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Sebastian Skatulla
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Editors

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Editors
Sebastian Skatulla
Department of Civil Engineering
University of Cape Town
Rondebosch, South Africa

Hans Beushausen
Department of Civil Engineering
University of Cape Town
Rondebosch, South Africa

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Preface

The Proceedings of the 19th International Conference on Computing in Civil and Building Engineering (ICCCBE) presents findings concerning current and future applications of computing in a wide range of civil and building engineering disciplines.

The conference was the latest in a sequence of ICCCBE International Conferences being held for the first time in Africa where it took place in Cape Town, South Africa, during 26–28 October 2022. It promoted innovation in civil engineering through digital twin technology; geometric modelling; simulation and process modelling; monitoring, information and communication technologies; big data, artificial intelligence and machine learning software; robotics, automation and control; computational structural mechanics. The conference therefore provided a forum and a unique opportunity for researchers and students from the African continent to interact with members of the civil engineering community from around the world.

ICCCBE 2022 has received excellent support by researchers and practitioners all across South Africa, with authors being drawn from numerous research and industrial organisations. The Proceedings contains scientific contributions presented at the conference, classified into a total of 16 themes split over two volumes. Only original contributions were considered for inclusion. All papers submitted were subjected to a full process of double-blind peer review. The review of manuscripts was undertaken by the members of the Scientific Advisory Board and other identified leading experts, acting independently on one or more assigned manuscripts. This invaluable assistance, which has greatly enhanced the quality of the Proceedings, is gratefully acknowledged.

Special acknowledgments are due to our supporters and partners in the industry:

- CIOB
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Finally, the editors wish to thank the authors for their efforts towards producing and delivering papers of high standard creating a base for discussion and providing suggestions for future development and research.

S. Skatulla
H. Beushausen

Contents

Information and Communication Technologies (IoT, Crowdsourcing, Social Networks)

Trends and Recommendations for IoT-Based Smart City Applications

Jose Joaquin Peralta Abadia and Kay Smarsly

Abstract Smart monitoring and wireless sensor networks have advanced the worldwide implementation of smart city applications, improving the quality of life and reducing negative effects on the environment. The Internet of Things (IoT) has received special attention in recent years in the context of smart city applications, providing the technological backbone necessary to perform real-time smart monitoring of the built and the natural environment. Nevertheless, due to the variety of IoT elements and technologies used in IoT frameworks for smart city applications, new implementations of IoT frameworks for smart city applications may have redundant IoT elements or may use inappropriate technologies. This paper aims to summarize and compare emerging IoT elements and technologies utilized in IoT frameworks for smart city applications by means of a systematic review. As a result of this study, a summary and comparison of trends in IoT frameworks for smart city applications are provided. Furthermore, recommendations for future implementations of IoT frameworks for smart city applications are provided, based on the findings of the systematic review. It is expected that the findings of the systematic review and the recommendations for future implementations of IoT frameworks presented in this study may serve as a guideline and a foundation for IoT framework implementations in the context of smart city applications.

Keywords Smart cities · Internet of Things (IoT) · Wireless sensor networks · IoT frameworks · IoT applications

J. J. P. Abadia
Faculty of Engineering, Mondragon University, Mondragon, Spain

K. Smarsly (✉)
Institute of Digital and Autonomous Construction, Hamburg University of Technology, Hamburg, Germany
e-mail: kay.smarsly@tuhh.de

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1 Introduction

Industry 4.0, cyber physical systems, and artificial intelligence have brought rapid advancements in smart cities and smart city applications, effectively replacing traditional civil engineering applications [1, 2]. Discussions regarding the constituents of a smart city may be found in research, where other terms, such as "intelligent city", "digital city" and "ubiquitous city", have also been used. However, common concepts in the discussions may be identified, such as the use of information and communication technologies (ICT) [3]. Essentially, smart cities improve the quality of life by means of user-friendly technologies and applications, i.e. smart city applications [4]. Smart city applications are usually supported by the Internet of Things (IoT), where billions of interconnected "things" (IoT elements or devices) are coupled through wide area networks and the Internet [5]. In this regard, IoT frameworks provide the means for connecting IoT elements, serving as a basis for using IoT technologies.

Although IoT frameworks provide the means for connecting IoT elements, implementing IoT framework for smart city applications may become complicated, costly, and inefficient, in light of the variety of IoT technologies. Literature reviews of IoT frameworks and smart cities have given emphasis on different aspects, such as definitions of the term "smart city" and the domains smart cities are composed of [6]. Other reviews have compared IoT technologies used in smart city applications [7]. Furthermore, challenges and opportunities for smart cities have been given [8]. Nevertheless, a lack of focus on trends in the technologies used by IoT frameworks for smart city applications has been identified. As such, this paper reviews the trends in IoT frameworks for smart city applications. The remainder of this paper is structured as follows. The next section presents the concepts of smart cities and IoT frameworks required to perform the review. Then, the review of trends in IoT frameworks for smart city applications is provided, followed by a discussion of the trends. Finally, a short statement on conclusions and future work is given.

2 Concepts and Guidelines

This section presents the concepts of smart cities and IoT frameworks used as a basis for the review of trends in smart city applications. Working definitions and domains of smart cities are presented, followed by working definitions and architectures of IoT frameworks.

When first coining the term "smart city", it described an intelligent city, which portrays a technopolis and hard infrastructure [9]. Subsequently, the term has been defined in several ways. For example as territories with the capacity for learning and innovation, building upon knowledge creation and creativity of their population, as well as digital infrastructure [10]. In addition, research has attempted to define the domains constituting smart cities, as described in [11]. From the aforementioned review, two examples have been selected as a basis for this study. In [12], the authors have listed the smart city domains as smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Thereupon, in [13], the list has been expanded to include smart buildings, while categorizing the smart city domains into soft domains and hard domains. On the one hand, soft domains refer to intangible characteristics of smart cities. On the other hand, hard domains refer to tangible characteristics of smart cities. Considering the smart city domains mentioned above, this study considers smart economy, smart governance, smart citizens (replacing smart people), and smart living as soft domains of a smart city, and smart mobility, smart environment, and smart infrastructure (replacing smart buildings) as hard domains of a smart city.

As with the several definitions of the term "smart city", IoT frameworks have been defined in several ways. For example, IoT frameworks have been defined as a user-friendly environment capable of supporting billions of IoT devices, facilitating the development and testing of new functionalities [14]. Regarding the architecture of IoT frameworks, the IEEE Internet Initiative (2015) has proposed a three-layered IoT framework architecture constituted by an application layer, a networking and data communications layer, and a sensing layer [15]. Additionally, a similar IoT framework architecture has been proposed, consisting of an application layer, an integration middleware layer, a gateway layer, a device layer, and a sensor and actuator layer [16]. In this study, both architectures are merged into a three-layered IoT framework architecture, composed of sensing layer (including gateways, devices, sensors, and actuators), middleware layer (including networking and data communications), and application layer. Based on the concepts presented thus far, the following section identifies the trends in IoT frameworks for smart city applications, comparing the smart city domains targeted by the IoT frameworks and the IoT elements and services offered by the IoT frameworks.

3 Review of IoT Frameworks for Smart City Applications

This section reviews the trends in IoT frameworks for smart city applications. To make this study brief, the application layer of the IoT frameworks, which is primarily used for data visualization, has been omitted because it does not include IoT elements and technologies to be reviewed.

The review methodology pursued in this study includes three phases. In the first phase, data has been collected. In this phase, 42 studies between the years 2016 and 2020 and indexed in the Web of Science Core Collection, supplemented by conference papers indexed in the Scopus database, have been gathered. The search string used for the data collection is ("smart cities" OR "smart infrastructure" OR "smart living" OR "smart environment" OR "smart mobility" OR "smart economy" OR "smart citizens" OR "smart governance") AND ("Internet of Things" OR "IoT" OR "IoT framework" OR "IoT platform"). In the second phase, the data has been organized and the IoT elements of each layer of the IoT frameworks have been tabulated, based on the concepts presented in previous section. The focus on the sensing layer has been put on the IoT devices (hardware) used in the IoT frameworks. The focus on the middleware layer has been put on the IoT services (software) provided by the IoT frameworks. In the third and final phase, the data is analyzed, summarized and compared. The results of the review, in accordance with the methodology, are the listed as follows.

- **Smart city domain:** As presented in the previous section, smart cities are constituted by seven domains and IoT frameworks for smart city applications are usually developed to be used in only one of the domains. However, several studies have presented IoT frameworks that may be used in more than one smart city domain [17]. Figure 1 presents the quantity of IoT frameworks that can be used in each of the seven smart city domains. Hard domains are presented in yellow, soft domains are presented in green stripes, and an extra category presented in white is used to group the IoT frameworks that may be used in any of the seven smart city domains. It may be observed that 39 IoT frameworks have been used in hard domains of a smart city, while eight IoT frameworks have been used in soft domains. In addition, eight IoT frameworks have been developed to be used in any smart city domain.

- **Sensing layer:** As mentioned previously, focus in this study is put on the IoT devices used in the sensing layer. Figure 2 presents the IoT devices used in the sensing layer and the quantity of IoT frameworks that use the IoT devices. IoT frameworks may be developed to accept any IoT device or specific IoT devices. It has been found that 15 IoT frameworks have been developed to use any IoT device, enabling interoperability. Contrarily, it has been found that 31 IoT frameworks have been developed to use specific IoT devices. However, some IoT frameworks have reported being able to use more than one specific IoT device type, as in [18].

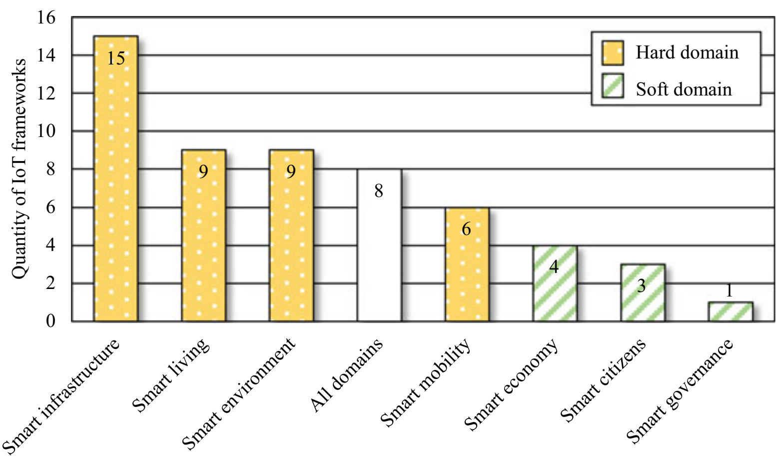

Fig. 1 Categorization of IoT frameworks into the smart city domains

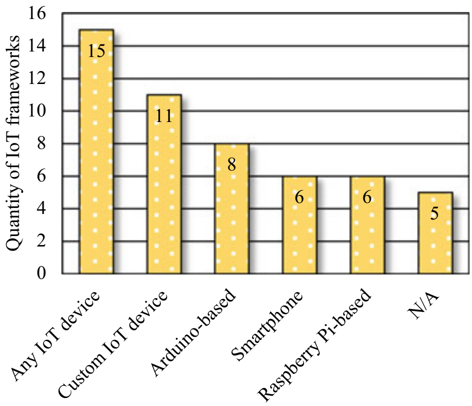

Fig. 2 IoT device types used in the sensing layer of IoT frameworks

In this regard, it has also been found that custom IoT devices are used 11 times, Arduino-based IoT devices are used eight times, smartphones are used six times, and Raspberry Pi-based IoT devices are used six times.

