research on the benefits and challenges faced by smaller construction firms when adopting BIM. Thus, this paper focuses on the cause-and-effects of BIM adoption in the construction industry. To achieve this objective, first, a literature review covering different aspects of BIM adoption was conducted. Second, large-sized construction firms who already have implemented BIM in several of their projects were interviewed through questionnaires. Based on the findings from the interviews, a set of survey questions was prepared and distributed among all types of construction firms to identify their innovativeness and level of BIM adoption. The survey contains company and demographics, innovativeness, and BIM-specific questions. Survey results show that small-sized construction companies are indeed far behind large-sized companies in respect to BIM adoption. This paper highlights the findings from the literature review and survey. Future research will take place to dive further into the survey data results and develop a roadmap that identifies a BIM function that can be adopted easily by small-sized construction companies.

Keywords

BIM • Innovativeness • Small-sized construction companies

105.1 Introduction

The nature of construction projects has become increasingly more complex; the complexity demands extensive planning, increased quality control, reliable communication, and constant collaboration. Roughly 90% of large-sized companies (more than 250 employees) are using Building Information Modeling (BIM) to some extent, while less than half of small-sized companies (fewer than 250 employees) are using it [16]. Advanced technologies have become available for use but are not being utilized as they have been in other industries. Roughly 50% of construction companies have reported spending 1% annually on technology; nearly 60% of construction companies are not considering any new technologies; and, 28.1% of these companies indicated that they do not bid on projects involving BIM [33]. Given that the construction industry is predominantly known as being traditionalists and more reluctant to adopt new developments, relative to other industries, it is crucial to explore the different explanations as to why that might be. This paper covers literature that discusses crucial BIM-related topics as well as preliminary survey data.

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105.2 Background

105.2.1 Innovativeness in the Construction Industry

Construction is continuously changing; the industry is plagued by insurmountable amounts of risk, a constant pursuit of improving sustainability, and increased complexity of designs. This changing industry is slow to embrace new technology. According to a survey conducted by Armstrong and Gilge [3], only 8% of the 218 senior executives participated are categorized as innovators, while 20% stated new technologies are "aggressively disrupting their business models." Gallaher et al. [8] noted that the problem in the construction industry is the continued paper-based business practices and the inconsistency of technology innovation.

Rogers [27] labels innovativeness as an excellent indicator of whether or not a company will be successful regarding implementing new technology into their current processes. According to Rogers [27], companies can be characterized into one of five categories: Innovators, Early Adopters, Early Majority, Late Majority, or Laggards (Fig. 105.1).

Innovators have the stability to manage successes and errors, as well as the financial resources, which are necessary due to the uncertainty that new technologies and software contain. From the survey conducted by Armstrong and Gilge [3], only 8% of the industry falls into this category. Early Adopters serve as role models to others. The Early Majority shows a willingness to adopt new technologies but are not the ones to lead the charge. The Late Majority represents the firms that only implement new technologies when it is an economic necessity. Laggards are the last individuals and companies to adopt new technologies after they are approved by the rest of the industry and have very low risk associated with them. The traditionalist mindset of these individuals and companies is the reason that their technology awareness is behind everyone else.

According to the Armstrong and Gilge [3], 69% of the construction industry are labeled as "followers" or "behind the curve;" similarly, Rogers would classify "followers" as the Late Majority and "behind the curve" as the Laggards.

Gholizadeh et al. [9] state that companies who want to stay competitive, regardless of size, need to invest in different applications of BIM and train their employees. Armstrong and Gilge [3] acknowledges that medium-sized construction companies, ranked by annual turnover ($1 to $5 billion), are the most innovative companies in the industry. The medium-sized companies credited this to the competitive advantage that technology provides; also, their manageable company size makes them more susceptible to adapt to new technologies and methods quickly.

Another management issue regarding innovation within the construction sector is merely the nature of the industry. According to Murphy [21], project management accounts for different constraints including problems with project objectives, regulatory requirements, and external factors. Project leadership often fails to address the management of newly available technology. Guo et al. [10] emphasize the need for implementing innovative management software throughout all phases of projects. Previous studies have developed successful theoretical processes involving innovative management; however, the majority of those studies do not provide practical tools for efficaciously implementing and managing those processes into construction projects [21].

105.2.2 The Effect of Workers' Age on New Technology Adoption

Previous studies suggest that the workers' age is not the reason for the lack of new technology implementation; instead, it is the workplace climate and how it is managed [22]. Though it should be noted, a study by Meyer [20] presents data showing that workers older than 30 years old can hurt the implementation of new technology. This is not surprising since workers

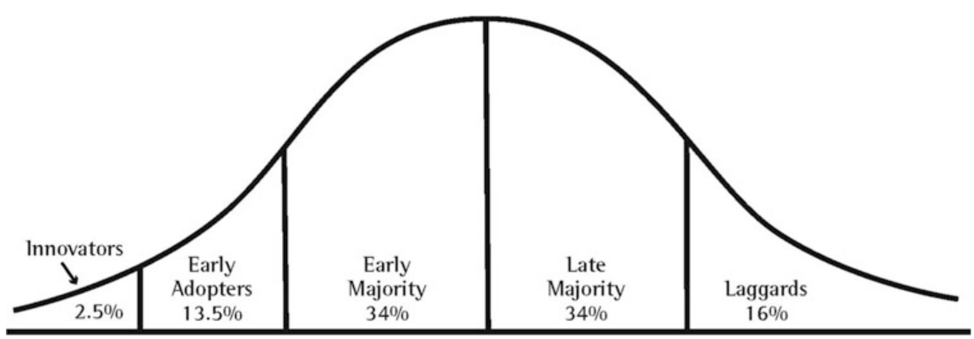

Fig. 105.1 Diffusion of innovation curve. Adopted from Rogers [26]

below the age of 30 have a higher potential and productivity rate regarding mastering new software [31]. Nonetheless, several other studies state that the innovativeness of the workplace has much more impact on the employee adaptiveness to new technology, compared to the age of the workplace [22, 20, 23].

105.2.3 BIM Applications in the Construction Industry

BIM is making a push as the new-age technology in the construction industry. Several studies have reported that BIM can improve the quality and efficiency of construction projects [13]. According to Forgues et al. [7], value engineering at the beginning of the design phase could result in a more cost-effective project delivery method, higher quality buildings, and increased control and predictability for the owner. BIM can increase the efficiency of the value engineering at the design phase if companies can manage the processes of the different applications. Hartmann et al. [13] examined seven commonly used BIM applications in the construction industry: photorealistic renderings, virtual design review, analyzing design options/building operations, analyzing construction operations, construction document production, bid package preparation, and cost estimating [33, 9]. This study focuses on photorealistic renderings, virtual design review, and analyzing construction operations. These functions were chosen due to their feasibility to be adopted by small construction companies.

Photorealistic Renderings: Virtual 3D models can be a potent tool for construction and architecture sales. Research conducted by Welsh [33] showed that 34.7% of companies that use BIM, use it for marketing presentations. Gholizadeh et al. [9] predicted that using BIM for facility space planning and logistics adoption would reach its peak by 2021.

Virtual Design Review: Having the ability to communicate design issues, clash coordination, and collaborate with other engineers without scheduling an in-person meeting can save time and money. Traditionally, different trades would meet and discuss designs over 2D drawings. BIM enables multiple design models to be combined, which then can be automatically checked for clashes using BIM supporting tools, such as Autodesk Navisworks or Tekla BIMSight. Gholizadeh et al. [9] showed that clash detection was the second most-adopted BIM function [16, 33, 7, 12]. Sixty-three percent of companies use BIM for clash detection [33].

Analyzing Construction Operations: The analysis of construction operations is the most widely used application, according to Hartmann et al. [13]. Gholizadeh et al. [9] agree with Hartmann, showing that constructability analysis is the third-most adopted application. BIM tools such as Synchro Pro or Navisworks can be used to combine the 3D building models with the project schedule. The result is a time-stamped 3D model, which enables visualization of construction sequencing. Having the opportunity to track and visualize the project process can be a potent tool for project managers to make crucial decisions [4]. Being able to see the logistics of the project allows project teams to identify any issues with the sequencing of the construction.

Having superior technical support is necessary when linking different software with BIM due to the interoperability challenges [4, 2]. Nevertheless, Porwal and Hewage [24] stated that the most significant challenges of implementing BIM are the organizational and people-centered problems [4, 28]. The technology itself can better the construction industry, but it cannot be utilized if the management is not willing to create a well-put-together process.

105.2.4 Trade Specific BIM Applications

There is a shortage of studies that explore trade-specific BIM tools. The mechanical, electrical, and plumbing (MEP) industry is the only sector of the construction industry that has a substantial amount of research. The following subsections explore different projects and BIM tools that are trade specific.

MEP Construction. MEP construction has been the focal point for BIM use [16]. As previously mentioned, 63.5% of companies rely on BIM for coordination and clash detection, which is done by using AutoCAD MEP or Autodesk Navisworks; used by 23.4 and 15.9% of companies, respectively [33]. These tools can merge BIM models are automatically detect clashes. Specialty trades' management can then manage clashes [7]. Fixing potential clashes before the construction starts has been the reason for many companies implementing BIM [16].

Steel Construction. Tekla Structures software provides steel detailers, fabricators, and erectors with many tools that enhance management and constructability. Some of Tekla's tools include model design, estimating, detailing, and field visualization [32]. Models can be created for all types of construction ranging from stadiums to bridges. Tekla Structures has been a reliable tool for the Mercedes Benz Stadium project, a $1.5-billion Leadership in Energy and Environmental Design—platinum certified stadium [32].

The Barclays Center project, in Brooklyn, New York, was almost entirely engineered utilizing BIM models. The architectural firm used Revit for design, the engineering firm used Tekla Structures to model the structural steel system, and then the structural model was distributed to all of the subcontractors to work on [17].

Concrete Construction. Different technologies including laser scanners and total stations are used to add information to BIM models [22–25]. By using these technologies, as-built data can be captured as soon as activities are finished. Using BIM models for quality assurance and quality control has proved to be more accurate and efficient in concrete construction [14]. For concrete, as-built BIM models can reduce rework; therefore, save time and money. Using BIM to document location in-concrete components helps mitigate rework and, most importantly, improve workers' safety [25]. For example, the locations of post-tension cables can be inputted in the BIM model and then can easily be located after the concrete is poured.

Fire Protection. A ubiquitous component that is commonly left out of the clash detection discussion is fire protection systems. The International Building Code (IBC) has many regulations that fire protection systems must abide [15]. The power of BIM allows designers and engineers alike to give each component of active and passive fire protection systems characteristics. Another element that gets left out of clash detections is walls. Fire-resistant walls are highly regulated by the IBC, which causes many issues with their location, concerning the other systems of the building. BIM also allows facility managers to remotely access the type of fire protection equipment that may need maintenance from the model [29].

105.2.5 Effect of Project Delivery Method on BIM Implementation

According to Porwal and Hewage [24], no specific project delivery method is best suited for implementing BIM to a project. Although, the integrated project delivery (IPD) method that has worked well with BIM integrated projects. The traditional project delivery methods, such as Design Bid Build (DBB) tend to separate the design and construction phases, which is detrimental to the communication between teams [4, 24, 19].

***Design-Bid-Build* (DBB)**. In DBB project delivery, the owner, designer, and constructor are all separate entities, which results in poor constructability and ultimately increased project costs, value engineering, as well as an ineffective transfer of information between project parties [24, 5, 6]. Although BIM enables collaboration and communication among stakeholders, the DBB method does not allow project teams to form until post-bidding. Gholizadeh et al. [9] showed that 38% of BIM users and 58% of non-BIM users worked on projects delivered via DBB.

Design-Build (DB) and Construction Manager/General Contractor (CM/GC). DB method is growing in popularity due to its ability to reduce project costs and improve project schedule and construction quality [4, 5]. Since the designer and the constructor are one entity, BIM can be more effectively utilized for constructability and value engineering [4, 28]. Projects with a construction manager also promote the use of BIM due to the increased communication between stakeholders. Both DB and CM/GC methods allow projects to be fast-tracked in owner's favor.

Integrated Project Delivery (IPD). This project delivery method forces the project stakeholders to communicate and make decisions together resulting in enhanced collaboration and better-quality projects. According to Zhang and Guangbin [34], one of IPD's characteristics is that it can fully utilize the technological capabilities of a project; therefore, IPD is a BIM-friendly project delivery method because BIM and IPD promote many of the same characteristics [28, 19, 6].

Three most commonly used project delivery methods were discussed above to understand better the circumstances of using BIM. Conclusively, the owners, managers, designers, and contractors must be able to work as a team to successfully construct a project. For BIM to be successful, not only do previous processes need to be changed, new procedures for each of the BIM functions need adoption and implementation [4, 28].

105.3 Methodology and Data Collection

To further explore the advantages and limitations of BIM in the construction industry, 800 surveys were sent out to companies located predominately on the West Coast of the United States. Out of the 800 surveys, 83 ($\sim$10%) participated in the survey. Companies completed the survey voluntarily and uncompensated. The survey was not limited to any types of construction companies, due to comparative reasons.

The data collection was broken down into two components: preliminary interviews and an official survey. The preliminary interviews were informal. Two companies that used BIM were interviewed through a questionnaire to gain more knowledge about how BIM was being perceived in the industry. The information gained from these interviews and a literature review were then used to develop a survey consisting of sixteen questions. The survey questions can be divided into three main categories: (1) company demographics, (2) innovativeness, and (3) BIM-related questions.