- **Middleware layer:** Opposing the sensing layer, focus in this study is put on the IoT services provided in the middleware layer. Thus, Fig. 3 presents the services that are provided by the middleware layer and the quantity of IoT frameworks that provide the services. It has been found that the most-provided services are database management and authentication services, which are used in 32 IoT frameworks, and event and alert management, which has been provided in 27 IoT frameworks. Following, resource management and resource discovery has been provided in 23 and 21 IoT frameworks, respectively, allowing the management and registration of the IoT devices of the sensing layer. It has also been found that 12 IoT frameworks provide machine learning functionality, performing data analytics and forecasting. Furthermore, 11 IoT frameworks have provided encryption services, adding an extra layer of security to the IoT frameworks. Finally, it has been identified that the least provided service, offered in three IoT frameworks, is code management.

4 Discussion and Implications

This section discusses the results of the review of trends in IoT frameworks for smart city applications presented in the previous section. Discussions of the trends of IoT frameworks for smart city applications, in relationship to smart city domains and sensing and middleware layers of IoT frameworks, are presented as follows.

- **Smart city domains:** On the one hand, it has been identified that hard domains of smart cities are targeted by the majority of IoT frameworks, probably due to ease of implementation and quantification of results, as hard domains refer to tangible assets and characteristics of a smart city. On the other hand, soft domains

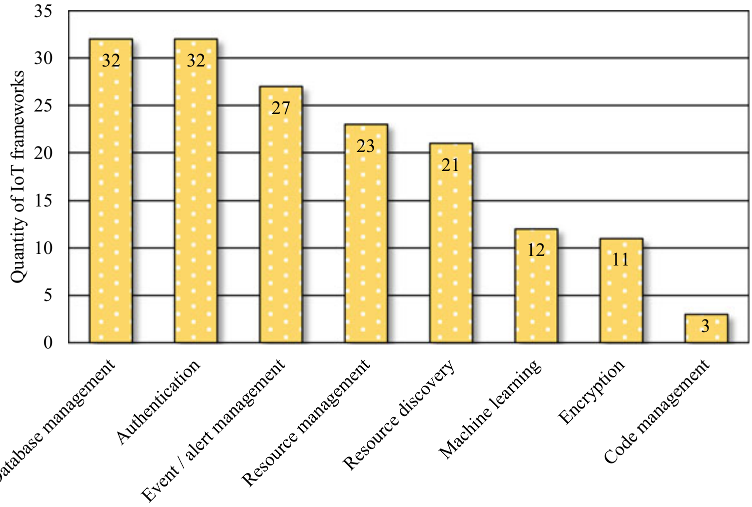

Fig. 3 Services provided by the middleware layer of the IoT framework

have rarely been targeted, where the results are harder to quantify, probably due to the intangible nature of soft domains. Therefore, it has been noticed that smart cities seem to prefer to invest more in smart city applications that provide fast and quantifiable results.

- **Sensing layer:** It has been found that the usage of specific IoT devices has been preferred by the majority of IoT frameworks. However, the preference for specific IoT devices derives in a lack of interoperability and possible problems of upgradeability, when new IoT technologies and IoT devices become available.
- **Middleware layer:** Representing basic services for the operation of the IoT middleware layer, database management and authentication services have been identified as the services that are mostly offered. Therefore, additional services of interest, such as machine learning and data analytics services, emerge in IoT frameworks, as large amounts of data are readily available. Nevertheless, it has been observed that some IoT frameworks may be vulnerable to security breaches, related mainly to the lack of data encryption.

5 Summary and Conclusions

In this study, definitions and concepts of smart cities and IoT frameworks, as well as a review of trends in IoT frameworks for smart city applications, have been presented. The IoT technologies and IoT devices have been summarized and compared. This paper is a short version of a journal paper. This paper has exclusively been written to present and discuss the systematic review with the ICCCBE audience. In the corresponding journal paper, 86 sources have been incorporated, and details may be found in [19].

Since IoT frameworks are usually based on a three-layered architecture, constituted by a sensing layer, a middleware layer, and an application layer, which can distributedly be located in distant geographical positions, it becomes necessary to guarantee secure communication between the layers. As a result of this study, it has been identified that, in spite of most IoT frameworks offering authentication services, there are possible security vulnerabilities in the IoT frameworks, as few offer encryption services. In addition, the lack of interoperability and code management has to be targeted as well, thus enabling the use of future IoT devices and IoT technologies. As a result of the findings of this study, it has been identified that IoT frameworks for smart city applications should address decentralization, interoperability, security, and modularity, as well as a need to address the use of the IoT frameworks in the soft domains of a smart city.

Future research may focus on the development of new IoT framework concepts for smart city applications, targeting the issues revealed in this study, i.e. a lack of interoperability and decentralization of the services as well as security and modularity. Furthermore, the development of IoT frameworks that can be used in soft domains of a smart city may be addressed, thus giving focus to the quality of life of the citizens.

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Text Mining-Based Patent Analysis for Automated Rule Checking in AEC

Zhe Zheng, Bo-Rui Kang, Qi-Tian Yuan, Yu-Cheng Zhou, Xin-Zheng Lu, and Jia-Rui Lin

Abstract Automated rule checking (ARC), which is expected to promote the efficiency of the compliance checking process in the architecture, engineering, and construction (AEC) industry, is gaining increasing attention. Throwing light on the ARC application hotspots and forecasting its trends are useful to the related research and drive innovations. Therefore, this study takes the patents from the database of the Derwent Innovations Index database (DII) and China national knowledge infrastructure (CNKI) as data sources and then carried out a three-step analysis including (1) quantitative characteristics (i.e., annual distribution analysis) of patents, (2) identification of ARC topics using a latent Dirichlet allocation (LDA) and, (3) SNA-based co-occurrence analysis of ARC topics. The results show that the research hotspots and trends of Chinese and English patents are different. The contributions of this study have three aspects: (1) an approach to a comprehensive analysis of patents by integrating multiple text mining methods (i.e., SNA and LDA) is introduced; (2) the application hotspots and development trends of ARC are reviewed based on patent analysis; and (3) a signpost for technological development and innovation of ARC is provided.

Keywords Automated Rule Checking (ARC) · Patent analysis · Text mining · Social Network Analysis (SNA) · Latent Dirichlet Allocation (LDA) · Application hotspots and future trends

1 Introduction

Authorities' rules such as design guidelines, codes, standards, and international, national, or local authorities' laws stipulate the safety, sustainability, and comfort of the entire lifecycle of a built environment [1]. For a long time, the regulatory compliance of a building design was checked manually by domain experts. However,

Z. Zheng · B.-R. Kang · Q.-T. Yuan · Y.-C. Zhou · X.-Z. Lu · J.-R. Lin (✉)
Department of Civil Engineering, Tsinghua University, Beijing 100084, China
e-mail: lin611@tsinghua.edu.cn

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this process is not only immensely time-consuming but is also challenging for project participants [2] due to the complexity and ambiguity of rules and regulations [3]. Therefore, automated rule checking (ARC, also known as ACC) has been extensively studied by many researchers for nearly 70 years [4], and several rule-based ARC systems have been established [5]. For example, CORENET (short for COnstruction and Real Estate NETwork), which is the first large effort of ARC, was initiated in 1995 in Singapore [6]. A universal circulation network (UCN) is developed as a plug-in based on the Solibri model checker (SMC) to check occupant circulation rules of the US court design guide [7]. Other rule-based ARC systems include BCAider [8], Jotne EDModelChecker [9], and so on. However, the above rule-based ARC systems are costly to maintain and inflexible to modify and are often referred to as black-box approaches [10]. Hence, to make the process more flexible and transparent, attempts have been made to (1) automated interpretation of the rules based on natural language processing (NLP) [11–13], (2) automated alignment of BIMs and computer-interpretable regulations [14], and so on.

To promote future development in the field, many efforts have been devoted to the analysis of the development trends. For example, Eastman et al. [5] examined and surveyed five rule checking systems that assess building designs according to various criteria in detail. Ismail et al. [15] reviewed the previous studies, which successfully employed the appropriate techniques in interpreting the rules for checking purposes. Fuchs [16] assessed the state-of-the-art of NLP for building code interpretation by analyzing 42 research articles published since 2000. These works have pointed out the key research areas and analyzed the current and ongoing research and development (R&D) directions. However, the existing studies mainly focused on the existing ARC systems or research articles, while seldom considering the patent analysis. Patent analysis is valuable to throw light on the innovation and development of a technological field over the course of time [17, 18].

Therefore, this work aims to explore the application hotspots and trends of compliance checking by analyzing the related patents based on text mining methods. The patents from the database of the Derwent Innovations Index database (DII) and China national knowledge infrastructure (CNKI) are taken as data sources. Then the analysis is comprised of three steps. First, the quantitative characteristics and annual distribution analysis of patents are carried out. Second, several topics of the ARC patents are identified using a latent Dirichlet allocation (LDA). Third, to reveal the relation between different topics, the identified ARC topics co-occurrence analysis is carried out based on Social Network Analysis (SNA). Finally, based on the analysis results, the application hotspots and trends are revealed. The findings are expected to be valuable for the related stakeholders including researchers, ARC system developers, and companies. The introduced approaches to the analysis of ARC patents are also useful for other scenarios.

2 Methodology

This study utilizes patents as data resources and integrates several text mining technologies including the LDA topic identification technology, and the SNA topic correlation analysis to identify the application hotspots of ARC and forecast its trends. Figure 1 shows the outline and workflow of this research. Meanwhile, the toolkits used to implement the workflow are also displayed at the bottom of Fig. 1. The methods deployed are detailly illustrated from Sect. 2.1 to Sect. 2.3.

2.1 *Data Acquisition*

In this work, the patent retrieval process consists of (1) screening by keywords and, (2) screening manually by domain experts to filter the patents that are not relevant to the rule checking. The Chinese and English patents are obtained from the CNKI and DII database, respectively, and the retrieval time is from 2010 to 2021. For the Chinese patents, the keyword is “design review”, and after the manual screening, total 113 Chinese patents were collected for analysis. For the patents in English, the keywords include “rule checking”, “compliance checking”, “design review”, “automated compliance checking”. After the manual screening, finally, total 121 patents in English were collected for analysis.

The abstracts of the collected patents are used for further analysis. After the patent retrieval process, the data preprocessing consists of tokenization, special characters (e.g., !%$#& ∗ ?,/.;”\) removal, and stop words removal. For the Chinese patents, the original texts are tokenized and removed stop words using the Python lib named Jieba, while the English patents are processed using the Python lib named NLTK (Natural Language Toolkit).