The essential demographics of the survey participants are listed below:

- 37% of the companies are small-sized (<250 employees).
- 63% of the companies are general contractors.
- 76% of the companies currently use BIM.
- 83% of the companies claim to be ahead of the majority of the industry or be one of the first to adopt and implement new technology in the industry.

The basis of this study focuses on comparing small-sized construction companies to large-sized construction companies to determine similarities and differences. The threshold of company size is based on findings in a SmartMarket Report, where companies with less than 250 employees were considered small [18]. Once the similarities and differences between small and large sized companies are identified, an appropriate BIM function will be chosen, and an adoption roadmap will be developed. The adoption roadmap will be customized for practical use and sent out to construction industry professionals to be verified. If necessary, modifications will be made to the adoption roadmap by using Delphi method [11]. The results presented in this paper highlight the critical findings from the survey.

105.4 Results

The data collected from the survey is analyzed under the following sections: (1) Company size (number of employees) and average annual budget, (2) innovativeness, and (3) the potential and risks of BIM. The survey presented company size and average annual budget in ranges that allow the researchers to classify company size.

The survey results show that large-sized companies (Table 105.1) use BIM technologies at a higher rate compared to small-sized companies (Table 105.2). It should be noted that large-sized companies also have a higher average annual budget; similarly, of the 33 companies with an average annual budget of less than $150 million, 16 (~48%) of them used BIM.

The survey asked participants to evaluate the rate at which their company uses the following tools: Microsoft Suite, Bluebeam, AutoCAD, Revit/Tekla Structures, Synchro PRO, and NavisWorks. Microsoft Suite was used most often on a daily basis (~93%), followed by Bluebeam (~88%), while Synchro PRO was only used daily by 8 companies (~9%). Interestingly, the three tools that are not being used at all are Synchro PRO (~61%), Navisworks (~30%), and Revit/Tekla Structures (~24%). BIM technology has significantly increased in the workplace. Only two companies were using BIM before 1995, while 56 have used it before 2016. It should be noted that five companies state they do not use BIM anymore but have used it before 2017. Of the 20 companies that do not currently use BIM, 13 (65%) of them plan on adopting it in the future.

Tables 105.3 and 105.4 report the potential and risks, respectively, when deciding to implement BIM. Company productivity (~65%) and cost benefits (~65%) had the highest amount of potential when deciding to adopt BIM. Technical issues (~41%) and the implementation process (~36%) of BIM were associated with a high amount of risk.

Table 105.1 Large-sized companies' average annual budget

Large-sized companies (more than 250 employees)							
Average annual budget (millions)							
	Less than $50	$50–$100	$150–$250	$250–$400	More than $400	Total	BIM (%)
General contractor	1	3	1	3	23	31	27/87
Engineering firm/consultant	0	0	1	0	2	3	3/100
Specialty contractor	1	2	4	4	4	15	15/100

Table 105.2 Small-sized companies' average annual budget

Small-sized companies (less than 250 employees)							
Average annual budget (millions)							
	Less than $50	$50–$100	$150–$250	$250–$400	More than $400	Total	BIM (%)
General contractor	9	5	3	2	0	19	10/53
Engineering firm/consultant	1	0	0	0	0	1	1/100
Specialty contractor	10	1	0	0	0	11	5/45

Table 105.3 BIM potential during the decision to adopt

BIM potential during the decision to adopt							
	Negative	None	Low	Mild	High	Exceptional	Total
ROI	3	5	8	13	30	7	66
Company productivity	1	5	2	10	43	5	66
Proposal acceptance rate	0	6	10	22	23	5	66
Schedule benefits	0	5	6	16	31	8	66
Cost benefits	1	5	2	10	43	5	66
Total	5	26	28	71	170	30	

Table 105.4 BIM risks during the decision to adopt

BIM risks during the decision to adopt						
	None	Low	Mild	High	Exceptional	Total
Cost (initial investment, ROI, maintenance, etc.)	3	19	25	15	3	65
Contractual issues (liability, risk, ownership of model, etc.)	5	27	24	8	1	65
Technical issues (learning curve, interoperability, etc.)	3	11	23	27	2	66
Implementation process	3	4	31	23	3	64
Total	14	61	103	73	9	

105.4.1 Limitations and Further Research

The limitation of this research is the diversity of the survey. The survey was only distributed to the companies based on the West Coast of the United States. Currently, the research team is working on distributing the survey to Midwest construction companies to obtain a more diverse sample size.

In future research, a more in-depth statistical analysis will be conducted on a more diverse and large dataset to ensure the accuracy of the similarities and differences between small and large-sized construction companies. As mentioned previously, choosing a BIM function and developing an adoption roadmap is the primary goal of this research.

105.5 Conclusions

This paper presented the results from a literature review and survey obtained from 83 construction companies. The results showed that the number of construction companies that utilize BIM technologies has undoubtedly increased within the last decade, but the small-sized construction companies are falling farther and farther behind large-sized companies. The ultimate goal of this study is to identify the BIM function that can be readily adopted by small-sized construction companies and develop a roadmap for them to adopt BIM at the same rate as large-sized companies. By doing so, small-sized construction companies can stay competitive and relevant within the industry. In future research, a roadmap will be developed by combining the knowledge gained through literature review, interviews, and survey analysis to encourage small construction companies to explore the advantages of BIM.

References

1. Anil, E.B., Tang, P., Akinci, B., Huber, D.: Deviation analysis method for the assessment of the quality of the as-is building information models generated from point cloud data. Autom. Constr. **35**, 507–516 (2013). https://doi.org/10.1016/j.autcon.2013.06.003
2. Arayici, Y., Fernando, T., Munoz, V., Bassanino, M.: Interoperability specification development for integrated BIM use in performance based design. Autom. Constr. **85**, 167–181 (2018). https://doi.org/10.1016/j.autcon.2017.10.018
3. Armstrong, G., Gilge, C.: Building a Technology Advantage, https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2016/09/global-construction-survey-2016.pdf (2016)
4. Azhar, S.: Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. Leadersh. Manag. Eng. **11**, 241–252 (2011). https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127
5. Bernstein, H.M., Laquidara-Carr, D.: Project Delivery Systems: How They Impact Efficiency and Profitability in the Buildings Sector (2014)
6. Bynum, P., Issa, R.R.A., Olbina, S.: Building information modeling in support of sustainable design and construction. Am. Soc. Civ. Eng. **139**, 24–34 (2013). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560
7. Forgues, D., Iordanova, I., Valdivesio, F., Staub-French, S.: Rethinking the cost estimating process through 5D BIM: a case study. Constr. Res. Congr. **3**, 778–786 (2012). https://doi.org/10.1061/9780784412329.079
8. Gallaher, M.P., O'Conor, A.C., Dettbarn, J.L., Gilday, L.T.: Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry, NIST, pp. 1–210. https://doi.org/10.6028/nist.gcr.04-867 (2004)
9. Gholizadeh, P., Esmaeili, B., Goodrum, P.: Diffusion of building information modeling functions in the construction industry. J. Manag. Eng. **34**, 04017060 (2018). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000589
10. Guo, F., Jahren, C.T., Turkan, Y., Jeong, H.D.: Civil integrated management: an emerging paradigm for civil infrastructure project delivery and management. Manag. Eng. **33**, 1–10 (2017). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000491
11. Hallowell, M.R., Gambatese, J.A.: Qualitative research: application of the Delphi method to CEM research. J. Constr. Eng. Manag. **136**, 99–107 (2010). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000137
12. Hanna, A., Asce, F., Boodai, F., El Asmar, M., Ph, D., Asce, M.: State of practice of building information modeling in mechanical and electrical construction industries. J. Constr. Eng. Manag., ASCE **139**, 1–8 (2013). https://doi.org/10.1061/(asce)co.1943-7862.0000747
13. Hartmann, T., Gao, J., Fischer, M.: Areas of application for 3D and 4D models on construction projects. J. Constr. Eng. Manage. **134**, 776–785. http://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9364(2008)134:10(776) (2008)
14. Hayes, C.: Transforming Concrete Construction with BIM, Web Artic, pp. 9–11 (2013)
15. International Code Council: Chapter 9: Fire Protection Systems (2015)
16. Jones, S.A., Bernstein, H.M.: The Business Value of BIM in North America (2012)
17. Jones, J.: Barclays Center Delivered Using BIM. Civ. Eng. **82**, 14–17. http://ezproxy.leedsbeckett.ac.uk/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=79893133&site=eds-live&scope=site (2012)
18. Jones, S.A., Laquidara-Carr, D.: SmartMarket Report The Business Value of BIM for Infrastructure (2017)
19. Kent, D.C., Becerik-gerber, B.: Attitudes toward integrated project delivery. J. Constr. Eng. Manag. **136**, 815–825 (2010). https://doi.org/10.1061/ASCECO.1943-7862.0000188
20. Meyer, J.: Workforce age and technology adoption in small and medium-sized service firms. Small Bus. Econ. **37**, 305–324 (2011). https://doi.org/10.1007/s11187-009-9246-y
21. Murphy, M.E., Perera, S., Heaney, G.: Innovation management model: a tool for sustained implementation of product innovation into construction projects. Constr. Manag. Econ. **33**, 209–232 (2015). https://doi.org/10.1080/01446193.2015.1031684
22. Olofsson, : Benefits and lessons learned of implementing Building Virtual Design and Construction (VDC) technologies for coordination of Mechanical, Electrical, and Plumbing (MEP) systems on a large Healthcare project. Electron. J. Inf. Technol. Constr. **13**, 324–342 (2008). https://doi.org/10.1016/j.ijproman.2012.12.001
23. Peansupap, V., Walker, D.H.T.: Factors enabling information and communication technology diffusion and actual implementation in construction organisations. Electron. J. Inf. Technol. Constr. **10**, 193–218 (2005). Doi: http://www.itcon.org/2005/14
24. Porwal, A., Hewage, K.N.: Building information modeling (BIM) partnering framework for public construction projects. Autom. Constr. **31**, 204–214 (2013). https://doi.org/10.1016/j.autcon.2012.12.004
25. Puri, N., Turkan, Y.: Toward automated dimensional quality control of precast concrete elements using design BIM. WIT Trans. Built Environ. **169**, 203–210 (2017). https://doi.org/10.2495/BIM170191
26. Rogers, E.M.: Diffusion networks. J. Netw. Knowl. Econ., pp. 130–179 (2003)
27. Rogers, E.M.: Diffusion of Innovations. Doi: citeulike-article-id:126680 (1995)
28. Sacks, R., Koskela, L., Dave, B.A., Owen, R.: The interaction of lean and building information modeling in construction. Constr. Eng. Manag. **136**, 1–29 (2009). https://doi.org/10.1061/?ASCE?CO.1943-7862.0000203
29. Shino, G.K.: BIM and fire protection engineering. Consult. Specif. Eng. **50**, 34–41 (2013)
30. Tang, P., Akinci, B., Huber, D.: Characterization of laser scanners and algorithms for detecting flatness defects on concrete surfaces. J. Comput. Civ. Eng. **4**, 129–134 (2015). https://doi.org/10.1016/j.csse.2015.06.002
31. Tijdens, K., Steijn, B.: The determinants of ICT competencies among employees. New Technol. Work Employ. **20**, 60–73 (2005). https://doi.org/10.1111/j.1468-005X.2005.00144.x
32. Trimble: Trimble Introduces Tekla 2018 BIM Software Solutions New Releases Leverage Control and Speed in Collaborative Construction Workflows (2018)
33. Welsh, L.: 2017 the 6th Construction Technology Report (2017)
34. Zhang, Y., Guangbin, W.: Cooperation between building information modeling and integrated project delivery method leads to paradigm shift of AEC industry. In: Proceedings of International Conference of Management Service Science MASS, pp. 1–4. https://doi.org/10.1109/icmss.2009.5305337 (2009)

106 BIM Implementation in Mega Projects: Challenges and Enablers in the Istanbul Grand Airport (IGA) Project

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Abstract

The Architecture Engineering and Construction (AEC) sector has been facing considerable challenges recently due to the scale and complexity of the projects. Mega projects are more difficult to manage in terms of decreasing cost and increasing quality and productivity. Innovative approaches have been proposed to overcome the various challenges that the AEC sector tries to address. Achieving integration and thereby a more collaborative project environment is essential in this process. Today's key trend in successful business strategy is put as "combine and conquer" which includes innovating business models together with transforming the core engineering systems around digital. Accordingly, it has been observed that there is rapid increase in implementing Building Information Modeling (BIM) in mega projects. BIM provides significant increase in efficiency of project execution through optimizing project constraints of scope, time, cost, quality, and resources. Therefore, incentivizing all project parties to work in a collaborative fashion can be considered as an important key success factor. This study investigates the challenges and enablers of BIM implementation through a case study on Istanbul Grand Airport (IGA) Project in Turkey to provide a solid understanding of BIM applications in mega infrastructure projects

Keywords

Building information modeling (BIM) • Enablers • Challenges

106.1 Introduction

The construction industry is strongly externally influenced, project based, highly competitive and susceptible to high risk of failure. As Tatum [20] states, driving forces in the construction industry indicate that the ability to innovate is quickly becoming a competitive necessity. Accordingly, to rise to the top in efficiency, construction industry individuals should seek for innovative management solutions. This notion becomes subtler as the increase of complexity and scale of projects are in demand due to the rise in global competitiveness of construction market. As a result, building information modeling (BIM) technologies and concepts have been increasingly employed as one of the most promising tools in the architecture, engineering, and construction (AEC) industry worldwide [3, 10, 18]. However, adopted managerial and utilization strategies differentiate significantly when the infrastructure projects are of concern. Even though there are numerous case studies associated with BIM use in building projects, previous studies have failed to focus on BIM utilization in mega size infrastructure projects. In this respect, this study presents a case study on a mega size airport project—Istanbul Grand Airport

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(IGA) Project—to depict a clear picture of BIM applications via demonstrating the challenges and enablers that were encountered throughout the project management process.

106.2 Background

National Institute of Building Sciences buildingSMART alliance (2007) defines BIM as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward." During the feasibility, planning, and development phase, BIM provides owners with information about the current state of the facility and generates information for analysis. During design and construction, BIM primarily supports information capture, communication, coordination, and construction. During the operations phase, BIM supports the performance monitoring of a facility and its systems [14]. BIM offers a holistic approach to construction management by creating and updating all necessary information in a digital environment and their reuse by responsible parties any time during a construction project's life cycle. Thus, it introduces a shared, interdisciplinary team experience and lifecycle evaluation concept to the highly fragmented AEC industry.

Smart Market Report on the trend of BIM use for infrastructure projects published by Dodge Data Analytics state that BIM users at a high level of implementation (on at least half of their projects) grew from 20% in 2015 to 52% in 2017 [11]. The forecasts show that between 2017 and 2019, there will be dramatic increase in BIM implementation among those deploying BIM on nearly all (75% or more) of their projects [11]. In the report, respondents determined the top benefits—that improve process and project outcomes—of BIM utilization for transportation infrastructure projects, as reduction in conflicts/field coordination problems, greater cost predictability, better understanding of project, improved schedule, and design optimization.

Ozorhon [15] proposed a framework to analyze project-based innovation in construction. The framework involves interacting components of innovation, where the rate of innovation is influenced by challenges and enablers that act as either negative or positive factors. In this research, these two components are investigated to better understand the BIM implementation as a digital innovation. Enablers can be described as major tools/strategies employed to realize innovation such as collaborative partnering, supportive work environment, leadership, commitment, knowledge management practices, reward schemes, innovation policy; whereas challenges are the primary factors that inhibit innovation such as unsupportive organizational culture, lack of financial resources, unwillingness to change, financial risks, temporary nature of projects, lack of collaboration among project partner [15].

Main enablers and challenges are identified specific to BIM implementation based on an extensive literature review. Enablers are collaborative working environment, advanced project monitoring and controlling system, BIM tools, and BIM Policy; whereas the challenges are lack of financial resources, lack of clear benefits, unsupportive organizational culture, lack of experienced BIM professionals, lack of awareness, lack of governmental support, and level of project complexity. Explanations and relevant sources for those factors can be found in Tables 106.1 and 106.2.

Similar to the enablers, main challenges of BIM implementation are also listed with their descriptions in Table 106.2.

Table 106.1 Enablers of BIM implementation

Enabler	Description	Source
Collaborative working environment	BIM integrates all stakeholders in a virtual environment to facilitate a collaborative working environment	[1, 3, 6, 14]
Advanced project monitoring and control system	BIM controls the subcontractors and eliminates any unforeseen cost over-runs while reducing waste on site as cost, time and quality	[8, 14]
BIM tools	Advanced digital tools provide rapid access to real-time project data	[1, 5, 8]
BIM policy	Companies' BIM strategies (e.g. BIM execution plans, workflows) and government mandates lead to increase in project individuals' awareness towards BIM use	[10]

Table 106.2 Challenges of BIM implementation

Challenge	Description	Source
Lack of financial resources	BIM utilization requires a significant initial investment due to high costs of sophisticated digital tools (e.g. BIM software, mobile tablets etc.), and education/training	[2, 5, 11]
Lack of clear benefits	It is hard to confirm that the realized benefits outweigh the costs of BIM implementation	[5, 13]
Unsupportive organizational culture	BIM implementation requires a change in technology and business process which may not easily aligned with organization's culture and capabilities based on the competencies of employees and technological assets	[5, 12]
Lack of experienced BIM professionals	Especially developing countries struggle with the socio-economic and technological environment that hinders the research and development so that the increase in qualified personnel	[9, 13]
Lack of awareness	Organizational awareness of the importance of BIM implementation is a critical factor for BIM maturity level which refers to the quality, repeatability and degree of excellence within BIM capability	[12, 19]
Lack of governmental support	There should be BIM policy dictating a systematic and standardized approach for BIM implementation together with incentives	[12, 13, 18]
Level of project complexity	BIM users having insufficient experience might have significant coordination problems while trying to implement BIM for highly complex projects	[17]

106.3 Methodology

This research adopts a qualitative methodology, in which a case-study approach is followed through semi-structured interviews for data collection. Case studies try to answer the how and why questions in research, allowing a more in-depth analysis [21]. There are four quality measures required to conduct case studies, as explained by Yin [21]: (1) construct validity, i.e., the quality of conceptualization or operationalization of the relevant concept; (2) internal validity, i.e., the causal relationships between variables and results; (3) external validity, i.e., the extent to which the findings can be generalized; and (4) reliability, i.e., repeatability with the same results.

In order to improve the validity of the case study, several strategies—such as focus groups, review of documents, and interviews—are employed as suggested by Yin [21]. Thus, this study adopts an exploratory case study in which the objective is to produce generalizations about BIM implementations in a mega-size infrastructure project through two components of construction innovation process framework. According to Scapens [16], main steps in a case study are as follows: preparation; collecting evidence; assessing evidence; identifying and explaining patterns; and report writing. In this study, similar approach is adopted. Accordingly, multiple key BIM users in the IGA project were interviewed to learn about the corporate policies and strategies regarding BIM implementation. The interviewees' roles and responsibilities are presented in Table 106.3 and the interview questions can be found in Table 106.4. Additionally, project documents related to the case study were compiled to be used in the analysis of enablers and challenges of BIM implementation. A case library has been created in order to allow repeatability of the study. Triangulation-which includes short descriptions of BIM journeys in Heathrow Airport and Denver International Airport (DIA) is also conducted to validate the claims made throughout the study. London Heathrow Airport has been using BIM since 2004 [14]. A case study was conducted on its BIM use during a 2008 airport terminal 5 project and it stated a high rate of direct savings related to its approach [14]. Also, DIA began to implement BIM in 2010 with its hotel and transit center project [4]. DIA's BIM model based approach leads to a faster construction pace with coordinated project timelines and effective collaboration around a central model [4].

Istanbul Grand Airport (IGA) is an international airport which has been under construction since 2015 in Arnavutkoy district on the European side of Istanbul, Turkey. IGA targets to be the largest airport in the world with 3 terminals, 6 runways, and an annual capacity of 200 million passengers. The project scope encompasses four phases. The first phase, that is planned to be completed in 2018, includes construction of 3 runways, a terminal with 5 piers with an area of 1.3 million m^2, and a carpark with an area of 700 m^2, and other site wide facilities. Based on the trend of rising passenger and air traffic

Table 106.3 Interviewees' roles and responsibilities

Interviewee	Role
BIM director	– Creation and execution of BIM strategy – Reviewing, monitoring and approving overall BIM process – Managing and providing necessary support for BIM implementation on the overall project – Reporting BIM delivery to the CEO and the board of the client
BIM manager	– Maintaining the BIM execution plan – Attending weekly BIM coordination meetings and BIM workshops – Performing regular QA/QC checks on discipline models to ensure compliance with project BIM standards – Ensuring the BIM project execution plan is followed through the project duration on a daily basis
BIM engineers	– Establishing communication between disciplines and BIM production team –Following RFI and clash procedures – Managing Vault and Buzzsaw environments – Ensuring up-to-date project information is transferred to BIM production

Table 106.4 Interview questions

Interview questions
Could you tell us about the airport project scope?
What are the key performance indicators?
Could you tell us about your role in BIM execution at the IGA project?
Could you tell us about the development of BIM plan from the conceptual stage?
Could you tell us about how BIM is applied at the IGA project?
How will BIM be used over the lifecycle of the airport?

movements to and through Istanbul (as current international airport—Ataturk Airport—is operating at or beyond its maximum capacity), IGA is considered as a potential world hub for international travel.

To actualize a fast track, mega scale project, like the IGA Project, in a time and cost efficient way; an innovative project delivery system—which could enable integration and control of all project individuals at all times—was required. Accordingly, it was decided to utilize BIM applications at its all dimensions (3D–7D) throughout design, engineering construction, and operation phases. Overall, BIM Plan of the IGA Project follows a fundamental strategy of providing digital transformation together with cultural change, which is basically bringing people, and technology together, in a single virtual platform.

106.3.1 Challenges

There are mainly two categories of problems that are encountered in the project, including engineering and managerial issues. These two categories associated with the challenges include lack of experienced BIM professionals, level of project complexity, and lack of awareness.

Regarding engineering problems, clash resolution process related to coordination between mechanical, electrical, plumbing (MEP) systems and special airport systems (SAS) has become one of the major issues both in design and construction phase concerning a wide variety of project individuals. Managing the flow of request for information (RFIs) and incorporating the solutions, which have been generated from different discipline perspectives, represent a major engineering management problem.

An airport project, due to its nature requires much different and complex type of mechanical systems that need large areas to be placed and to be activated altogether (Fig. 106.1). Figure 106.1 can indicate the challenge of project complexity, as there is a cluster of various types of pipe, duct and cable tray systems (e.g. HVAC ducting; plumbing pipes; fire sprinklers, electrical and IT cable trays, and heating and cooling pipes) at different levels of the terminal building which require to be coordinated accurately to aid in practicality on site.

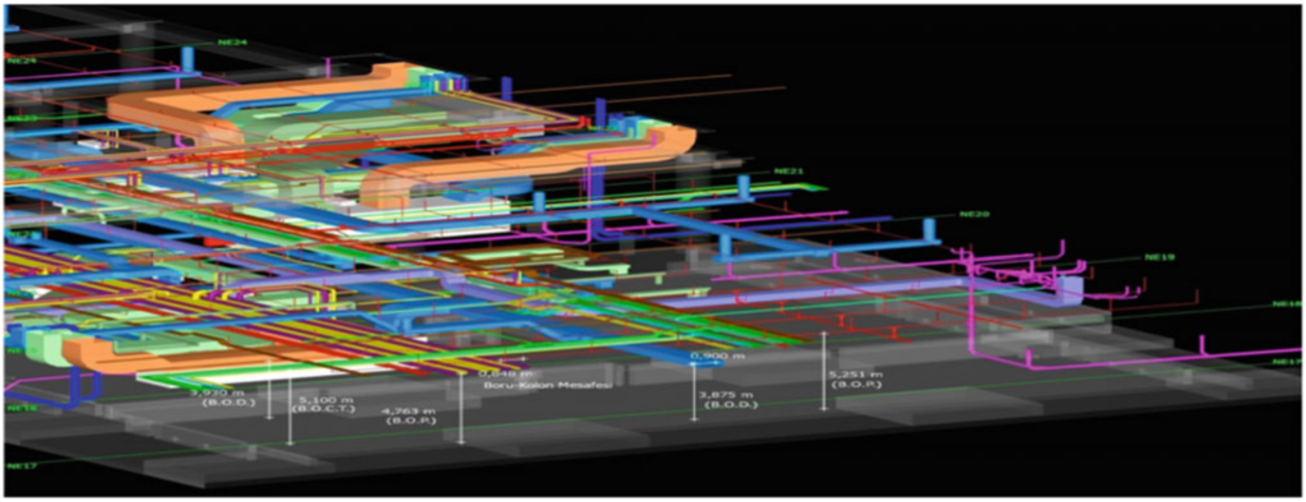

Fig. 106.1 Viewpoint of MEP systems

Moreover, baggage handling systems (BHS) placement has been a significant engineering challenge in IGA Project due to the requisite accuracy and the length (42 km) of the baggage routing. Initial engineering decisions are made upon for BHS systems' placement. Then, MEP systems including HVAC ducting, piping, electrical and IT cable trays are placed appropriately in architectural and structural envelope, and coordinated accordingly. However, because MEP subcontractors had limited experience in making interdependent disciplinary decisions in such a large-scale project, the coordination period included many conflicting iterative processes that needed to be defined and managed properly.

Regarding managerial issues, the major problem has been monitoring and controlling work on site. As far as the size and complexity of the project is concerned, managing all project individuals, mainly the subcontractors, becomes a very challenging issue that requires a substantial management plan. In the very beginning of the project, lack of awareness and experience of subcontractors and so that their resilient attitudes against engaging BIM process in their daily site and office work leaded to a necessity of training all subcontractors through facilitated workshops.

Not only the IGA Project case, but also the other aforementioned mega airport project case studies—Heathrow T5 and DIA expansion—bear similarities in managerial issues. Heathrow was firstly challenged by different project managers bringing different management styles and approaches to the project in the space of four years [7]. Secondly, it had space constraints which prevented co-location and full integration at the beginning of the project [7]. On the other hand, DIA mostly tackled the problem of reaching a consensus on collaboration in BIM environment [4].

All in all, achieving cultural change in complex projects is a struggling process. Incompatibility of site work with BIM model is one of the most crucial problems, because it has been known that the issues detected regarding discrepancies between coordinated BIM model and already manufactured zones on sites have potential to cause future coordination problems, waste and cost over-runs.