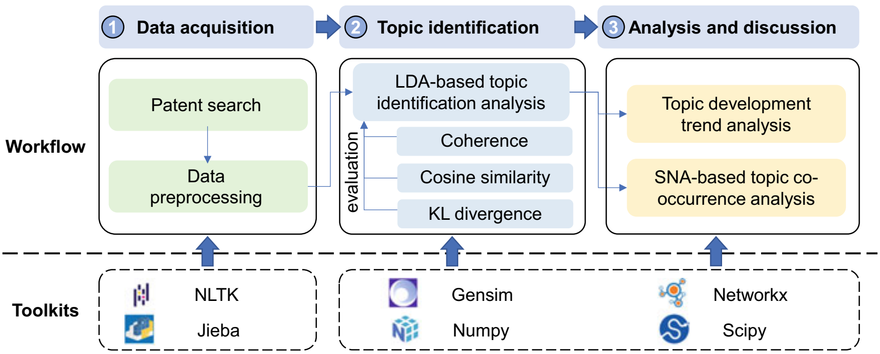


Fig. 1 Workflow of this research

2.2 Topic Identification

After the acquisition and pre-processing of the patent data, the topic identification is performed to mine the latent information of patents. Topic identification methods (i.e., topic modeling methods) are typical text mining methods. The Latent Dirichlet Allocation (LDA) model proposed by Blei et al. [19] is one of the most widely-used topic modeling methods [18, 20–22]. LDA model is a generative probabilistic model of corpus where each document is represented as random mixtures over latent topics, and each topic is characterized by a distribution over words [19]. The basic idea of the LDA model is shown in Fig. 2. The hyperparameter α is the Dirichlet prior on the document-topic distributions and the hyperparameter β is the Dirichlet prior on the topic-word distributions. LDA model assumes the following steps to generate a document [18, 19].

1. For each document ***d***, sample a topic proportion θd from the Dirichlet distribution $Dir(\alpha)$.
2. For each word wd, n to be generated in the document ***d***:
    a. Choose a topic $zd, n \sim Multinomial(\theta d)$
    b. Choose a word $wd, n \sim Multinomial(\varphi k|k = zd, n)$, where the word proportion per topic φk is sampled from the Dirichlet distribution $Dir(\beta)$.

To determine the optimal number of topics generated by the LDA model, the coherence scores of the topics are used [24]. The coherence metric uses statistics and probabilities extracted from the reference corpus to evaluate how well a topic is. The larger the coherence scores are, the better the effect of LDA topic identification. The coherence measure method consists of four main steps: (1) segmentation, (2) probability calculation, (3) confirmation measure, and (4) aggregation [24]. The coherence model in the genism toolkit is used to implement the evaluation process.

Besides, to evaluate the performance of the topic generation results, the topic distances among the topics are measured via Kullback–Leibler (KL) divergence and cosine similarity analysis. According to the LDA model, each topic is represented as a set of words with proportional. So, based on KL divergence and cosine similarity, the distance matrix should be constructed, where the element in the *i* row and the

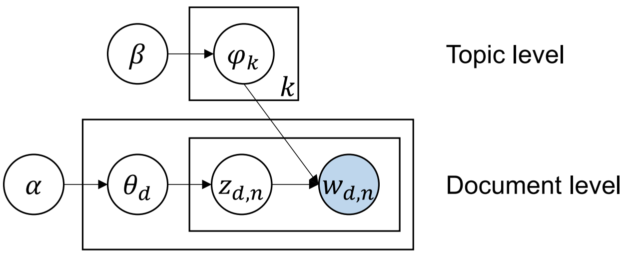


Fig. 2 Latent Dirichlet Allocation (LDA) model

j column represents the specific distance value between the number *i* topic and the number *j* topic. For the KL divergence analysis, the distance matrix is an asymmetric matrix. The larger the value of the non-diagonal elements of the distance matrix, the greater the differentiation of words between two topics and the better performance of topics generated by the LDA model. For the cosine similarity analysis, the distance matrix is a symmetric matrix. The smaller the value of the non-diagonal elements of the distance matrix, the greater the differentiation of words between two topics and the better performance of topics generated by the LDA model.

2.3 Topic Co-occurrence Analysis

After the LDA analysis, the topic of each patent is recognized. To further explore the topic relevance between the identified topics, the SNA-based topic relevance analysis is performed. SNA is often used to explore the publication, citation, and cocitation networks, collaboration structures, and other forms of social interaction networks [25].

In this work, the nodes in the topic relevance graph are the identified topics. Meanwhile, the link between two nodes means there is at least one article that contains the two topics at the same time. According to the LDA model, each article consists of a bag of topics, where the larger the percentage of topics, the more important the topic is. Therefore, when a topic accounts for more than 10%, we consider this topic to be the article's main topic. If an article has multiple main topics at the same time, these topics are called co-occurrence topics. Then a link will be generated for these two topics. The attribute of each link means the number of articles that contains the two topics. Therefore, the topic relevance graph is a typical undirected symmetric network. After the construction of the topic relevance graph, Gephi [26] is then used to perform the visualization of network analysis.

3 Results

3.1 Quantitative Characteristics of ARC Patents

The annual publication numbers of patents can reflect the development trend and research interests. Therefore, after the patent data acquirement and preprocessing, the trend analysis is conducted, as shown in Fig. 3. The first Chinese patent on rule checking appeared in 2011, while the first English patent appeared in 2013. The trend of the Chinese and English patents is similar. The number of patents grows slowly until 2015. From 2016 to 2021, the growth rate of the related patents has significantly accelerated, which indicates that the rule checking methods and systems are gaining more and more interest in recent years.

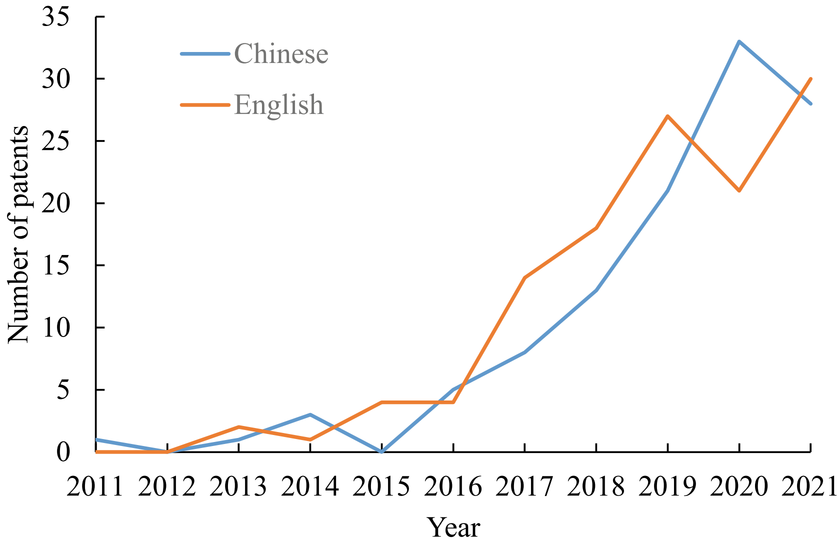
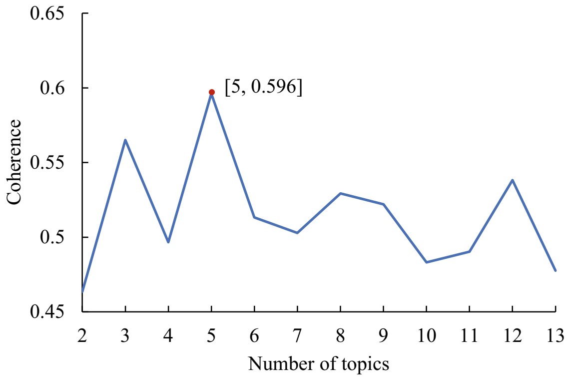


Fig. 3 The number of patents on rule checking

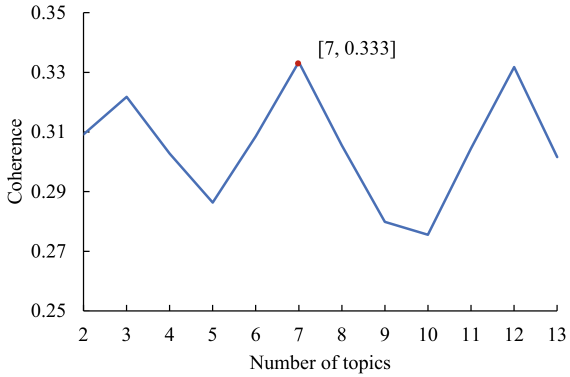
3.2 LDA-Based Topic Clustering of ARC Patents

To further analyze the application hotpots and development trends of the ARC patents, the LDA model is utilized to explore the main topics and their corresponding keywords from the collected ARC-related patents. First, the relatively proper topic numbers are searched, as shown in Fig. 4. The coherence values are used to measure the rationality of the topics. The best topic number is 5 and 7 for the Chinese patents and English patents, respectively. The coherence value of the Chinese topics is higher than that of the English topics, indicating that the quality of Chinese topics is higher than that of English topics.

To further evaluate the performance of the topic generation results, the topic distances among the topics are calculated via Kullback–Leibler (KL) divergence and cosine similarity analysis. The distance matrixes of the topics are shown in Fig. 5. For the Chinese patents, as shown in Fig. 5a, A13 (A_{ij} means the element at the number i row and the number j column) and A_{25} have the largest cosine similarity. A_{13} and A_{25} have the smallest KL divergence, as shown in Fig. 5b. The results of the two matrixes are consistent, indicating that topic 2 and topic 5 have the highest similarity, and topic 3 and topic 2 have the second-highest similarity. For the English patents, as shown in Fig. 5c, A25, A27, A56, and A67 have the largest cosine similarity. A_{52} and A_{76} have the smallest KL divergence, as shown in Fig. 5d. The results of the two matrixes are consistent, indicating that the similarity between topics 2 and 5 and the similarity between topics 6 and 7 are relatively high. In general, the similarity between Chinese topics is lower than that between English topics, indicating that the



(a) Chinese patents



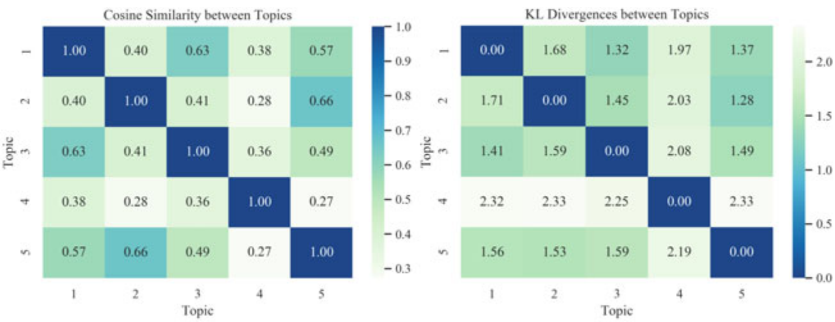
(b) English patents

Fig. 4 Coherence values of the topics constructed by LDA

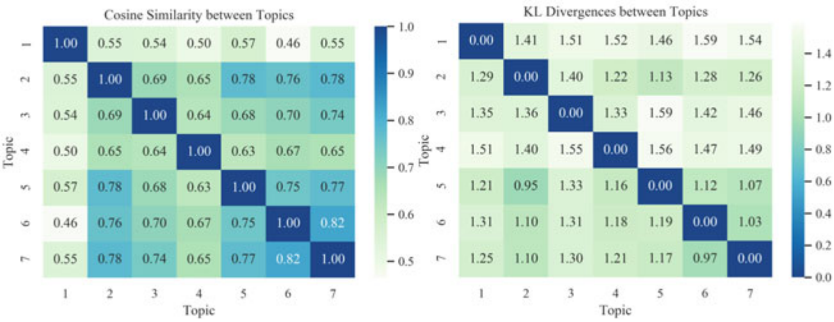
quality of Chinese topics is higher than that of English topics. This is consistent with the result of coherence analysis, as shown in Fig. 4.