106.3.2 Enablers

To overcome the challenges faced throughout the implementation of BIM in this mega airport project, there are strategic control mechanisms including periodic BIM workshops for educational purposes.

It is essential to demonstrate how BIM is taken over to the subcontractor on site and how BIM leads to the installation work of subcontractor on site. There are control mechanisms provided by the pre-set BIM execution plan and strategy, and also BIM Workflow (Fig. 106.2) at the very beginning of the project; and via these mechanisms subcontractors are fully integrated into BIM environment. The BIM Department—that is represented as BIM Management Team in Fig. 106.2—is responsible of managing, integrating, and monitoring and controlling of the BIM model data input from project subcontractors of various airport design disciplines. BIM models are generated at different level of details and the concurrent engineering and design proceeds. Clash reports; 4D scheduling; reporting quality assurance and quality control (QA/QC) on site are provided BIM Department to have effective control mechanism on subcontractor's work. Weekly BIM workshops, and BIM coordination meetings are used as communication tools to oblige subcontractors to use BIM tools. Also, these BIM

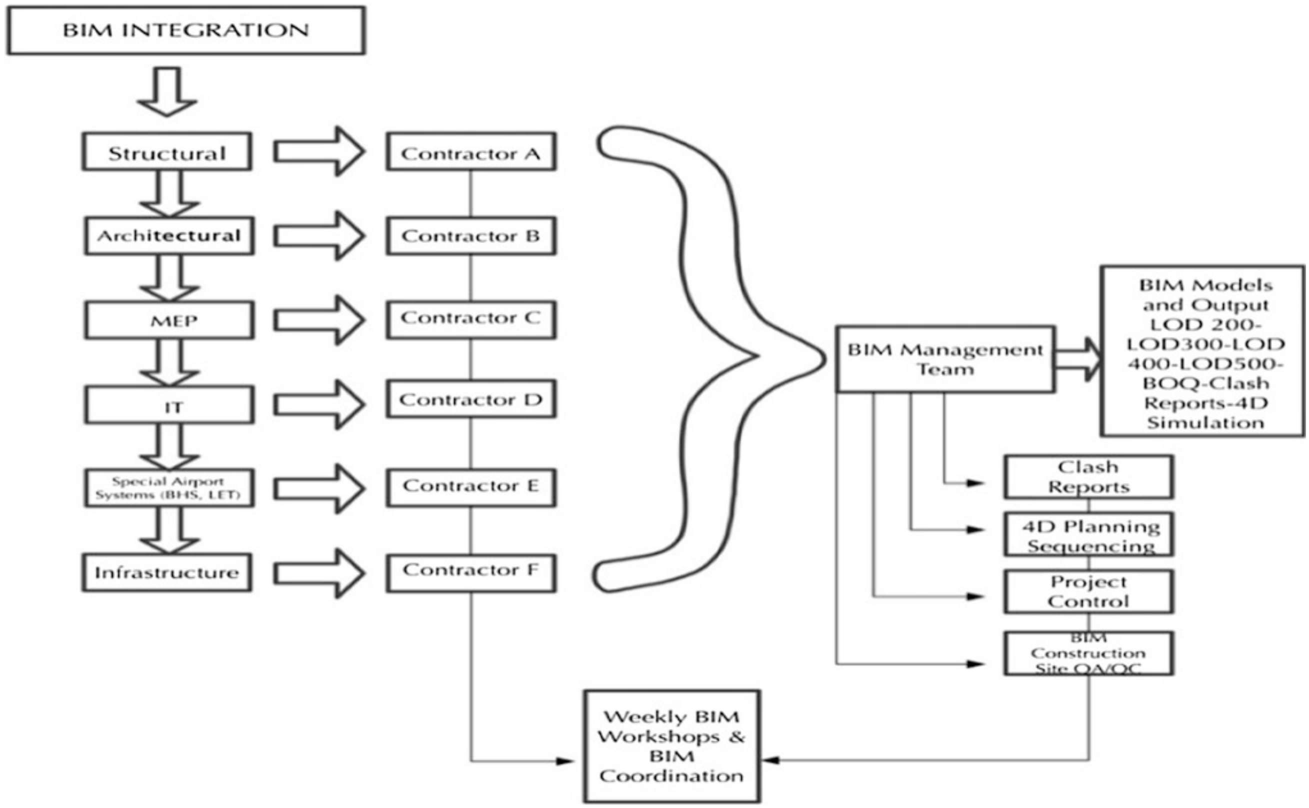

Fig. 106.2 IGA project BIM workflow

tools used to provide a cloud-based virtual platform for BIM integration are presented in Fig. 106.3. The use of these BIM softwares enables the IGA Project individuals to have controlled work—sharing, BIM coordination, design review, change visualization, quality management, and issue management, access to RFIs and submittals, and notification of inspection documents.

BIM policy of the company declares strict contractual obligations for all subcontractors to make them follow and utilize BIM process into their work processes such as using mobile tablets on site for filling out Notification for Inspection (NFI) Documents to get their progress payment. All coordination issues are detected on site by the client's BIM site engineers for each manufactured zone. The issues are reflected on Autodesk BIM 360 Field system periodically to track each subcontractor's performance on site. These reports are internally shared weekly so that BIM processes enhance the control mechanism. Accordingly, project parties who consist of the designers and subcontractors are led to get familiarized with

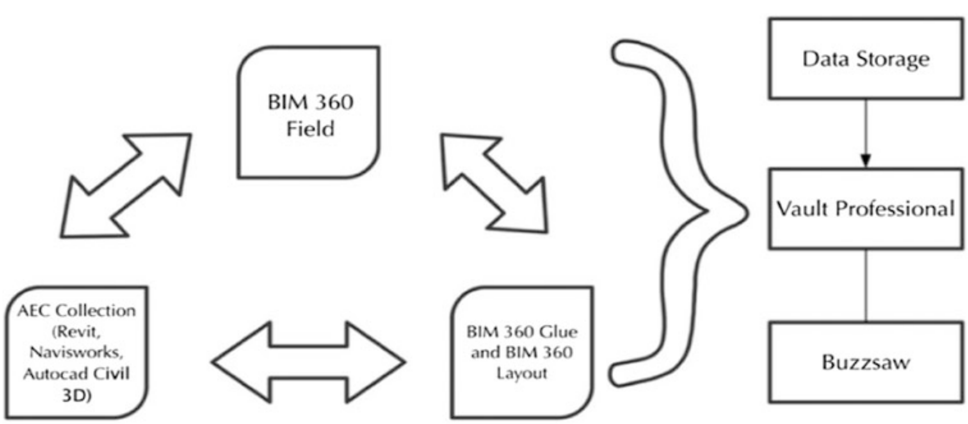

Fig. 106.3 IGA project BIM tools for virtual platform

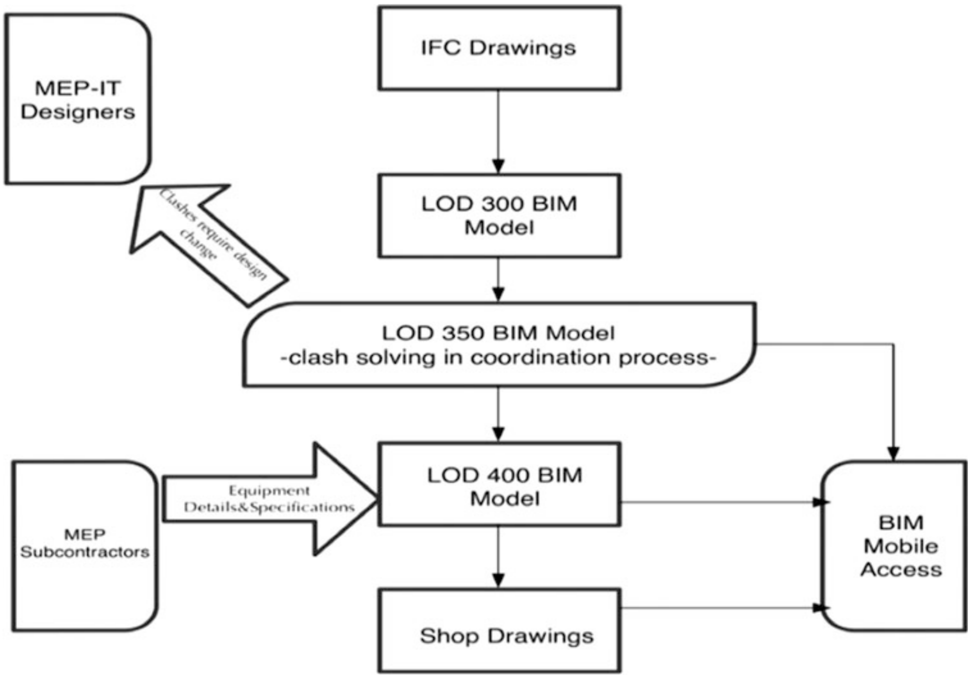

Fig. 106.4 MEP-IT coordination workflow

using the products of BIM in a harmonized fashion. For instance, on the site, there are 150 mobile tablets that provide all coordinated BIM models to the site engineers to assist them in carrying out zone wise production. Apart from 3D models, approved 2D shop drawings are also provided for the field via mobile tablets.

Along with the production on site, QA/QC is conducted with the help of digital documentation which supports cloud-based access for all related site engineers. All of these applications take place on Autodesk 360 Field platform. Additionally, a 4D model including 30,000 activities has been generated to track the progress on a daily and monthly basis to have dynamic control over the progress of the project.

Disciplined and zone-wise clash detection is utilized throughout design and construction phases. The frequency of clash detection and resolutions depend upon the frequency of design revisions. The airport systems integration is dynamically controlled via periodic clash detection. The periodicity is determined by the submission schedule of subcontractors. However, the BIM department determines and controls the coordination process of mechanical, electrical, plumbing and information technologies (MEP-IT) systems with a separate coordination workflow due to their highly complex nature in such a mega scale airport project (Fig. 106.4). The workflow depicts concurrent engineering and design in a fast track fashion and the responsible parties in this process. The main objective is to resolve the clashes in LOD 350 BIM level with MEP designers and proceed to the extraction of shop drawings out of the clash-free BIM model to push the work on site. The BIM model are continuously fed by various details such as equipment details and specifications throughout the workflow. Every update on BIM models and shop-drawings are shared in cloud system and made accessible via mobile tablets on site.

Heathrow and DIA also followed similar approaches to overcome the major challenges they faced to in the BIM implementation process. "Central to the delivery of T5 has been the concept of integrated teams" [7] indicates the enabler of collaborative working environment. On the other hand, BIM policy can be seen as the major enabler for DIA to be proactive in their BIM process as the project team stated "We tried to predict the obvious issues and create a number of workflows to help solve those problems before they arose" [4].

106.4 Conclusion

Implementation of BIM in the airport projects significantly differentiates from the typical applications of BIM to new building construction in which the focus is on design and construction of a lone building. BIM use for airport construction requires more complex BIM implementations compared to buildings, because the airport design and construction incorporate a varying mix of infrastructures including terminals, runways, passengers' gates, car parks and transportation systems including railways and roads so that an airport construction project comprehensively covers the aspects of those different construction types. In the case study, BIM is being used from the early briefing and concept design through detailed design and construction phases. Since the project stakeholders have recognized the crucial benefits and advantages of using BIM that make concurrent design and construction possible, it has been also decided to use BIM in the facility management phase after the completion of the construction. Essentially, it is realized that BIM has a significant impact on the following matters: power of having authority on subcontractors while managing the work and delivering on site; improving quality of design and construction stage; reducing waste both on site and office; fast resolution of issues on site; enhancing collaborative work.

Holistically, the research proposes a systematic way of assessing the BIM applications via two components of innovation framework that are enablers and challenges. Even though the success of the BIM implementations can not be quantified at this stage since the IGA Project is still ongoing, via referring to previous studies in the literature and similar real life case studies on completed projects, one can conclude that BIM—as construction innovation—brings benefits at all levels. The interviews, observations, analysis of documentations show that even though introducing cultural change is difficult to achieve, the willingness of the project team members to integrate their work on BIM platform overcomes the barriers.

For further studies, to deepen the discussion of BIM implementation measures, a comparative analysis of two case studies from different geographies encompassing similar type and scale of infrastructure projects may be conducted; and same framework for analyzing innovation in construction may be used.

References

1. Arayici, Y., Egbu, C.O, & Coates, S.P.: Building information modelling (BIM) implementation and remote construction projects: issues, challenges, and critiques. J. Inf. Technol. Constr. **17**, 75–91 (2012)
2. Autodesk. (2016). Achieving Strategic ROI Measuring the Value of BIM. Autodesk
3. Azhar, S.: Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. Leadersh. Manag. Eng. **11**, 241–252 (2011)
4. Ball, M.: Denver's Airport Expansion Primes a Push Toward BIM for Facility Management. Retrieved June 2018, from Informed Infrastructure (2015). https://damassets.autodesk.net/content/dam/autodesk/www/case-studies/denver-international-airport/dia-bim-for-facility-management.pdf
5. Barlish, K., Sullivan, K.: How to measure the benefits of BIM—A case study approach. Autom. Constr. **22**, 149–159 (2012)
6. Becerik-Gerber, B., Rice, S.: The perceived value of building information modeling in the U.S building industry. J. Inf. Technol. Constr. **15**, 185–201 (2010)
7. Brady, T., Davies, A., Gann, D., Rush, H.: Learning to manage mega projects: the case of BAA and heathrow terminal 5. In: IRNOP VII project research conference, Xi'an, China, 11–13 Oct 2006
8. Bryde, D., Broquetas, M., Volm, J. M.: The project benefits of building information modelling (BIM). Int. J. Project Manag. **31**, 971–980 (2013)
9. Bui, N., Merschbrock, C., Munkvold, B.E.: A review of building information modelling for construction in developing countries. In: Creative Construction Conference 2016, pp. 487–494. Elsevier, Budapest (2016)
10. Chang, C.-Y., Pan, W., Howard, R.: Impact of building information modeling implementation on the acceptance of integrated delivery systems: structural equation modeling analysis. J. Constr. Eng. Manag (2017)
11. Jones, S., Laquidara-Carr, D.: The Business Value of BIM for Infrastructure 2017. Dodge Data & Analytics, Bedford (2017)
12. Khosrowshahi, F., Arayici, Y.: Roadmap for implementation of BIM in the UK construction industry. Eng. Constr. Architectural Manag. **19**, 610–635 (2012)
13. Li, H., Wang, Y., Yan, H., Deng, Y.: Barriers of BIM application in China—preliminary research. In: ICCREM 2016, pp. 37–41. ASCE, Edmonton (2016)
14. McCuen, T., Pittenger, D.: Building Information Modeling for Airports. The National Academies Press, Washington, D.C. (2016)
15. Ozorhon, B.: Analysis of construction innovation process at project level. J. Manag. Eng 455–463 (2013)
16. Scapens, A.W.: Researching management accounting practice: the role of case study methods. Br. Acc. Rev. **22**, 259–281 (1990)
17. Senescu, R.R., Aranda-Mena, G., & Haymaker, J.R.: Relationships between project complexity and communication. J. Manag. Eng 183–197 (2013)
18. Shibeika, A., Harty, C.: Diffusion of digital innovation in construction: a case study of a UK engineering firm. Constr. Manag. Econ. **33**, 453–466 (2015)
19. Succar, B., Sher, W., Williams, A.: Measuring BIM performance: five metrics. Architectural Eng. Des. Manag 120–142 (2012)
20. Tatum, C.B.: Organizing to increase innovation in construction firms. J. Constr. Eng. Manag. **115**, 602–617 (1989)
21. Yin, R.K.: Case Study Research. Sage Publications, Thousand Oaks, California (2003)

107 Virtual Learning for Workers in Robot Deployed Construction Sites

Soyoung Moon, Burcin Becerik-Gerber, and Lucio Soibelman

Abstract

This paper provides various aspects to consider during the creation of a novel virtual learning environment (VLE) for the education of construction workers interacting with robots. First, the characteristics of existing VLEs in the construction industry, including user interface, navigation method, content, and procedure of learning were reviewed. Several drawbacks of existing environments were identified during the review. Then, the novel features of VLEs in other industries were investigated to find what can be incorporated in the VLEs for the construction industry to mitigate the drawbacks. The existing VLEs in various industries do offer novel features that can be adapted for robot-included work-site trainings and education. However, the construction industry has specific characteristics that are unique and therefore the construction industry-specific characteristics need to be considered when adapting the features of other industries' VLEs.

Keywords

Virtual learning for construction • Human-robot interaction • Construction robots

107.1 Introduction

107.1.1 Background

Existing learning opportunities in the construction industry mainly consist of lecture-based classroom learning, text-based training materials, apprenticeships, hands-on training, and on-the-job training. Despite the ongoing efforts in worker education, more than 50% of the fatalities in construction are still reported to be due to "unskilled performance," which signifies the need in placing more emphasis on frequent and skill-focused worker education [1]. Since the existing classroom training efforts are mostly lecture based, they do not provide realistic experiences, and do not allow the workers to repeatedly practice the construction skills that they have learned [2]. Furthermore, classroom-based traditional learning does not provide workers the opportunity to build work-site adaptability since these traditional methods do not fully address the unstructured nature of construction tasks, the environmental dynamicity of work sites, and various team interactions [3].

Other traditional learning methods, such as hands-on training and on-the-job training, provide the workers the opportunity to practice construction skills using real construction equipment but these trainings are often too costly to be frequently and widely adapted [4]. Virtual learning environment (VLE) has been recently emerging as an alternative method of construction

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education [5]. Following the features described by Dillenbourg et al., the definition of VLEs in this paper is determined to be an interactive social learning space that contains information in the form that varies from text-based visual animations to 3D immersive reality [6]. Unlike the existing lecture-based education efforts, the virtual learning is expected to bring increased participation and engagement of learners [6].

107.1.2 Motivation

Among various topics in construction education, we focus specifically on the education for those working in robot deployed construction sites. For clarity, in this paper, robots are defined as machines that have the potential to be programmed to do multiple tasks with increased precision or productivity rates. With this definition, a remotely controlled demolition machine is a robot as its software allows a more precise positioning of the machine arm based on the task type. In comparison, a regular excavator is not a robot as it is not programmable and therefore, does not have the potential to better its performance without having a skilled operator. The motivation behind this specific focus is that, with the introduction of robots on construction sites, a reformation is expected. According to the McKinsey Global Institute's report, the construction industry has 47% of automation potential [7]. With this expected increased level of automation, construction sites will soon be incorporated with construction robots, such as bricklaying robots and demolition robots. However, this trend does not mean that construction robots will replace construction workers. The World Economic Forum (WEF) predicts that the construction robots, slowly integrated into the construction industry, will replace certain construction tasks, but not jobs entirely [8]. In other words, construction workers will soon work side-by-side or collaboratively with construction robots and will need to learn how to interact with various robots, which will require drastically different skills, compared to the current construction workers' skills. Currently, we lack the knowledge about how the interaction between construction workers and robots will work or what kinds of dangerous situations the workers can face. Therefore, educating workers through direct hands-on trainings can put the worker at risk and can be limited in terms of covering all the possible situations the worker might face in real work sites. VLEs on the other hand, can offer hands-on trainings in virtual settings and therefore, VLEs will not put the worker at severe risk and can cover a wider range of possible situations that can happen in real work sites. Considering these characteristics of VLEs, we chose VLEs as the main education method to focus on for this review.

107.2 Objectives and Research Questions

The objectives of this paper are to review the existing literature on VLEs for workers in robot incorporated construction sites, analyze the current level of development and adaptability, and suggest ways to improve. However, our search results did not yield any paper that was directly related to VLEs for construction workers working with construction robots. To accommodate this lack of relevant publications, the objectives were slightly modified. The updated objectives of this study are first, to review the existing literature on VLEs for workers in robot deployed work sites and second, to review the current VLEs in regular construction educations. With the result of the review, we discuss what should be considered, when incorporating the features of robot-included VLEs, to the construction VLEs. Specific research questions for this study are the following:

- What are the main characteristics of the existing VLEs in the construction industry? What visualization methods and user interfaces are used for VLEs in the industry? What are the drawbacks of current VLEs used in the industry?
- What are the novel features of human-robot interaction focused VLEs used in other industries? What are the features that can be adapted or improved upon?
- What features should be included in a VLE for workers in construction robot incorporated work sites? How should the current VLEs be improved to match the needs of the construction work sites?

107.3 Methodology

Based on our objectives, which are to review the existing literature on VLEs on robot incorporated work sites and to review and analyze the current VLEs used in regular construction education efforts, several keywords were selected for the literature search. The selected keywords for the review on existing VLEs on robot deployed work sites in various industries are,

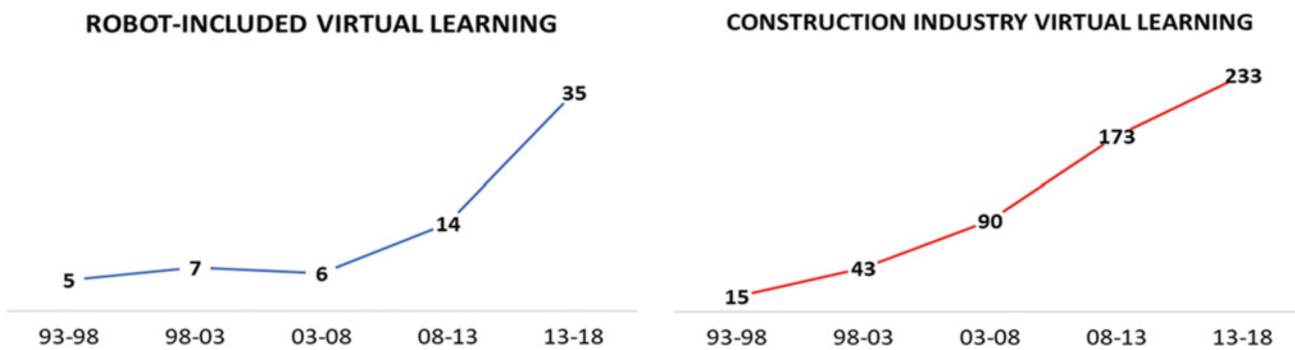

Fig. 107.1 Number of articles found in 5-year interval

"(train* OR educat* OR learn*) AND (virtual* OR virtual real*) AND (environment* OR tech* OR simulat* OR applicat*) AND (human-robot* OR human-machin* OR worker-robot* OR worker-machin* OR operator-robot* OR operator-machin*) AND (collaborat* OR interact* OR cooperat* OR team*)". The selected keywords for the review on existing VLEs in the overall construction industry are "(construct*) AND (job OR work* OR industr*) AND (train* OR educat* OR learn*) AND (virtual* OR cyber* OR virtual real*) AND (environment* OR tech* OR simulat* OR applicat*)". To focus on the most recent status of education environments, the timespan of 2008 to 2018 was used for the search. The year 2008 was chosen because for both keywords, on existing VLEs on robot deployed work sites in various industries and on existing VLEs in construction industry, the number of searched articles has significantly increased starting from 2008 (see Fig. 107.1). Using the selected keywords and timespan, a search was conducted on two main search engines: Web of Science and Google Scholar.

Web of Science was selected as one of the primary search engines for this review, considering its comprehensiveness in fields included in the library and its selectivity of the human-based publication inclusion process [9]. Comparatively, Google Scholar is a machine-automated database and is less selective than Web of Science. However, it includes the most recent conference papers. To include the VLEs that are developed most recently, Google Scholar was chosen as another main search engine.

The searched publications were then manually selected based on their titles and abstracts. The primary standards used for this selection process were, "Does the topic of this publication match the main topic of this paper: VLEs in robot incorporated industries and construction industry?" and "Can this publication be part of the answer to the research questions of this paper?"

After the above search and selection process, 37 papers [3, 4, 10–44] were included in this paper. 17 papers were about existing VLEs in construction industry and 20 papers were about robot/agent/machine-included VLEs in other industries. Overall, this review identifies what to adapt from the existing VLEs and what to further develop to match the specific needs of preparing construction workers for the future robot deployed construction sites.

107.4 Main Findings

107.4.1 Status of Virtual Learning Environments in Construction Industry

Several VLEs for the construction industry were reviewed [3, 4, 10–24]. Since the main purpose of reviewing existing VLEs in the construction industry is to find the main characteristics and the level of development of current VLEs, the user interface and visualization method for each environment were identified as the main features to focus on in terms of technological aspects of virtual learning. It was found that 52.9% of the VLEs in the construction industry included in this paper use static PC monitor as the visualization method along with mouse and keyboard as the user interface. PC monitor with mouse and keyboard however, does not provide the user the feeling of being immersed in the VLE, which can make learning less engaging and thus, having PC monitor as visualization method does not offer a learning experience that matches the level of real-life hands-on trainings [45]. Another type of VLE used in the construction industry is a "power wall". 17.6% of papers on VLEs in the construction industry included in this paper use power walls and similar physical platforms [3, 14, 15]. A power wall is a wide, large-sized virtual environment screen that surrounds the environment of the users, who are wearing active see-through glasses. With the increased immersiveness, power walls make learning more realistic [25] and worker-friendly [37]. It was also found that increased immersion has positive effects on increasing learner's motivations and helping learners remember the material better in the long term [46]. Although the power wall environments provide enhanced immersive experiences, one drawback of the current learning programs is that they only allow third-person views. A third-person view in VLEs allow the users to see not just parts of their bodies but also their full-body as avatars. In third-person views, since the users can see the motions of their whole bodies, they can be more aware of their postures, gestures, and proximity to other workers and machines [47]. Although having this view is important in robot-included VLEs for the users' enhanced understanding of the consequences of interactions with virtual robots, in third-person views, the users consider themselves to be apart from the avatar and therefore, the users will not feel like they are present in realistic training simulations [27, 28].

Another 17.6% of VLEs in the construction industry, included in this paper, use Head Mounted Displays (HMDs) as the platform for learning environment [21–23]. Unlike the power wall, the currently developed construction education environments with HMDs mostly support only first-person views. First-person views in VLEs display only the parts of the users' bodies, similar to what the users would see in real life. In other words, the users will not see their entire bodies or what is happening behind them unless they turn around. First-person views increase immersiveness but do not provide the users the sense on how the users are interacting with other workers [21, 22]. In terms of user interface, the existing HMD-based environments mostly use handheld controllers or keyboards as their navigation and user-interaction tools. Not having a freedom to navigate and interact with the environment without the controller means that the users will have to focus on the environment itself while learning, which can scatter their attention, make the learning environment less immersive and less natural [48].