Then all the patents are analyzed, and the identified topics according to the word distributions are listed in Tables 1 and 2. The top 10 words and their corresponding weight values (percentage) are also listed in Tables 1 and 2. For the Chinese patents, the topics are topic 1 "codes database and auxiliary software", topic 2 "drawings and models information extraction", topic 3 "CAD element identification modules", topic 4 "User interaction", and topic 5 "Auxiliary devices and systems". Topics 2 and 5 may share some keywords on drawings or model information; therefore, the similarity is relatively high.

For the English patents, the topics are topic 1 "digital system and terminal", topic 2 " BIM applications in design and construction", topic 3 " data integration and management", topic 4 "computer-executable rule and knowledge base", topic 5 "BIM-based management platform", topic 6 "Auxiliary tools for rule checking", and topic 7 "Rule Checking systems". Topic 2 and topic 5 are about BIM-related applications; therefore, the similarity between the two topics is relatively high. And



(a) Cosine similarity for Chinese patents (b) KL divergence for Chinese patents



(c) Cosine similarity for English patents (d) KL divergence for English patents

Fig. 5 Distance matrixes of the topics

topics 6 and 7 are about auxiliary tools or systems for rule checking; consequently, the similarity between the two topics is also relatively high, which is consistent with the results of Fig. 5c and 5d.

3.3 Analysis and Discussion

After the topic construction via the LDA models, the topic-based quantification analysis is conducted to explore the trends, and the SNA-based topic co-occurrence analysis is performed to provide more insight into the combination and development of the technologies.

Table 1 Distributions of the topic of the Chinese ARC-related patents

Topics	Keywords and probabilities									
Codes database and auxiliary software	Design review	Rule check	module	codes	target	system	data	database	method	region
	2.7	2.7	2.3	1.5	1.4	1.2	1.1	1.1	1.0	1.0
Drawings and models' information extraction	drawings	check	component	Design review	building	method	information	application	target	acquirement
	7.7	2.8	2.8	2.6	1.8	1.5	1.3	1.3	1.2	1.1
CAD element identification modules	data	Design review	information	module	Construction drawings	model	Rule check	terminal	method	CAD
	2.7	2.3	1.8	1.6	1.4	1.3	1.3	1.3	1.2	1.2
User interaction	Design review	interface	display	design	change	Phase diagram	method	model	files of drawings	click
	3.6	2.9	2.6	2.5	1.7	1.7	1.4	1.4	1.4	1.2
Auxiliary devices and systems	drawings	target	Design review	information	module	building	project	component	application	detection
	3.1	2.6	2.3	1.7	1.6	1.5	1.3	1.2	1.1	1.1

Note: The numbers in the table represent the percentage of words in the topic

Table 2 Distributions of the topic of the English ARC-related patents

Topics	Keywords and probabilities									
Digital system and terminal	design	digital	information	drawing	building	review	delivery	terminal	modeling	description
	3.3	2.9	2.9	2.8	1.8	1.5	1.3	1.3	1.2	0.9
BIM applications in design and construction	model	information	BIM	drawing	software	building	construction	design	rtm	3D
	3.7	2.5	2.0	1.8	1.3	1.3	1.3	1.2	1.2	1.2
Data integration and management	BIM	information	model	drawing	building	system	based	object	data	unit
	2.6	2.4	1.9	1.8	1.7	1.5	1.2	1.2	1.1	0.9
Computer-executable rule and knowledge base	drawing	BIM	model	module	substation	system	building	review	information	arch
	2.1	1.9	1.9	1.8	1.4	1.4	1.2	1.2	1.1	1.1
BIM-based management platform	construction	drawing	BIM	model	design	information	data	project	according	management
	3.3	2.8	2.6	2.5	2.0	1.7	1.4	1.3	1.2	1.2
Auxiliary tools for rule checking	model	BIM	rule	drawing	component	design	construction	description	building	set
	4.0	3.8	2.4	2.3	1.6	1.3	1.2	1.0	0.9	0.9
Rule Checking systems	model	BIM	component	information	data	building	drawing	design	construction	check
	3.5	2.7	2.2	2.1	2.1	2.0	1.8	1.6	1.4	1.0

Note: The numbers in the table represent the percentage of words in the topic

As shown in Fig. 6a, for the Chinese patents, with the development of information technology (e.g., natural language processing, deep learning), the patents related to ARC have shown an increasing trend since 2016, and have grown substantially since 2018. Topic 2 "Drawings and models' information extraction" has the highest growth rate and quickly became the most published topic. The result indicates that researchers are more concerned about how to extract and integrate the information from drawings and models. Topic 1 "Codes database and auxiliary software" has received sustained attention in recent years. Topic 4 "User interaction" and topic 5 "Auxiliary devices and systems" have also grown rapidly since 2018. The result shows that good user interaction methods and more convenient auxiliary tools are important to ARC systems. Topic 4 and topic 5 started late and developed rapidly, which shows that making the ARC system more convenient may be the future research direction.

As shown in Fig. 6b, for the English patents, the patents related to ARC have shown an increasing trend since 2016. Topic 5 "BIM-based management platform", topic 6 "Auxiliary tools for rule checking", and topic 7 "Rule Checking systems" grew faster and were published the most. This shows that many researchers pay attention to the development of platforms and systems. Among them, topic 5 contains the most patents because it's about the whole life cycle of BIM-based management where automated rule checking may be used in different steps. Topic 4 "Computer-executable rule and knowledge base" currently receives relatively little attention. However, Ismail pointed out that rule interpretation is the most vital and complex stage in the rule checking process [15]. To achieve a fully automated rule checking system, more attention may be paid to the topic 4 related research. Topic 2 "BIM applications in design and construction" has a downward trend, which may be a result of many studies not only focusing on the design stage and the construction stage but also focusing on the whole life cycle of the buildings.

It can be concluded from Fig. 6a and 6b that the content of Chinese patents and English patents are different. Chinese patents pay more attention to the various components of the ARC system. In contrast, the English patents focus more on integrating the ARC system in various BIM-based applications.

For the co-occurrence analysis, the results are shown in Fig. 7. For the Chinese patents, topic 1 "Codes database and auxiliary software" and topic 2 "Drawings and models information extraction" have the most co-occurrences. The results show that when the patent involves drawing and model information extraction, it will also include other auxiliary tools. For the English patents, topic 5 "BIM-based management platform" co-occurs with topic 3 "Data integration and management", topic 6 "Auxiliary tools for rule checking", and topic 7 "Rule Checking systems", respectively. Because topic 5 mainly includes a full life cycle building management platform, which involves data integration and other auxiliary tools.

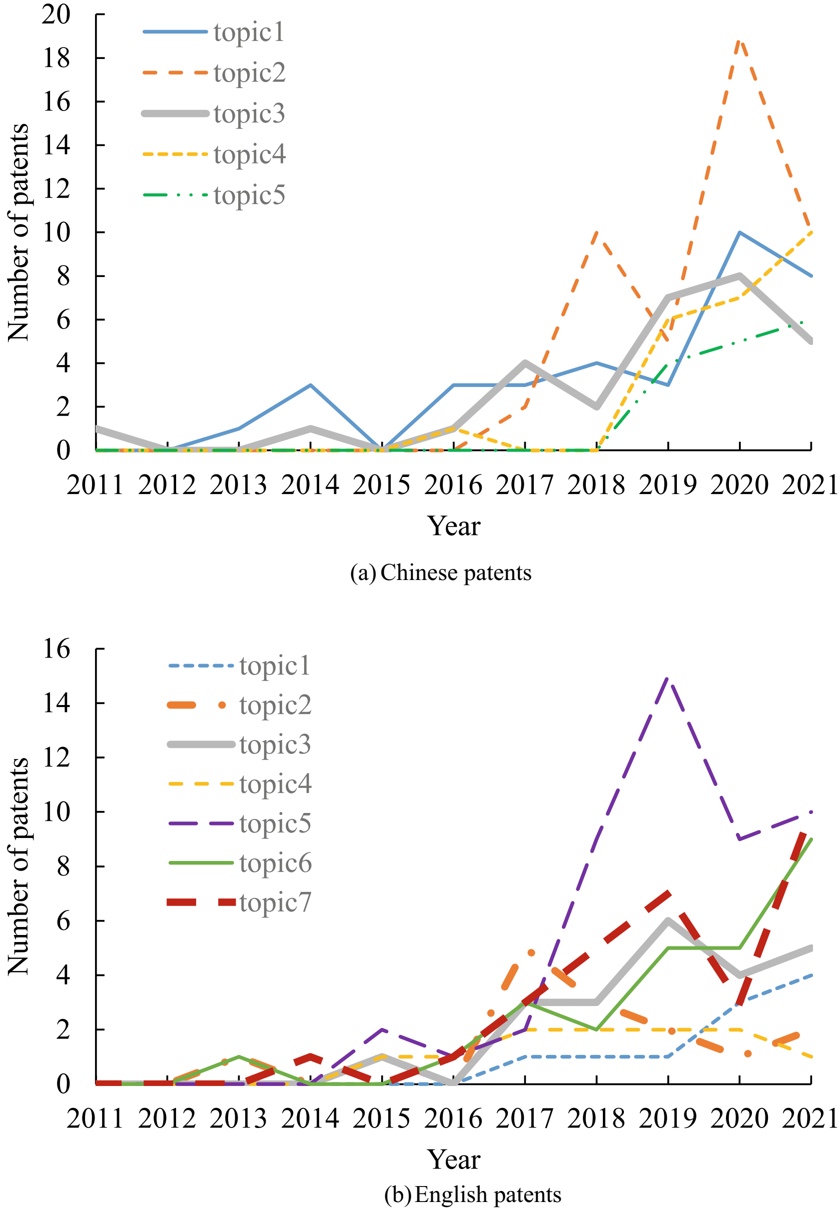
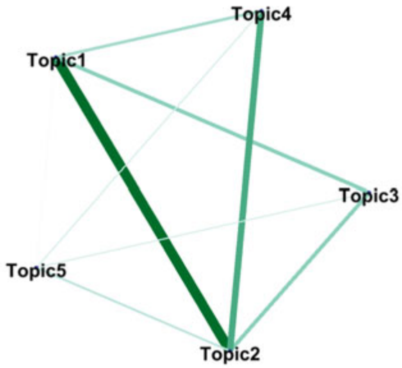
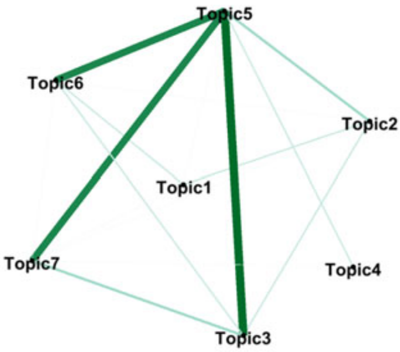


Fig. 6 The number of patents on different topics constructed by LDA



(a) Chinese Patents



(b) English patents

Fig. 7 Co-occurrence of the topics

4 Conclusions

ARC is expected to promote the efficiency of the compliance checking process in the AEC industry. To analyze the trend development and hotpots of the ARC, this paper first extracted the patents' texts from the database of Derwent Innovations Index database (DII) and China national knowledge infrastructure (CNKI). Subsequently, a three-step analysis approach is carried out, which includes (1) quantitative characteristics (i.e., annual distribution analysis) of patents, (2) identification of ARC topics using a latent Dirichlet allocation (LDA), and, (3) SNA-based co-occurrence analysis of ARC topics. The conclusions are as follows:

(1) The trend of the Chinese and English patents is similar. The number of pa-tents grows slowly until 2015. From 2016 to 2021, the growth rate of the related patents has significantly accelerated.
(2) The topic models are identified based on the LDA model, and the quality of the constructed topics has been measured via three methods, including coherence value, cosine similarity, and Kullback–Leibler (KL) divergence. The results of the three methods are consistent.
(3) For the Chinese patents, the patents related to "drawings and models information extraction" are gaining more attention. Besides, the results show that the number of patents that focus on improving the user experience of the ARC system has grown rapidly. Therefore, making the ARC system more convenient may be the future research direction. For the English patents, the patents related to " BIM-based management platform" are gaining more attention. While the patents related to "Computer-executable rule and knowledge base " received relatively little attention currently. The rule interpretation is one of the most vital stages in the rule checking process. Future research can pay more attention to the rule interpretation to achieve a fully automated rule checking system.