In terms of content of virtual learning, 88.2% of construction industry VLEs, included in this paper, are in the format of tutorial-like games [3, 4, 12–24]. Although the games provide different levels of difficulties and example scenarios, these VLEs are only focused on the acquisition of a specific skill or on safety training in pre-determined conditions [13, 14, 19, 20]. Therefore, these environments do not provide any interactive scenarios where the learner collaborates with other workers. If these environments were to be used for robot-included virtual learning, the lack of interactive scenarios would be a drawback because learning how to work with or sharing the same space with robots requires interaction between the user and the virtual robots and virtual avatars. One environment included in this review provides interaction with virtual machines but does not offer collaborative interaction between the user and other workers represented as virtual avatars [18].

In terms of learning procedures, although VLEs can offer activity-based learning, only 11.8% of environments included in this review [19, 20] utilize learning while doing activities. The majority of environments still follow the traditional sequence of learning the material and skill sets based on virtually-provided lectures or texts and then applying the already learned material to examples that are not as complex as on-site situations [10]. Considering that construction workers are adult learners who are experienced and self-directed, one of the drawbacks of the current VLEs in construction industry is that it is hard to correlate the immediate relevance between what the workers learned and what the workers will need on-site [49].

In terms of focus of the existing VLEs in construction industry, 76.5% of papers included in this review have environments that focus exclusively on safety [3, 4, 10, 12–17, 20, 22–24]. Some specific topics are safety inspection and hazard identification. For robot-included VLEs in construction, interactive skill learning as well as safety will be necessary topics to cover [50].

107.4.2 Advancements of Virtual Learning Environments on Robot Incorporated Work Sites

Several robot-included VLEs in other industries including the manufacturing and mining were also reviewed [25–44]. To answer one of the main research questions, the novel features of human-robot interaction-focused VLEs were identified. One characteristic unique to the robot-included VLEs, was that 35% of these environments were interactive scenario-based [27, 28, 33, 37, 39, 42, 43] and therefore, promote "learning while doing." For example, "beware of the Robot" is a heterogeneous VLE in the manufacturing industry that lets the user complete a tape-laying task in collaboration with an industrial robot. This environment goes further than simply showing the user how to interact with robots and puts the user in different scenarios, helping the worker build the necessary safety-related situational awareness near robots. In addition, 55% of the robot-incorporated environments included in this review offer interaction between the robot and the user as the main content [25–27, 30–35, 42, 43].

In terms of technological features, only three of the environments included, in this paper, offer both first-person and third-person views to the workers and give the users the freedom to choose the view that fits the purpose of learning [11, 13, 27]. Although not commonly adapted yet, these three environments can serve as good references when creating a VLE that provides both views to the users. Moreover, 25% of existing robot-included VLEs are controller-free and let the users navigate freely, using a motion-sensing device. If adopted, the mentioned features have the potential to solve the identified drawbacks of current VLEs in the construction industry. However, these features should not be simply re-used. Instead, they should be carefully adapted, considering the specific conditions of the construction industry.

In terms of other characteristics of existing VLEs, 80% of the robot-included VLEs in this review, require the user to be stationary, either sitting down or standing up, wearing an HMD [25–36, 41–44]. Some environments allow walking, but only a few steps [37–40]. In addition, 90% of robot-included VLEs in other industries have only one or no virtual avatar present in the environment [25–36, 39–44]. In terms of displayed environment, 80% of robot-included VLEs in other industries are based on indoor environments [25–27, 29, 31, 32, 34–40, 42–44].

107.5 Discussion

Adapting the useful features of the most recent technologies used in VLEs in other industries can be the first step in advancing VLEs in the robot deployed construction industry. However, when adapting such features, unique characteristics derived from worker-robot interaction need to be considered.

First, utilizing both first and third-person views and providing the learners the freedom to choose the view that suits the purpose of learning are recommended. First-person views are useful for learning equipment controls but do not provide the learners, a sense on their interaction behaviors. Third-person views, on the other hand, are less immersive but provide full body views for the learners and are useful for learning dynamic interaction behaviors.

Second, implementation of controller-free navigation system is recommended for increased diversity of interactions. When workers control or assist robots, the workers oftentimes walk around the robots to see the robots' movements. Considering that the learners will be equipped with robot controllers, having another controller for navigation can inhibit natural interactions between the robot and the learner.

In addition, unique characteristics of the tasks and sites in the construction industry need to be considered. Even the environments with above features have a drawback that the virtual objects in the environments do not have physical mass and therefore, the users cannot get any force feedback during operation. This will not accurately represent construction tasks with heavy and bulky materials.

Additionally, as shown in the findings, the majority of VLEs require the users to be stationary. User being stationary is not a major issue in other industries like manufacturing because manufacturing cells are not as spacious as construction sites. However, the construction work processes would require workers to walk around the site and interact with other workers and robots without the limitation of area size [50].

Furthermore, in most of the current VLEs, only up to one avatar is present, which does not fit the dynamic nature of construction tasks. The existing construction robots require collaboration of multiple workers. For example, for bricklaying robot SAM, a human worker needs to feed brick piles to the robot while another worker checks the quality of the wall joints [51]. Therefore, it is recommended for future VLEs to have a multi-avatar platform where virtual workers interact with human workers and robots.

Lastly, existing robot-included VLEs in other industries mostly show indoor environments and therefore do not provide displays of uneven surfaces and dust or weather conditions like glare, wind and rain. Since construction sites are usually outdoors and since even small effects, such as shadows can affect the realistic response of the user [41], the display conditions need to be enhanced.

107.6 Conclusion

In this paper, the existing VLEs in the construction industry, as well as robot-included VLEs in various other industries were reviewed. To summarize, the main technological drawbacks of the current VLEs are: (1) The current VLEs support either first-person or third-person view, but not both and do not provide the user the opportunity to choose the view that suits the specific learning purposes; (2) Even the most recently developed HMD-based environments require handheld controllers and lack free navigation, which reduces user's immersion to the environment. The main learning content-related drawbacks are: (1) The current VLEs are in the form of tutorial-like games and do not provide interactive scenarios; (2) Majority of VLEs follow traditional sequence of "learning before practicing" but for construction workers, "learning by doing" needs to be utilized; (3) The focus of the majority of existing VLEs is exclusively on safety but for robot deployed VLEs, interactive skill learning will also be an important topic to focus on. The identified drawbacks can be solved by adapting the novel features of robot-included VLEs in other industries. However, before the adaption of novel features, the dynamic and complex conditions of construction sites need to be considered.

References

1. Khodabandeh, F., Kabir-Mokamelkhah, E., Kahani, M.: Factors associated with the severity of fatal accidents in construction workers. Med. J. of the Islamic Rep. of Iran **30**, 469 (2016)
2. Kaskutas, V., Dale, A.M., Lipscomb, H., Evanoff, B.: Fall prevention and safety communication training for foremen: Report of a pilot project designed to improve residential construction safety. J. Saf. Res. **44**, 111–118 (2013)
3. Sacks, R., Perlman, A., Barak, R.: Construction safety training using immersive virtual reality. Constr. Manage. Econ. **31**, 1005–1017 (2013)
4. Wang, X., Dunston, P.S.: Design, strategies, and issues towards an augmented reality-based construction training platform. J. of Inf. Tech. in Const. (ITcon) **12**, 363–380 (2007)
5. Holt, E.A., Benham, J.M., Bigelow, B.F.: Emerging technology in the construction industry: perceptions from construction industry professionals. In: 2015 ASEE Annual Conference and Exposition, June 14–17. Seattle, Washington (2015)
6. Dillenbourg, P., Schneider, D.K., Synteta, P.: Virtual learning environments. In: A. Dimitracopoulou (ed.) Proceedings of the 3rd Hellenic Conference "Information & Communication Technologies in Education", pp. 3–18. Kastaniotis Editions, Greece (2002)
7. McKinsey Global Institute: A future that works: automation, employment, and productivity, January 2017. McKinsey & Company (2017)
8. Renz, A., Solas, M.Z., Almeida, P.R., Buhler, M., Gerbert, P., Castagnino, S., Rothballer, C.: Shaping the Future of Construction a Breakthrough in Mindset and Technology. World Economic Forum, pp. 1–64 (2016)
9. Claritive Analytics. Journal Selection Process, https://clarivate.com/essays/journal-selection-process/. Accessed 28 Apr 2018
10. Le, T., Pedro, A., Park, S.: A social virtual reality based construction safety education system for experiential learning. J. Intell. Rob. Syst. **79**, 487–506 (2015)
11. Goedert, J., Cho, Y., Subramaniam, M., Guo, H., Xiao, L.: A framework for virtual interactive construction education (VICE). Autom. Constr. **20**(1), 76–87 (2011)
12. Lin, K., Lee, W., Azari, R., Migliaccio, G. C.: Training of low-literacy and low-english-proficiency Hispanic workers on construction fall fatality. J. Manag. Eng. **34** (2017)
13. Zhao, D., Lucas, J., Thabet, W.: Using virtual environments to support electrical safety awareness in construction. In: Winter Simulation Conference, pp. 2679–2690 (2009)
14. Li, H., Chan, G., Skitmore, M.: Multiuser virtual safety training system for tower crane dismantlement. J. Comput. Civ. Eng. **26**, 638–647 (2012)
15. Zhao, D., Lucas, J.: Virtual reality simulation for construction safety promotion. Int. J. Inj. Control Saf. Promot. **22**(1), 57–67 (2015)
16. Fang, Y., Teizer, J., Marks, E.: A framework for developing an as-built virtual environment to advance training of crane operators. In: Construction Research Congress 2014: Construction in a Global Network, pp. 31–40 (2014)
17. Landorf, C., Ward, S.: The learning impact of a 4-dimensional digital construction learning environment. Int. J. Soc. Behav. Educ. Econ. Bus. Ind. Eng. **11**(5), 1158–1163 (2017)
18. Goulding, J., Nadim, W., Petridis, P., Alshawi, M.: Construction industry offsite production: a virtual reality interactive training environment prototype. Adv. Eng. Inform. **26**, 103–116 (2012)
19. Pour Rahimian, F., Goulding, J.S.: Game-like virtual reality interfaces in construction management simulation: a new paradigm of opportunities. In: 9th International Detail Design in Architecture Conference, U. of Central Lancashire, (November, 2010)
20. Nikolic, D.: Evaluating a simulation game in construction engineering education: the virtual construction simulator 3. The Pennsylvania State University (2011)
21. Rezazadeh, I.M., Wang, X., Firoozabadi, M., Golpayegani, M.R.H.: Using affective human–machine interface to increase the operation performance in virtual construction crane training system: a novel approach. Auto. in Constr. **20**(3), 289–298 (2011)
22. Froehlich, M., Azhar, S.: Investigating virtual reality headset applications in construction. In: Proceedings of the 52nd ASC (2016)
23. Lyne, D.S.: Development of virtual reality applications for the construction industry using the Oculus RiftTM head mounted display. In: N. Dawood, M. Kassem (eds.) Proceedings of the 13th International Conf. on Const. App. of VR, pp. 553–563. London, UK. (2013)
24. Luo, X., Wong, C.K., Chen, J.: A multi-player virtual reality-based education platform for construction safety. In: 16th International Conference on Computing in Civil and Building Engineering, pp. 1637–1643 (2016)
25. Lee, A., Yang, U., Son, W., Kim, Y., Jo, D., Kim, K., Choi, S.: Virtual reality content-based training for spray painting tasks in the shipbuilding industry. ETRI J. **32**, 695–703 (2010)
26. Bredl, K., Groß, A., Hünniger, J., Fleischer, J.: The avatar as a knowledge worker? How immersive 3D virtual environments may foster knowledge acquisition. Lead. Issues Knowl. Manage. Volume Two **2**, 222 (2015)
27. Monahan, T., McArdle, G., Bertolotto, M.: Virtual reality for collaborative e-learning. Comput. Educ. **50**(4), 1339–1353 (2008)
28. Orr, T.J., Mallet, L., Margolis, K.A.: Enhanced fire escape training for mine workers using virtual reality simulation. Min. Eng. **61**, 41 (2009)
29. Kenney, P.A., Wszolek, M.F., Gould, J.J., Libertino, J.A., Moinzadeh, A.: Face, content, and construct validity of dV-trainer, a novel virtual reality simulator for robotic surgery. Urology **73**(6), 1288–1292 (2009)
30. Van Wyk, E., De Villiers, R.: Virtual reality training applications for the mining industry. In: Proceedings of the 6th International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa, pp. 53–63. ACM (2009)
31. Watanuki, K.: Virtual reality based job training and human resource development for foundry skilled workers. Int. J. Cast Met. Res **21**(1–4), 275–280 (2008)
32. Altenhoff, B.M., Sewall, A.S., Shannon, B., Duchowski, A.T.: Effects of haptic feedback and stereoscopy on a surgical training task in virtual reality (2012)