The limitations of this study are listed as follows:

(1) The performance of LDA analysis can be further improved for better topic detection. Besides, more methods should be utilized to validate the results of LDA.

(2) Only the abstracts of the patents are used to perform the analysis, more structured and unstructured data from patents is expected to use in the future.

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Unravelling the State of the Art of Blockchain Development for Improved Infrastructure Delivery in the Built Environment: A Bibliometric Review

Motheo Meta Tjebane, Innocent Musonda, Adetayo Onososen, and Molusiwa Ramabodu

Abstract Information management is critical to the smooth operation of infrastructure delivery. It is the process of gathering, storing, distributing, archiving, and deleting/destroying data. Information and data management are critical to decision-making toward achieving improved, resilient, and responsive infrastructure delivery. While innovative tools abound for managing information in the built sector, barriers such as technical challenges, expertise needed, and cost of procurement inhibit the adoption of these technologies. In contrast, blockchain offers opportunities for accessibility, lighter and faster transaction speed, and secured data processing. However, research in this area is limited and slowly emerging. Therefore, this study adopts a bibliometric review to avail current progress, critical discussions, and vital strategies to advance the adoption of Blockchain development in the construction industry. Blockchain has emerged as important to built environment innovation discourses with energy management, payment processing, documentation, and asset lifecycle management opportunities. This study is therefore important in improving extant studies and availing future directions. This paper uses bibliometric analysis to examine blockchain as a tool for infrastructure delivery in the built environment. Empirical data from Scopus was analysed to establish the publication and citation pattern, specifically publications published between 2011 and 2021. This also identifies research trends, common gaps, and best practices among researchers who use Vosviewer. The most influential authors, institutions, journals, countries, and cooperation networks are then identified. This study presents the relevance of blockchain in the built environment and its movement, adoption, and adaptation, which further enables the spark of innovative ideas to realize and comprehend the current and future technological transformation in infrastructure delivery.

M. M. Tjebane (✉) · I. Musonda · A. Onososen · M. Ramabodu
Center of Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: tjebane.motheo@mut.ac.za

M. M. Tjebane
Department of Construction Management and Quantity Surveying, Mangosuthu University of Technology, Durban, South Africa

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Keywords Built Environment · Blockchain · State of the art · Infrastructure · Resilient · Responsive

1 Background

The built environment faces numerous challenges and fragmentation, impacting the infrastructure delivery rate. Infrastructure delivery processes in the built environment are highly fragmented, dispersed, and complex. As a result, massive efforts, resources, and intermediaries are required to plan, monitor, and track these processes under the schedule, cost, quality, and scope. Furthermore, delays and accidents occur at multiple stages and varying degrees, affecting the project's key objectives [1]. Various management processes have been developed and integrated to increase productivity and effectiveness while decreasing the likelihood of misalignment [1]. However, most have seemed to fail over time as they cannot address all issues simultaneously.

Although no technology or approach can address this, all the issues listed above, blockchain technology and the circular economy, have revolutionized supply chain management in several ways. Blockchain technology is a key component of digital transformation, promising transparency, improved privacy, faster settlement, cost savings, quality, and productivity through a distributed approach [2]. The use of blockchain networks in such processes is part of that development. However, as the fourth industrial revolution support market progresses, the built environment is experimenting and developing innovative tools and technologies. One of the key issues impeding industry modernization is the failure to adopt technological developments that could have aided the industry's achievements [3].

The blockchain is a digitized, decentralized public ledger of data, assets and all pertinent transactions that have been executed and shared among participants in the network. According to [4] blockchain technology allows multiple parties to transact on a shared synchronous ledger. Each transaction is validated with a digital signature to ensure its authenticity. Blockchain has several key features, including decentralization, distributed computing, and consensus. While it is most associated with digital cryptocurrencies such as Bitcoin, blockchain is an emergent technology. Blockchain can revolutionize and transform the current digital operational landscapes and business practices of finance, computing, government services, and virtually every existing industry [5].

Previous studies have been conducted on blockchain in the built environment [4]. conducted an exploratory literature review of blockchain in the construction industry. [6] looked at blockchain-based security solutions with IoT applications in the construction industry [7]. conducted a bibliometric review on the risks and opportunities of blockchain in the built environment. Little study has focused on blockchain in infrastructure delivery in the built environment.

Beginning in 2011, the literature on this topic consists of bibliometric research articles or review articles. The bibliometric review aims to provide the reader with general research directions, research groups, and gaps in the literature [7]. This article aims to provide a bibliometric overview of blockchain's state of the art in improving infrastructure delivery in the built environment. The article is as follows. Section 1 looks at the background and needs for the study. This is followed by a methodology chapter, Sect. 2, which shows how the bibliometric was conducted. Section 3 provides the results for the analysis. Section 4 is the conclusion.

2 Research Design and Method

To fulfill the research objectives, a quantitative bibliometric approach was used in this study. a systematic approach was used in scoping and selecting publications. The flowchart in Fig. 1 below shows the research method used.

Fig. 1 Research Method Flowchart

The bibliometric analysis employs a hybrid technique to present or capture research trends and features of publications by combining evaluative and descriptive approaches [8, 9]. This study is the result of the current blockchain scenario for infrastructure delivery, as it employs a systematic literature review with the assistance of bibliometric network analysis to document the publication on the topic [10].

A thorough search is conducted on the Scopus database, which is a trustworthy and unbiased source of reputable journal articles and fundamental requirement of bibliometric analysis [11, 12].

2.1 Inclusion and Exclusion Criteria

Inclusion and exclusion was used to select publications for the bibliometric analysis. The eligibility criteria address the inclusion and exclusion of studies for bibliometric analysis [13]. In general, inclusion criteria form the basis for including articles that provide the information required to answer the research question. While exclusion criteria include the reason for excluding non-relevant articles, duplicate articles, and articles with no full-text available, the inclusion criteria looked at the following:

- Publications made between 2011 and 2021
- Articles and review articles
- Published in the English language

2.2 Search Query

This study collects data from a Scopus dataset by searching the title, abstract, and keyword search fields of articles published between 2011 and 2021. The query string was blockchain AND built AND environment OR construction AND industry OR infrastructure). three main segments were linked by the Boolean operator 'AND' each segment consisting of at least two fields linked by the 'OR' operator [14].

2.3 Data Analysis

VOSviewer is bibliometric network construction and visualization software. Journals, researchers, and individual publications can all be part of these networks based on citation, bibliographic coupling, cogitation, or co-authorship relationships. They also provide text-mining functionality for network construction, visualization occurrences of terms extracted from scientific literature [15].

VOSviewer was chosen for this study to draw science mappings because it has exceptional text-mining capabilities and is well-suited for dealing with larger

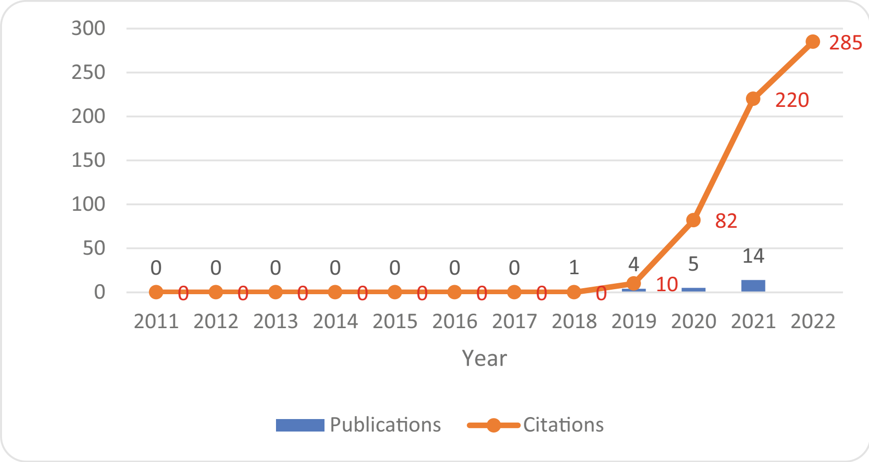

Fig. 2 Publication verses citation from 2011 to 2021

networks [16]. VOSviewer is currently used in construction industry research to create science mappings for several topics.

3 Results

3.1 *Descriptive Analysis*

From 2011 to 2021, 28 documents on the role of Blockchain development for improved infrastructure delivery in the built environment were published on Scopus. The distribution of publications and citations by year. During the first seven years, no publication was made concerning the subject matter. The first article was done in 2018, and the publication rate increased in 2019 to 4 articles. 2020 saw five articles being published, with 2021 saw the highest number of publications with fourteen. In terms of citations, by mid-2022, there was a citation of 285 for all twenty-eight articles on the Scopus index (Fig. 2).

3.2 *Country Analysis*

The United Kingdom had the highest number of article publications; Australia and South Africa followed this with four each. Singapore, Hong Kong, and China had two publications each. Regarding citations, the United Kingdom had the highest with 377, Australia followed this with 120 citations, and United States with seventy-seven.

The United Kingdom had the most publications and citations, while South Africa, China, and Singapore had the most collaborations (Fig. 3 and Table 1).

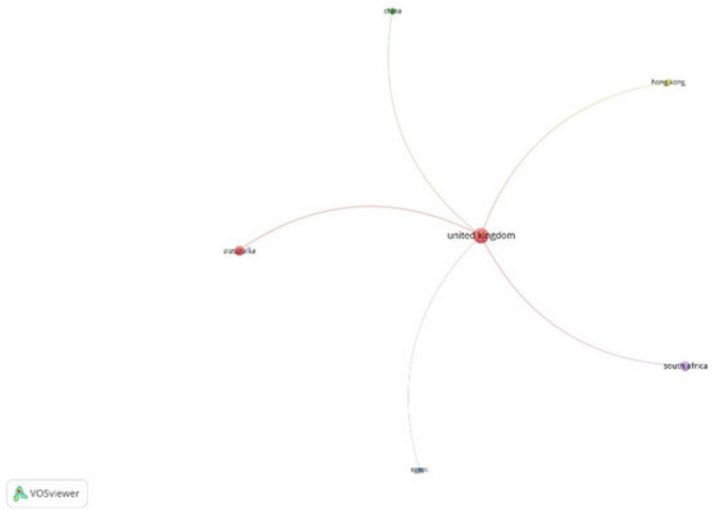

Fig. 3 Country collaboration

Table 1 Country analysis

Country	Documents	Citations	Total strength
United Kingdom	9	377	3
Australia	4	120	2
United states	1	77	0
Netherlands	1	24	1
Switzerland	1	24	1
Iran	1	22	0
Singapore	2	21	4
South Africa	4	20	4
Hong Kong	2	13	1
Italy	1	12	0
France	1	6	2
Germany	1	6	2
Japan	1	6	2
Sri Lanka	1	3	0
Belarus	1	2	3
China	2	2	4

Table 2 Author analysis

Author	Documents	Citations	Total Strength
Kassem M	2	179	3
Li J	2	179	3
Greenwood D	1	168	2
Nawari N.O	1	77	1
Ravindran S	1	77	1
Abrishami S	1	73	2
Elghaish F	1	73	2
Hosseini M.R	1	73	2
Edwards D	2	70	4
Parn E.A	1	70	1
Batty M	1	40	6
Engin Z	1	40	6
Lan T	1	40	6
Longley P.A	1	40	6
Penn A	1	40	6

3.3 Authorship

Table 2 shows the top authors in terms of the number of citations. From the list of fifteen authors, two authors have 179 citations from publishing two articles. This was followed by greenwood d. with 168 citations from the article. Furthermore, three authors had ninety-nine citations from one published article. Newari N.O and Ravindran S. had seventy-seven citations. Of the fifteen top authors, four authors had the lowest number of citations, with forty. Figure 4 shows the lines of collaborations among the different authors.

3.4 Journals

Table 3 shows the top seventeen journal articles in terms of article publications relating to blockchain development for improved infrastructure delivery in the built environment. The tables measure against the number of citations. Automation in construction had the highest number of citations, with 262 from five published articles. It also has the most links with six, as shown in Fig. 5 This was followed by the journal of building engineering with seventy-seven citations from one article. However, from this list, three journals had no citations. Moreover, nine journals had no links to other related journals.

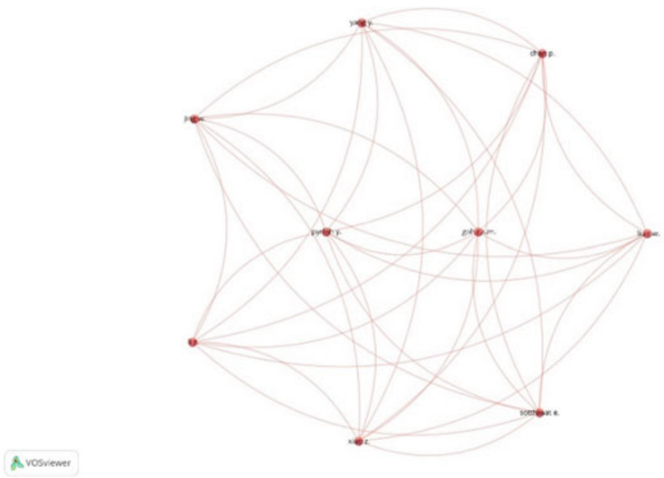

Fig. 4 Authorship collaboration network

Table 3 Journal source analysis

Journal	Documents	Citations	Total strength
Automation in Construction	5	262	8
Journal of Building Engineering	1	77	0
Engineering, Construction, and Architectural Management (ECAM)	1	70	3
Buildings	2	47	1
Sustainability (Switzerland)	3	43	0
Journal of Urban Management	1	40	1
IEEE Access	1	22	0
Journal of Cleaner Production	1	13	1
Frontiers in Energy Research	1	12	0
Future Internet	1	6	0
Internet of Things (Netherlands)	1	6	0
Journal of Facilities Management	1	3	0
IEEE Transactions on Computational Social Systems	1	2	0
Journal of Engineering, Design and Technology	1	1	1
African Journal of Science, Technology, Innovation and Development	1	0	3
Building and Environment	1	0	2
Journal of Global Operations and Strategic Sourcing	1	0	0

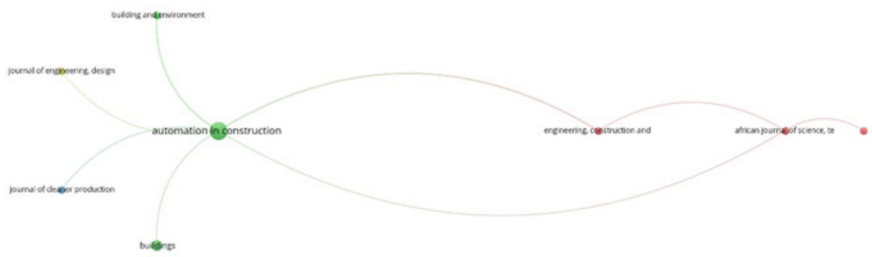

Fig. 5 Journal network

3.5 Clustering

A keyword frequency visualization graph of blockchain in infrastructure was generated by VOSviewer, as seen in Table 4 and Fig. 6. Among the most frequently mentioned keywords were blockchain(o = 17, TlS = 97), smart contract(o = 8, TlS = 66), architectural design (o = 7, TlS = 57), block-chain(o = 6,TlS = 48), construction industry(o = 8,TlS = 48), built environment (o = 8, TlS = 47), information management (o = 5, TlS = 41), smart contracts(o = 5,TlS = 34), building information modelling(o = 4, TlS = 33) and project management (o = 5, TlS = 32).

4 Discussion

4.1 Cluster Analysis

Cluster one

This cluster consists of twelve keywords including circular economy, digitalisation, and industry 4.0, among others. Industry 4.0, which includes global standards, the digitisation of business processes, and cyber-physical systems that collaborate with supply chain and logistics networks, is fundamentally driven by Artificial Intelligence (AI) [4]. [1] also noted AI, robotics, serverless computing, blockchain networks, and the Internet of Things (IoT) are all considered to be components of this trend. Many research efforts were focused on converting management procedures and activities in the construction sector from manual processing to electronic processing utilizing Information and Communication Technologies with the introduction of Industry 4.0 and the expansion of automation (ICT).

Blockchain, smart contracts, BIM, IoT, blockchain-smart contracts, and blockchain-information security are some of the current academic trends that are attracting a lot of interest. These current study topics are implicitly influenced by Industry 4.0 because IoT and blockchain-smart contracts have Industry 4.0 as a common denominator [17].

Table 4 Keyword cluster

Cluster one	Cluster two	Cluster three	Cluster four	Cluster five
Artificial Intelligence	Block-chain	BIM	architectural design	design/methodology/ approach
blockchain technology	blockchain	digital storage	building information modelling	information and communications technology
built environment	construction industry	distributed ledger	building information modelling (BIM)	risk assessment
circular economy	decentralisation	future applications	construction sectors	
construction	digital twin	hypeledger fabric	distributed ledger technology (DLT)	
digital technologies	internet of things	information management	project management	
digitalisation	network architecture	network security		
digitalisation	smart city	smart contract		
industry 4.0	smart contracts			
procurement processes	supply chains			
sustainability				
sustainable development				

In the delivery of infrastructure, there is not much active research linking sustainability with blockchain. Blockchain technology have received less attention in relation to sustainability initiatives including green procurement, sustainable procurement, and circular economy. Furthermore, sustainability might be linked with current blockchain technologies to develop a market for green construction materials [17]. The circular economy seeks to improve resource use throughout the whole construction process, from design through operation and destruction, using blockchain technology. It focuses on reducing waste by reusing materials, whether by removing substances that would hinder reuse, recycling materials, or engaging in any other activity that substitutes the idea of end-of-life [18].

Cluster two

This cluster consists of ten keywords including blockchain, construction industry, decentralisation, and digital twin, among others. The blockchain's transparency and immutability make it an ideal platform for testing if smart contracts may be used to automatically check the compliance of objects in digital models [4]. Smart contracts

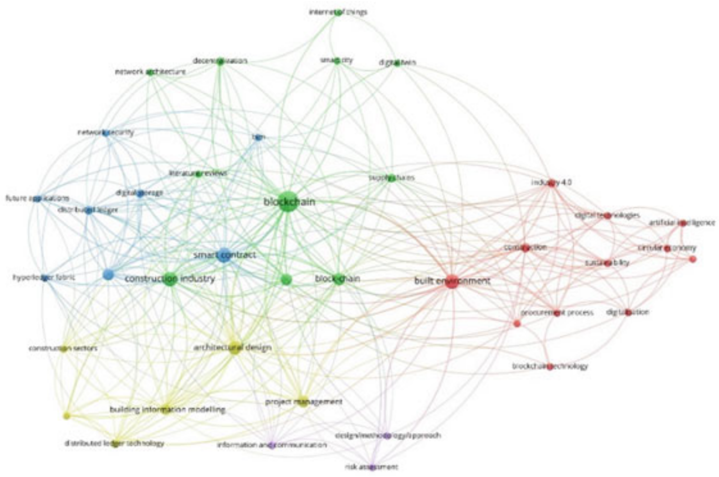

Fig. 6 Keyword cluster network

are among the most noteworthy features of blockchain for the construction industry. They are self-executing pieces of code that conduct a contract's provisions when certain conditions are satisfied. As some components may still need human input and control, smart contracts can alternatively be seen as regular contracts that can be automated [19].

The prototype of an artefact that contains the data necessary to represent the virtual model is referred to as its "digital twin." This can be developed for operations, processes, and aircraft [20]. The concept of a digital twin is a broader phrase that is evolving in tandem with the expanding deployment of IoT devices [21]. However, there are still challenges of integrating blockchain with digital twin [22] Decentralization, which distinguishes blockchain technology from the current, conventional, centralized standard database system or platform, is its primary characteristic. Decentralization guarantees that the contract's terms are legitimate without the need for a facilitator or central authority [3]. Additionally, [23] noted blockchain technology is being integrated with other technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI), for use cases such as enabling IoT device interoperability in a decentralized environment with fog computing acting as the orchestrating layer, on a blockchain-based access control layer to the IoT data storage, and on decentralized AI applications for enhanced data security and improved trust in AI.

Cluster three

This cluster consists of eight keywords including BIM, digital storage, distributed ledger, and future applications, among others. Blockchain technology, offers a distributed tamper-proof ledger with the agreement of many players to allay trust issues. It facilitates reliable computing and processing automation for a variety of applications and cross-organisational collaborations when used in conjunction with smart contracts [24]. Although blockchain has already demonstrated effective uses in the financial sector, it is thought to be a disruptive technology that has the potential to alter a wide range of industries, including supply chains and the healthcare sector.

Distributed ledger technology, or the use of Blockchain for the execution of Smart contracts, may help to improve network integration among participants and provide an appropriate means of monitoring the materials and waste cycle [25]. The information stored on the Blockchain can be accessible at any moment to track the proper management of building waste and its effects on the environment, while fully transparently documenting all information or acts.

Implementing blockchain-based BIM is an administrative process that has evolved significantly over time. This system uses blockchain technology to manage modelled data on the BIM platform, keeping the data private while allowing access to all stakeholders involved [3]. The Digital Twin is occasionally mistaken for BIM since it could refer to a rich BIM produced by the designer prior to the construction phase and utilized to create a building [20].

Cluster four

This cluster consists of six keywords including architectural design, construction sector and project management, among others. According to [4] blockchain is currently used in smart contracts for effective project management. Project management processes in the construction sector are extremely dispersed, fragmented, and complex, particularly throughout the execution and monitoring phases and more particularly while delivering infrastructure. To plan, monitor, and manage these processes in accordance with schedule, cost, quality, and scope requires a great deal of effort, resources, and intermediates [1].