33. Lucas, J., Thabet, W., Worlikar, P.: Using virtual reality (VR) to improve conveyor belt safety in surface mining. In: 24th W78 Conference Maribor 2007 & 5th ITCEDU Workshop & 14th EG-ICE Workshop: Bringing ITC knowledge to work, pp. 431–438 (2007)
34. Brough, J.E., Schwartz, M., Gupta, S.K., Anand, D.K., Kavetsky, R., Pettersen, R.: Towards the development of a virtual environment-based training system for mechanical assembly operations. Virtual Reality **11**(4), 189–206 (2007)
35. Bowyer, W., Streete, A., Muniz, M., Liu, V.: Immersive virtual environments for medical training. In: Seminars in Colon and Rectal Surgery, 19(2), pp. 90–97. Elsevier (2008)
36. Lucas, J.: Benchmarking user Performance by using Virtual Reality for task-based training (2007)
37. Grabowski, A., Jankowski, J.: Virtual reality-based pilot training for underground coal miners. Saf. Sci. **72**, 310–314 (2015)
38. Matsas, E., Vosniakos, G.: Design of a virtual reality training system for human–robot collaboration in manufacturing tasks. IJIDeM **11**, 139–153 (2017)
39. Smith, S., Ericson, E.: Using immersive game-based virtual reality to teach fire-safety skills to children. Virtual Reality **13**(2), 87–99 (2009)
40. Chan, J.C., Leung, H., Tang, J.K., Komura, T.: A virtual reality dance training system using motion capture technology. IEEE Transac. Learn. Tech. **4**(2), 187–195 (2011)
41. Slater, M., Khanna, P., Mortensen, J., Yu, I.: Visual realism enhances realistic response in an immersive virtual environment. IEEE Comput. Graph. App. **29**(3) (2009)
42. Gregor, M., Polcar, J., Horejsi, P., Simon, M.: Factory virtual environment development for augmented and virtual reality, World Academy of Science, Engineering and Technology. International J. of Computer, Elec., Auto., Control and Info. Eng. **9**, 2433–2437 (2015)
43. Giorgio, A., Romero, M., Onori, M., Wang, L.: Human-machine collaboration in virtual reality for adaptive production engineering. Procedia Manuf. **11**, 1279–1287 (2017)
44. Gomez, P., Willis, E., Van Sickle, R.: Development of a virtual reality robotic surgical curriculum using the da Vinci Si surgical system. Surg. Endosco. **29**(8), 2171–2179 (2015)
45. Jennett, C., Cox, L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., Walton, A.: Measuring and defining the experience of immersion in games. Int. J. Hum. Comput. Stud. **66**(9), 641–661 (2008)
46. Huang, H.M., Rauch, U., Liaw, S.S.: Investigating learners' attitudes toward virtual reality learning environments: based on a constructivist approach. Comput. Educ. **55**(3), 1171–1182 (2010)
47. Salamin, P., Thalmann, D., Vexo, F.: The benefits of third-person perspective in virtual and augmented reality? In: Proceedings of the ACM symposium on Virtual reality software and technology, pp. 27–30. ACM (2006)
48. Pasch, M., Bianchi-Berthouze, N., Van Dijk, B., Nijholt, A.: Immersion in movement-based interaction. In: International Conference on Intelligent Technologies for Interactive Entertainment, pp. 169–180. Springer, Berlin, Heidelberg (2009)
49. Knowles, M.S., Holton, E.F., Swanson, R.A.: The Adult Learner: The Definitive Classic in Adult Education and Human Resource Development. Routledge (2014)
50. Lee, S., Moon, J.: Introduction of human-robot cooperation technology at construction sites. In: Proceedings on 31st International Symposium on Automation and Robotics in Construction and Mining, ISARC 2014, pp. 978–983 (2014)
51. YouTube: National Science Foundation – Meet SAM, the bricklaying robot, https://www.youtube.com/watch?v=MVWayhNpHr0. Accessed 18 Apr 2018

108 Building Energy Modeling in Airport Architecture Design

Maria Antonietta Esposito and Alessandra Donato

Abstract

Energy efficiency and Building Energy Modeling are two successful approaches to architecture, engineering, construction and operation (AECO) programs. In recent year several education initiatives focusing on buildings energy management have been carried out to provide professional profiles with specific skills in technology, architecture, engineering, economics, management and environmental science. It enables them to plan, design, evaluate or research energy supply and design strategies aimed to reduce energy consumption according to sustainability concepts. Building energy performance optimization requires an integrated design approach to explore and evaluate different strategies for building energy saving and to assist in the decision making process along the life cycle including design, operation, management and decommission phases. Moreover, BEM (Building Energy Modeling) is increasingly being included into architecture and engineering curricula, introducing new methodologies and tools for architecture design to provide interdisciplinary profiles in the professional practice. The main objective of this contribution is to report the application of BIM technologies and BEM tools into the Environmental Design Lab training course at the School of Architecture at University of Florence, where the authors are involved into a cross-disciplinary teaching program which students undertake in the fourth year of their curriculum within the 5 years degree program.

Keywords

Building Energy Modeling • Multidisciplinary education • Architecture training program
Airport Terminal Design

108.1 Introducing BIM Technologies into Architecture Curriculum

Education plays a fundamental role in the development of the future sustainable society, providing training for architecture and engineering students of the next generation [1]. Over the past decade, universities worldwide have been looking for better ways to integrate environmental issues into architectural education.

Energy efficiency training in architecture needs to overcome many challenges that first of all include the unavailability of well-structured and integrated curricula [2].

More recently the transition from CAD (Computer Aided Design) to BIM (Building Information Modelling) made it possible to apply building-performance analysis methods as part of the design collaborative process.

BIM technologies have been integrated into traditional architecture and engineering university training programs, focusing on generic topics related to sustainable architecture design, building energy efficiency, renewable energies, and computing technologies to sustainable practices [3].

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In several countries BIM courses have successfully implemented in AEC programs but they are mainly focused on 3D modeling skills as well as analysis tools of particular BIM software packages considering the benefits of BIM in sharing and simulating construction information. However, this approach appears to be a barrier to the successful integration of BIM technology in education, and students will not be able to fully understand the BIM management workflow in a construction project [4].

BIM is a helpful teaching tool for construction estimation and quantity take-off skills and highly contribute to design comprehension skills and understanding of construction materials, methods, and processes [5].

BIM helps stakeholders involved at different stages of the design process to interact remotely and to use real-time data solving any conflicts since the early stage of the project, improving working efficiency, estimates accuracy, decision-making and project schedule [6, 7]. BIM is a very complex concept, which leads to a collaborative work environment, and creates an easier approach to the universal access of the architectural information, due to the creation of a federate model characterized by a common data environment [8].

In Italy, BIM design process is mandatory from 2019 for all public building projects above 100 million. To satisfy the AECO industry improved skills requirements, more and more universities are providing BIM courses within AEC programs at different levels of implementation. Typical BIM courses offered in the Italian universities consisting in BIM training computer Lab for students. However, this education is oriented towards the use of particular BIM software packages, with little consideration to BIM Management (BIMM), process and methods. Few University like the University of Parma, the University of Brescia and the University of Naples have successfully implemented BIM classes in their curriculum highlighting BIM information requirements, approaches, rules and regulations, workflows, building modelling, project management and execution plan using BIM.

As best practice, the Polytechnic University of Milan offers an Integrated Project Management and Design Tool with a lab activity to help students to practice with project management activities on a BIM based project. Information are the main value in modern construction processes and students will be shown how to manage these information starting from the very early stage of the design process using BIM and the latest design tools.

The University of Brescia focused on Project Management practice using BIM and construction phase as well as built augmented information.

The University of Parma implemented a BIM Lab divided in two modules within the Environmental and Land Management Engineering degree focusing on BIM methodologies and structured in a series of laboratory experiences including Building energy analysis topics and BIM tools for the building energy certification.

The Environmental Design Lab Training Course at the School of Architecture at University of Florence developed a new course integrating BIM contents and building performance simulation tools that aims to help students to better understand the BIM workflow in a construction project and use BIM to manage the construction process.

The challenge for the authors is to encourage the connection between university and industry, training students who will provide advice and assistance to future customers understanding what skills are needed in the industry to facilitate graduated employment. This work aims to show the effects on the introduction of new BIM-teaching methods on students experience reporting pedagogical strategies, training methods, timelines and tools with specific reference on their implication and effectiveness on students motivation, satisfaction and performance.

108.2 Environmental Design Lab Training Course

108.2.1 Program and Topics First Section

BIM methodology, based on parametric modeling, is helpful to share knowledge resources and information with the aim to facilitate communication between investors, professionals and contractors.

Architecture curriculum at Florence University has already integrated BIM contents in several computer application courses focused on 3D modeling and energy simulations software, providing basic and intermediate knowledge on BIM and energy tools. However, none of these courses introduces BIM technology as an interdisciplinary coordination process oriented to building design, construction, use and decommissioning accordingly with the life cycle view.

As a result, the main objective of this contribution is to show how BIM technologies and BEM tools can be integrated into architecture program as a process instead of a modeling tools or software.

The reported experience concerns the Environmental Design Laboratory Training Course (12 ECTS) at the School of Architecture at University of Florence, which consists of two modules:

- Building Systems Design Module
- Environmental Control Strategies Module.

The Building Systems Design Module focuses on building envelope design technologies. The study is applied to the field of Airport Architecture Design and it has been structured with reference to some key issues in the sustainable approach both in the airport planning and terminal design, life service in operation and looking forward it's evolution and end of life as well [9].

The lab adopts applicative methods and BIM tools according to European Directive 2014/24/EU and D.Lgs.560/2017 italian law, that require the use of BIM procedures and digital processes in the construction of public buildings.

Environmental Control Strategies Module aims at educate and train students in the use and development of competitive skills and tools for energy efficiency and sustainable approach design in a life-cycle perspective focusing on building envelope technology [10]. Furthermore, by using energy BEM technologies into an integrated approach to the design process, students are able to evaluate alternative design solutions contributing to decision making at the early stages design process and improving the whole building construction quality into an interdisciplinary perspective [11].

Both modules are carried out simultaneously into a cross-disciplinary teaching program with the trainers co-presence.

The course runs over a year, and topics were developed to match the objectives of both modules and were scheduled based on 2 semesters with a 4-h class per week, mixing both short theoretical lectures and workshop sessions.

The course involved 45 students who are in the fourth year of their Architecture curriculum divided into 15 groups of 3–4 members.

As case of study, students are required to redesign extension of the Genoa Airport Passenger Terminal and to identify design solutions for building envelope, which are appropriate to energy performance targets set by building components technical specifications and materials certification. In order to be able to create their own project proposal, students are required to study the construction details up to the scale of components, their properties, technical specifications and application methods.

During the course students are introduced to different Best Practices in the field of Airport Terminal Design and to the most innovative solutions for envelope technologies currently available within the construction market such as high performance glass facades, textile and metal roofs, shading systems, integrated PV technologies, etc.

108.2.2 Industry Involvement in Architecture Education

A fundamental aspect of the course concerns the direct involvement of the industry. The course is organized in close collaboration with experts from the civil aviation industry and managers from the Genoa Airport interested in airport development methodologies and design verification. Furthermore Genoa airport owners are direct beneficiaries of students design project outcomes, so they are involved at the early stage of the course providing technical documents, helpful and informative materials to students to carry out their assignments.

This type of partnership would be valuable not only for learning integrated practices using BIM, but mainly for bringing students in real-world projects establishing professional relationships, internships, and employment opportunities.

Professionals believe that interdisciplinary BIM processes and work-sharing and BIM-based communication are need to integrate such AEC competencies and to prepare students for internship and collaborative experience into a professional practice.

108.2.3 Course Objectives, Training Methods and Tools

The course objectives were developed to match the architecture curriculum needs in Building Systems Design taking into account building energy saving issues.

The main purpose considering the learning process is to improve students understanding in real-world professional experience, suggesting a training method applied in project-based scenarios.

Objectives course are listed below:

- *Objective* 1—educate students to the concept of BIM as a process and its applications in construction management;
- *Objective* 2—enable students to perform model-based planning, estimating, scheduling, coordination, and teamwork using BIM approach;
- *Objective* 3—carry out energy simulations analysis in project-based scenarios to solve sustainable design issues taking into account energy, environment, economic and social aspects.

Instructors carefully design course activities and materials to help students engage in experiencing and self-construction knowledge of BIM implementation workflows.

As a project-oriented course, instructors provided day-to-day coaching in a class to students in software use for the case study project. This approach is similar to on-the-job trainings in which students are involved in real-world projects under BIM experts' supervision.

Students are strongly encouraged to use building performance analysis tools and BIM technologies which are applied on the field to the Airport Architecture Design. As part of this work, students must to verify the existing building capacity to present peak day needs and to evaluate building spatial units by looking at the Levels of Service Analysis (LoS Analysis) according to IATA (International Air Transport Association) international standards. They were introduced to climate and site analysis tools to perform several simulation on a 3D environmental analysis model to address design of their project.

In addition, they were involved in practical workshops to integrate BIM concept with energy simulation tools for building performance analysis as contributing to decision making at the early stages design process and to improve the whole building construction quality into an interdisciplinary perspective. This approach can be used to select the best energy efficient design solutions and reduce the need for later design modifications that require extra time and cost.

The course program includes a series of activities which consist of lectures, presentations, computer labs and workshops. The training approach proposes a methodology structured on five stages listed in Table 108.1.

To realize a collaborative environment and class competition, students are required to work in team to exchange knowledge with other colleagues and to experience and learn collaboration, integration and teamwork.