Design an apartment layout using a blockchain-based decentralized application to get consensus from participants, with voting rights based on reputation and tokens. This is specific to architectural design. Additionally, blockchain helps automate architectural design using shape grammars to facilitate distribution, decision-making, and collaboration [18].

Cluster five

This cluster consists of three keywords which are design/methodology/approach, information and communications technology, and risk assessment. To design a cogent approach to encourage blockchain adoption specifically in the construction industry, it is critical to analyze the existing situation of blockchain in the built environment and the construction sector [19]. Additionally, a methodology that offers a workable and realistic resolution for its application to the delivery of infrastructure, particularly in developing countries, needs to be developed [26].

The use of blockchain technology can significantly reduce administrative costs, effectively safeguard intellectual property rights, remove onerous paperwork, manual verifications, and contract execution. Evaluating and selling ideas and workflows could potentially open a new source of income for design professionals [5]. Researchers in the ICT sector are creating a Blockchain platform to evaluate the general effectiveness and performance of Blockchain-based project management [27].

5 Conclusion

Information management is critical to the smooth operation of infrastructure delivery. It is the process of gathering, storing, distributing, archiving, and deleting/destroying data. Information and data management are critical to decision-making toward achieving improved, resilient, and responsive infrastructure delivery. While innovative tools abound to managing information in the built sector, barriers such as technical challenges, expertise needed, and cost of procurement inhibit the adoption of these technologies. In contrast, blockchain offers opportunities for accessibility, lighter and faster transaction speed, and secured data processing. However, research in this area is limited and slowly emerging. Therefore, this study adopts a bibliometric review to avail current progress, critical discussions, and vital strategies to advance the adoption of Blockchain development in the construction industry. This study aimed to provide a state-of-the-art bibliometric review using Scopus data from 2011 to 2021.

The study's results clearly show that the first publication was made in 2018, with an increase of fourteen publications in 2021. Moreover, some of the top countries leading in publications include the United Kingdom, Australia, and South Africa. While the United Kingdom, Australia and the United States are leading in terms of citations.

The leading journal in terms of the number of publications is automation in construction, buildings, and sustainability (Switzerland). In terms of citations, automation in construction is leading. This was followed by the journal of building engineering and engineering, construction, and architectural management.

The most frequent words in the articles include blockchain, smart contract, architectural design, blockchain, construction industry, built environment.

The bibliometric review of the selected articles revealed the progress of research on Blockchain in improving infrastructure delivery. However, there were limits in conducting the study. The study only looked at articles, and the data was sourced from Scopus. Future studies should look at various kinds of scholarly publications through various databases. The development of built infrastructure that scales well and facilitates the interoperability of blockchain applications and services could be a promising area of future research.

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Project Design, Construction, Planning, and Management

Organisational Leadership as a Driver for the Adoption of Digital Technologies for Construction Project Delivery

Matthew Ikuabe, Clinton Aigbavboa, Samuel Adekunle, Babatunde Ogunbayo, and Rotshidzwa Mugaga

Abstract The uptake of digital technologies for construction activities seek to proffer solutions to some of the challenges plaguing the delivery of construction projects. Organisational leadership players a vital role in the drive for the espousal of digital technologies in construction management. This study evaluates the factors affecting the pursuit of adopting digital technologies by construction organisational leadership. The study utilised a quantitative technique by deploying questionnaire for data collection using built environment professionals as the target respondents and the study area was Gauteng province in South Africa. The methods of data analysis used were Mean Item Score, Kruskal Wallis H-test, and SNK post hoc test. Findings from the study presents influential factors to the adoption of digital technologies by the leadership of construction organisations. The study contributes significantly to the knowledge base on the call for digital transformation in the construction industry.

Keywords Construction · Digital Technologies · Drivers · Organisational Leadership · Project Delivery

1 Introduction

Construction projects are characterised with dynamic series of planned and unplanned tasks carried out to achieve goals that are often well established or envisaged *ex ante* [1]. With ever-increasing clients' demands in delivering sophisticated building designs, sustainable infrastructure, and projects within the ambits of stipulated standards, the delivery of construction projects is hugely becoming more challenging [2, 3]. These include health and safety challenges, delays in project delivery, cost overrun, and underperforming projects amongst others [4–6]. Despite the intense efforts to abate some of these challenges, not much has been attained.

M. Ikuabe (✉) · C. Aigbavboa · S. Adekunle · B. Ogunbayo · R. Mugaga
CIDB Centre of Excellence, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: ikuabematthew@gmail.com

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Ballard [7] affirmed that some of these challenges are a result of the engaging process peculiar to the construction industry which is quite different from other sectors due to their monotonous system such as manufacturing.

Evidence has shown other industries such as retailing, banking, health, and manufacturing have embraced multifaceted approaches to the uptake of innovative technologies, while the construction industry is still trailing [8, 9]. The espousal of digital technologies has been heralded as one that has the potential to yield process optimisation, cost saving, reduction of task time, and enhanced service delivery [10, 11]. Hence, the propagation for the espousal of digital technologies is timely as it seeks to proffer solutions to the aforementioned issues confronting the construction industry. Moreover, Kamara et al., [12] opined that the construction industry is the right candidate for an upgrade considering the numerous challenges confronting it. However, one significant feature in the drive for the adoption of digital technologies is the role played by organisational leadership among construction organisations. Alade and Windapo [13] noted that role of leadership of construction organisations is vital in its pursuit of digital transformation. Furthermore, Markowitz [14] affirmed that policy makers are significant determinants to propel the uptake of innovative technologies and its attendant benefits resulting. Based on this background, this study seeks to explore the factors influencing the pursuit of adopting digital technologies by construction organisational leadership, with a view to proffering enhancing measures that can aid in propagating the uptake of innovative technologies for construction project delivery.

2 Literature Review

The organizational structure is a system of roles, responsibilities, authority, and communication links that are designed to assist an organization in accomplishing its tasks and meeting its objectives [15]. Transformational leadership refers to adaptive leadership behavior that has been shown to influence innovation, particularly the tendency of organizations to innovate. The development of observable administrative processes is referred to as organizational structure, whereas social interactions, which are ethereal in nature, assist the coordination of organizational members [16]. The degree to which organization leaders completes tasks or achieves its objectives is known as leadership effectiveness [17]. Hence, the hierarchal structure of organisations must encourage the development of a business climate that strives to improve the delivery mandates of the organisation and also push for the attainment of core objectives set by the organisation.

According to Dall'omo [18], implementing new technologies comes at a high cost. Therefore, the availability of the financial resource would play a vital role in the choice of digital transformation by organisations. Also, the cost implication of training the required personnel plays a determining role towards its uptake. Moreover, cost of maintenance is a considerable influential factor in the deliberations of digital transformations [19]. For construction organisations, the ability to properly define the potential benefits resulting from the uptake of a given innovative technology would significantly influence the choice of its adoption [20]. Usually, this would entail development strategies by engaging in analysis or assessment of its uptake. Furthermore, organisations are undecided on the need to engage in research and development. This is as a result of the uncertainty of the potential yields from such an investment [21]. Investments in research and developments would potentially serve as a driver for the espousal of innovative technologies by construction organisations. Also, the return on investment serves as a considerable influence in the choice of digitalisation by organisations [22, 23]. This is propelled by the need for organisations to seek profitability in investments made.

Data security and protection is a considerable factor in the pursuit of innovative technologies by organisational leadership of construction organisations. Qu et al. [24] noted that construction organisations are particular about data protection and cyber security in the pursuit of digital transformation. Moreover, the support of top management of construction organisations is a significant determinant in pushing the transformation pursuit through digitalisation. Ofori and Toor [25] stated that the support of the top hierarchy of construction organisations would help expedite the motive or agenda under focus. Moreover, the strategy employed by organisations is influential to construction organisations' digital transformation. Strategies employed by organisational leadership is influential to the actualisation of digital transformation of the organisation [19]. The organisational culture attributed to construction organisations plays a vital role in influencing the decision by organisational leadership to embark on inculcating digital technologies for project delivery [26]. Also, the strategies deployed by competitors serve as being influential towards determining the need of digital transformation by construction organisations [27]. Since construction is a competitive business, organisational leadership of construction organisations would aim to keep tabs of competitors' strategies in order to maintain a comparative advantage for a favourable business environment.

3 Methodology

The study assessed the factors influencing organisational leadership of construction organisations to adopt digital technologies for construction projects. After the review of extant literature, factors were identified which were subsequently presented to construction professionals for rating based on their level of significance. This was actualized with the use of a well-structured questionnaire which consisted of two sections. The former focused on the demographic information of the respondents while the latter was focused on the identified factors for rating by the respondents. The target respondents of study which are construction professionals were architect, quantity surveyors, construction managers, engineers and project managers. Convenience and snowball sampling technique was adopted for the study, while the area of study was Gauteng province of South Africa. A total of seventy-four responses was retrieved and deemed appropriate for analysis. The methods of data analysis employed for the study was mean item score, Kruskal-Wallis (K-W) H-test, and Student Newman Kauls (SNK) post-hoc test. Mean item score was used in ranking the identified factors as rated by the respondents, while Kruskal-Wallis H-test was deployed to ascertain if there is a statistical difference in the opinion of the groups of respondents based on their professional affiliation. While the SNK post-hoc test was employed in differentiating the mean responses of the respondents based on their professional designation.

4 Findings

A total of fourteen factors were identified after the review of extant literature and thereafter presented to the respondents of the study for rating based on their significance. Table 1 presents the result of the ranking of the factors and also the result of the analysis of *K-W* test conducted. The findings from the table indicates that the most rated factors influencing construction organisational leadership in the adoption of digital technologies are return on investment with a mean score of 4.34, top management support having a mean score of 4.27, financial resource with mean score of 4.19, organisational culture and definition of benefit with usage with mean scores of 4.04 and 4.00 respectively. It is observed that all the factors have a mean core above 3.00, thus implying their significance. Furthermore, the result from the *K-W* test shows that there is no statistical significance difference in the opinions of the group of professionals for thirteen of the identified factors. This is because these thirteen factors all have a p-value above 0.05, thereby indicating that there is a convergent view among the different professionals on these factors. However, there is a discrepancy in views of the group of respondents on one of the factors (personnel training) due to the derived p-value of the factor being less than 0.05. This might be as a result of the different professional designations having different core professional mandates in delivery of construction projects.

Table 2 portrays the result of the SNK post-hoc test (multiple comparison) conducted for the study to showcase the mean difference of the group of respondents. The findings of the test shows that there is a significant difference in the factors influencing organisational leadership in adopting digital technologies among two groups of the respondents. The first group is made up of quantity surveyors and engineers with values of 2.7723 and 2.9148 respectively. While the other group comprises of construction managers, project managers and architects with values of 3.1052, 3.4992, and 3.6782 respectively.

Table 1. Factors influencing organisational leadership in adopting digital technologies

Factors	$\overline{X}$	R	*K-W*	
			X^2	Sig
Return on investment	4.34	1	1.319	0.290
Top management support	4.27	2	5.836	0.411
Financial resource	4.19	3	3.227	0.537
Organisational culture	4.04	4	7.092	0.465
Definition of benefits with usage	4.00	5	6.295	0.071
Organisations' objectives	3.95	6	4.003	0.173
Business environment	3.72	7	1.842	0.092
Market orientation	3.71	8	3.849	0.484
Organisation's strategy	3.69	9	2.274	0.712
Personnel training	3.62	10	1.582	0.021*
Organisation's corporate image	3.58	11	4.692	0.873
Competitive pressure	3.55	12	5.826	0.159
Research and development	3.42	13	8.379	0.585
Data security and privacy	3.37	14	6.662	0.231

Table 2. SNK Post Hoc Test

Groups	N	Subset for alpha = 0.05	
		1	2
Quantity Surveyors	14	2.7723	
Engineers	14	2.9148	
Construction Managers	14		3.1052
Project Managers	14		3.4992
Architects	14		3.6782
Sig		1.000	0.668

Means for groups in homogeneous subsets are displayed.
a. Uses Harmonic Mean Sample Size = 14.000.