Table 108.1 Summary on course structure and training methods

<table>
<tr><th>Program stage</th><th>Training methods</th><th>Assignments</th><th>Acquired skills</th></tr>
<tr><td>Airport design architecture and BIM processes</td><td>Lecture sessions
Group discussion</td><td>• Case study ID card + other 2 airports benchmarks
• Oral presentation on case studies</td><td>1. Know BIM regulatory framework (national and international)
2. Understand BIM process/ methods/tools
3. Investigate the state of the art on Airport Architecture Design</td></tr>
<tr><td>LoS (Level Of Service) analysis</td><td>Lecture sessions
Step by step instructions
Group discussion
Team work simulating Real-world professional practice</td><td>• Case study LoS analysis
• Oral presentation</td><td>1. Evaluate building spatial quality
2. Synthesize and report analysis results</td></tr>
<tr><td>Climate and site analysis</td><td>Lecture sessions
Software tutoring Lab
Step by step instructions</td><td>• Technical report
• Oral presentation</td><td rowspan="3">1. Analyze problems focusing on the objectives to be investigated
2. Learn how use software tools for parametric analysis and Interoperability
3. Apply BIM process/ methods/tools
4. Perform a model-based project evaluation
5. Synthesize and report analysis results</td></tr>
<tr><td>Building design modeling and energy simulation</td><td rowspan="2">Software tutoring
Project oriented course
Guest Lecturer for BIM approach
Team work simulating real-world professional practice
Lecture sessions
Software coaching</td><td rowspan="2">• BIM Project Case Study
• Oral presentation at final meeting</td></tr>
<tr><td>Technical solutions evaluation for building envelope</td></tr>
</table>

During a daily session, once instructor demonstrated how to use software tools solving case-specific BIM problems and providing a sequence of skill-building steps, then students followed step-by-step instructions to solve assignments on a series of interdependent problems. Step-by-step instruction, handouts and reading materials, video tutorials, coaching, and interactive simulations have been implemented as software tutoring methods in a physical class.

Also a virtual class has been created to facilitate group discussion and peer learning opportunities, and to raise stimulating topics for sharing knowledge and lecturing in class. Therefore students are required to sign up at Moodle online platform useful to publish announcements, news about the course program and assignments deadlines. Students need to use computers and tools, but also they need classrooms that facilitate team communication for improving interactions [12].

For integrated processes and teamwork, instructors turned classroom is a collaborative space simulating a real-world work environment, in which all teams collect information and make presentations to share their research activities and results with the whole class and facilitate work progress. This strategy appeared successful for modules integration and collaboration, simulating BIM processes and roles to create a collaborative learning for students with different skill and knowledge levels.

108.2.4 Assignments

Students have been involved in several activities in classroom to acquire critical-thinking abilities and practical experience working on a specific topic, developing a BIM execution plan through iterative design improvement cycles on a case study. Assignments have taken many forms considering the different stages of course program. As first team assignments, students carried out systematic analysis of Genoa Airport identifying two other benchmarks similar in terms of passengers traffic and size. By the end of first semester, working teams were asked to planning/designing a major expansion of Genoa Airport considering targeted LoS (Level of Service) analysis for the areas initial sizing. In order to investigate environmental issues, working teams performed a climate analysis on project site to identify strengths and weaknesses on design project, producing a short report to critically argue about different aspects of BIM implementation. In some cases individual assignments includes interviews, regulatory document analysis, BIM conference participation and students were asked to report results and observations to the classroom.

The final project, and the final presentation are useful to assess students ability to use BIM methods and sustainability approaches in project-based scenarios to develop more energy-efficient buildings (Fig. 108.1).

108.2.5 Assessment Methods and Students Evaluation

The course uses several assessment methods to provide the most useful and relevant information on students learning outcomes.

Direct assessments consist of tests, reports, assignments and presentations (individual or team). These methods report exactly what knowledge and skills students have acquired as a result of training course.

A weighted grading system was used to evaluate direct assignments outcomes according on inclusive criteria such as quality of technical contents, multidisciplinary approach, objectives achievement, clarity of work, graphics, communication and presentation skills, answering questions, and effort spent on teamwork.

Student work products have been reviewed throughout a year for evidence of learning during the course.

Students evaluation is based upon grading criteria depending on following factors:

- teamwork performance on final project and presentation at final workshop (up to 60%)
- participation in class discussions and training labs (up to 20%)
- assignments and oral presentations during the course (up to 20%)

Team-evaluation and peer assessment methods have been also used among student groups during classroom follow up on design project deliverables.

In addition to conventional assessment by instructors, working teams have been evaluated during a final Exam. Students presented their project proposals at a final exhibition "Redesigning GOA", a one-day workshop that took place at the end of the course at the Genoa Airport (Fig. 108.2). Experts from the civil aviation industry and professionals from the Genoa Airport have been invited to participate. Students have reported details of strategies they implemented in their project proposals: some students only listed their strategies without discussing the reasons of some choice and their impact on design

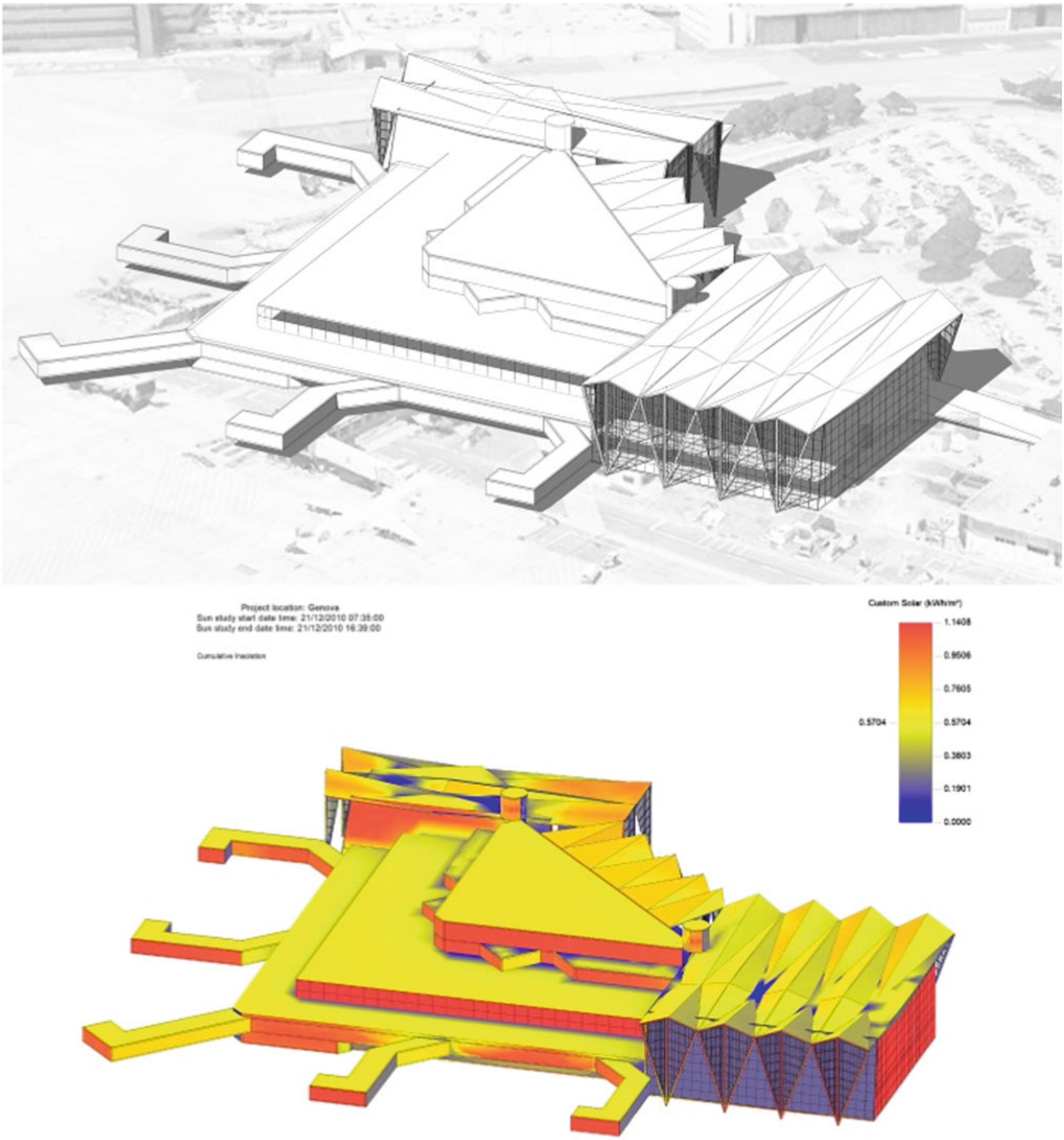

Fig. 108.1 Final Project: from BIM to BEM model of Genoa Airport expansion (Students: J. Amayou, G. Aspesi, D. Bufalo)

outcomes. Few students overcome this gap correctly interpreting client needs and showing results in a clearly and effectively way.

Assessments by professionals improved the learning experience of students leading to constructive comments on teams deliverables and outcomes. Authors initiative was so appreciated by the Genoa Airport General Manager, that led to internship opportunities for interested and qualified students who want to gain a general understanding of airport management and civil aviation industry.

Fig. 108.2 "Redesigning GOA" workshop and final exam at the Genoa Airport

108.3 Results

No data are available to evaluate quality course on students feedback and satisfactions before the end of the course. Students feedbacks on performance and quality of this cross-disciplinary teaching program will be available from surveys, interviews and online questionnaire designed for this course with rating and comments. This method includes a unified student rating of instruction used across the University of Florence to track the course results over time and improve overall course quality, including training methodologies and materials. Instructors monitored throughout a year percentages of students meeting the goal for each course objective to individuate successful strategies for future quality improvements. What appears is that the expected level of BIM competency for undergraduate students have reached intermediate levels on analysis, synthesizing, and evaluation abilities, while they still need to refine both technical and managerial skills.

Due to the high students number attending course, the main challenge into a cross-disciplinary perspective was to create a collaborative environment. This aspect requires more work for instructors to coordinate different tasks and to provide support to students which had more difficulties in learning from this kind of experience.

Authors believe that teamwork and classroom follow up are successful strategies to encourage students participation and joint-vision on final goals achievement.

108.4 Conclusions

Authors conclude that BIM competencies should be aligned with building energy efficiency and sustainability topics to provide the best educational outcomes in AEC education. Building modeling simulation tools play a key role in architecture design to assess overall building performances. A large literature review reported Building Information Modeling (BIM) adoption into AEC curriculum focusing on BIM modeling skills as well as analysis energy simulation tools, without taking into account BIM as process methodology [13, 14].

This paper proposed collaborative pedagogical methods reporting students experience within the Environmental Design Laboratory Training Course, providing students an effective method to approach the green building design issues using BIM and energy simulation tools to manage the overall design process. Course objectives, training methods and tools have been detailed focusing on the specific topic of Architecture Airport Design, with the direct involvement of experts from the civil aviation industry and managers from the Genoa Airport.

Assessment methods have been reported as well as students experience from the course and expected results for future improvements, and lesson learnt. Future challenges consist to take advantages over other international experiences and teaching strategies adopted by other educators in different countries, also creating opportunities for international student exchange programs between universities.

References

1. Jennings, P.: New directions in renewable energy education. Renew. Energy **34**, 435–439 (2009)
2. Ferrandiz, J., Fonseca, D., Banawi, A.: Mixed method assessment for BIM implementation in the AEC curriculum. In: Zaphiris, P., Ioannou, A. (eds.) Learning and Collaboration Technologies. LCT 2016. Lecture Notes in Computer Science, vol. 9753. Springer, Berlin (2016)
3. Rajagopalan, P., Wong, J.P.C., Andamon, M.M.: Building performance simulation in the built environment education Experience from teaching two disciplines. In: 50th International Conference of the Architectural Science Association Proceeding, pp. 359–368, University of Adelaide, Adelaide, Australia (2016)
4. Huang, Y.: Introducing an Advanced Building Information Modeling Course in Construction Management Programs, American Society for Engineering Education (2017)
5. Abbas, A., Ud Din, Z., Farooqui, R.: Integration of BIM in construction management education: an overview of Pakistani Engineering universities. In: International Conference on Sustainable Design, Engineering and Construction, Procedia Engineering, vol. 145, pp. 151–157, Springer (2016)
6. Ferrandiz, J., Banawi, A., Peña, E.: Evaluating the Benefits of Introducing "BIM" based on Revit in Construction Courses, Without Changing the Course Schedule. Springer-Verlag GmbH, Germany (2017)
7. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information, Modelling for Owners, Managers, Designers, Engineers and Contractors, 2nd edn. Wiley, New York (2012)
8. Forgues, D., Poirier, E., Staub-French, S.: The Impact of BIM on Collaboration: An Action-Cognition Perspective (2016)
9. Esposito, M.A., Bosi, F.: Architectural Design Technologies. Reshaping Design and Fabrication. Dida Press—Department of Architecture, Florence (2018)
10. Esposito, M.A.: Envelope's Details for the Green Airport Terminal. Firenze University Press, Florence (2010)
11. Nault, E., Aguacil, S., Rey, E., Andersen, M.: Energy performance analysis in interdisciplinary education—Lessons learned from a simulation-based teaching approach. In: PLEA 2017 Edinburgh—Design to Thrive, July 3–5, Edinburgh, UK (2017)
12. Zhao, D., McCoy, A.P., Bulbul, T., Fiori, C., Nikkhoo, P.: Building collaborative construction skills through BIM-integrated learning environment. Int. J. Constr. Educ. Res. **11**, 1–24 (2015)
13. Kandpal, T.C., Broman, L.: Renewable energy education: a global status review. Renew. Sustain. Energy Rev. **34**, 300–324 (2014)
14. Bozoglu, J.: Collaboration and coordination learning modules for BIM education. ITcon **21**, 152–163 (2016)

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