5 Discussion of Findings

Main factors to organisational leadership of construction organisations to the adoption of digital technologies was assessed in this study. Findings from the analysis conducted shows that the most influential factor is return on investment. This finding is corroborated by Oh et al., [22] who noted that the return on investment serves as a considerable influence in the choice of digitalisation by organisations. Moreover, organisations are propelled to commit funds for digital technologies when there is a clear mandate that the investments would yield financial returns [23]. Generally, the driving idea of engaging in digital transformation by organisational leadership is the assurance of attaining financial advantage. Furthermore, the study reveals that top management support is a significant factor in the quest for digitalisation by construction organisations. Ofori and Toor [25] stated that the support of the top hierarchy of construction organisations is crucial to important decisions of construction organisations. Hence, the support of top management of construction organisations is a significant determinant in pushing the transformation pursuit through digitalisation. Also, the financial resource at the disposal of the organisation is a considerable determinant in the choice of digitalisation by organisational leadership. According to Zhang et al. [21], implementing new technologies comes at a high cost. Therefore, the availability of the financial resource would play a vital role in the choice of digital transformation by organisations. Additionally, it is revealed that all the group of professionals making up the respondents for the study all have a convergent opinion on all the identified factors for the study except for personnel training. This might be as a result of the different professional designations having different core professional mandates in delivery of construction projects, thereby having different obligations with the digitalisation process.

6 Conclusion

The study assessed the factors influencing the pursuit of the adoption of digital technologies by construction organisational leadership. Subsequent to the review of literature, the study identified fourteen factors which were presented to the respondents of the study for rating with the use of a well-structured questionnaire. Retrieved data was subjected to statistical analysis which revealed the most significant factors as return on investment, top management support, and financial resource. Also, it was shown that there was a divergent view among the group of respondents in only one of the factors, which is personnel training; while other factors saw a convergent view among the group of professionals. Based on the findings of the study, it is recommended that organisational leadership of construction organisations should encourage digital transformation of construction organisations since it guarantees effective construction processes, efficient service delivery and optimisation of resources is guaranteed. Consequently, yielding to a potential return on investment in the digitalisation process. Also, the drive for the uptake of digital technologies should be one that should get the support of top management of construction organisation since they play a vital role in the management of organisations.

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Modeling Drywall Construction Process Using a Spatiotemporal Chronographical Scheduling

Adel Francis and Edmond Miresco

Abstract The Gantt/Predictive Diagram is the most widely used model for planning building construction projects. This diagram focuses on defining activities and constraints and then allocating resources to those activities. Space constraints are generally neglected. This makes it difficult to represent the sequence of work, traffic, and supply flow between different sites. Spatiotemporal models are considered more appropriate as scheduling models. These models aim to linearize activities, resources, and spaces at the same time. The objective of this research is to model drywall construction process using a spatiotemporal Chronographical scheduling. Partition drywall assembly involves many components. Each of these components has a wide variety of types, sizes, or other technical specifications. Space planning models the sequences of operations on the construction site by subdividing the construction site into areas to define work zones. Although this type of division is well suited for most construction stages of implementation, such as creation of spaces, systems, finishing, closing of spaces, and outdoor facilities; it is less suited, for the envelope and the division of spaces stages of implementation. Spatial divisions of the site must therefore be adapted to this reality. The novelty of this publication is that it proposes a new way of dividing spaces, and it demonstrates this through a practical example.

Keywords First Keyword · Second Keyword · Third Keyword · Forth Keyword · Sixth Keyword

1 Introduction

Traditional planning methods based on the Gantt/Precedence diagram focus on defining activities and constraints, and then allocating resources to these activities. Space constraints are usually neglected. Neglecting space may result in a congested

A. Francis (✉) · E. Miresco
École de Technologie Supérieure, University of Quebec, 1100 Notre-Dame Street West, Montreal, QC H3C 1K3, Canada
e-mail: adel.francis@etsmtl.ca

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or relaxed site, negatively affecting project duration. In addition, allowing traffic to occur haphazardly, without forethought or control, can produce traffic congestion [5]. Resource management, without consideration of work location, is inefficient. Resources cannot be used, even if available, beyond the capacity of the workplaces. The planner must also ensure proper rotation of teams across spaces.

Over the years, many space-based scheduling methods have been developed. Most of them rely on purely algorithmic solutions. These solutions define the model parameters considered important, but neglect others considered less important. Neglecting parameters in order to do complex modeling could harm the results.

This paper supports the idea that graphical solutions are more suitable for modeling complex construction sites. Graphical modeling acts as a decision support system that guides planners and managers to make better decisions. In the past, some researchers have selected graphical modeling for space-based planning. Winch and North [11] defined spaces by their occupancy status. Riley and Sanvido [7] focus on the division of work spaces and the sequencing of activities, Tommelein et al. [10] show constrained spatial planning for multi-story buildings, Akinci and Fischer [1] capture the spatial requirements of different trades, Francis [2–6] introduces the spatio-temporal concepts of the Chronographical modeling to represent worksite operations with various compatible graphical and tabular approaches, Winch and North [11] developed the Critical Spatial Analysis (CSA) to link the spatial and temporal aspects of a worksite, Seppänen et al. [8] use a location-based management system (LBMS) to plan and control production.

The objective of this research is to model drywall construction process using a spatiotemporal Chronographical scheduling. Space planning models the sequences of operations on the construction site by subdividing the construction site into areas to define work zones. Although this type of division is well suited for most construction stages of implementation, such as creation of spaces, systems, finishing, closing of spaces, and outdoor facilities; it is less suited, for the envelope and the division of spaces stages of implementation. Spatial divisions of the site must therefore be adapted to this reality. The novelty of this publication is that it proposes a new way of dividing spaces into linear strips according to the different specialties of the subcontractors, and it demonstrates this through a practical example.

2 Chronographical Modeling

To meet the needs of planners and address the shortcomings of current methods, Francis [2] developed the Chronographical modelling. A graphical modeling for scheduling the construction operations on the project site. This modelling considers simultaneously the different elements of construction, namely, work, crews, materials, and spaces. Various compatible graphical modelling approaches, using graphical means of distinction, association, scale and attributes, have been proposed. Each approach demonstrates the necessary information to meet a certain need. The planner can switch between these approaches by manipulating the different graphical parameters [3, 4]. The proposed tabular and graphical approaches allow grouping the scheduling information according to the specialties of the subcontractors, the works or the spaces. By modeling spaces, it is also easier to plan traffic and intermediate stocks.

The Chronographical modeling can also presents different spatiotemporal approaches in order to allow the modeling of site spaces in addition to activities and resources. These modeling could allow:

i) to model the site spaces (floors and zones) as the background of the schedule and demonstrates construction operations on the foreground (Francis [5]). Spatiotemporal approaches combine three linearities: resources, spaces and activities. These approaches prioritize the critical space in the critical path of activities by defining the optimal site occupancy rates. Graphical optimization as described in Francis [5] became easier and more realistic. By combining graphical, procedural and algorithmic aspects, planner could have better solution for building construction sites without a need of complex calculations;

ii) to conversely represent the planning of construction operations on the project site plan [6]. This second model is named a site-spatial-temporal scheduling. The scheduling modeling process for this modeling define for each floor, the layers that demonstrate the construction steps (creation of spaces, systems, divisions, finishes and closing of zones) and divide each layer into zones that ensure a Takt production. For each specialty, the model defines the sequence of work by linking the activities of the specialty between the different areas, respecting the predefined working direction. Figure 1, demonstrates an applied example for the site-spatial-temporal scheduling. This figure shows at the same time, the graphical site-spatial-temporal (in the upper part) and two tabular approaches (in the lower part). The first is grouped by site spaces (Zones) and the second is grouped by specialties (Teams).

3 The Design Model for Scheduling Drywalls Construction

The systematic graphical design model is used to create visual models for scheduling drywalls construction. It involves breaking down a problem into its components and analyzing each component using graphic elements to represent the structure of the system. This technique allows planners to plan crew rotation on the site and helps stakeholders to clearly understand how different parts interact with each other and also encourages collaboration, making it easier for teams to make decisions in a timely manner and reducing conflict on the site.

The design model is based on the process developed by Steenkamp and McCord [9]. This process specifies the following steps:

1. The context of use: In previous publications, the Chronographic modeling used areas to define work zones. Although this type of division is well suited for

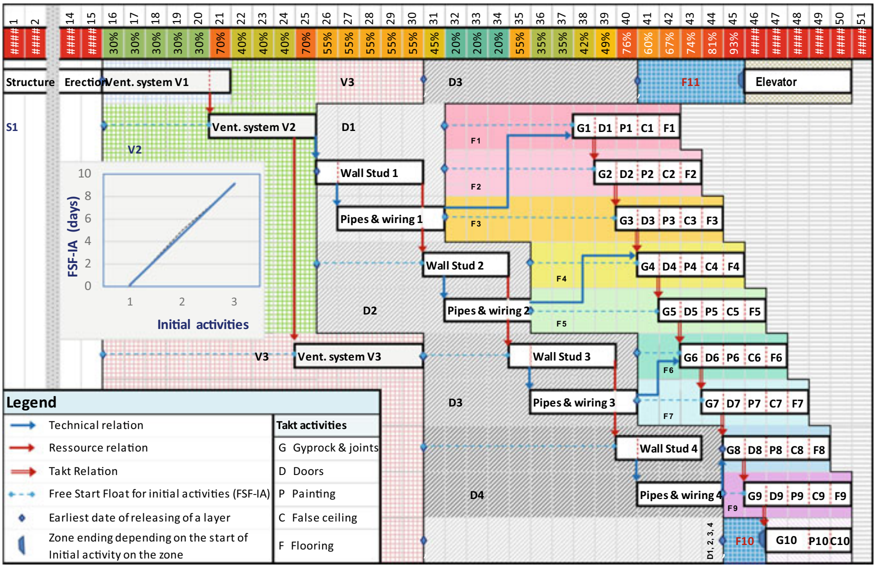

Fig. 1. Applied example Spatiotemporal Scheduling Optimization [5]

most construction stages of implementation, such as creation of spaces, systems, finishing, closing of spaces, and outdoor facilities; it is less suited, for the envelope and the division of spaces stages of implementation.

2. The need for new artifacts: For the envelope and the division of spaces stages of implementation, the advancement of the teams is done linearly. Spatial divisions of the site must therefore be adapted to this reality. The construction schedules must also be compatible with these types of operations. The developed artifacts show the dynamic evolution of the occupation of these types of works.
3. The structural specifications and the prototype: The conceptualization structure and the prototype of these artifacts are based on the Chronographical approach. The next section will explain the elements, and structures on a prototype based on a practical example.
4. The implementation and the evaluation: The applied example presented will demonstrate the implementation process. More complex examples have to done in the future on real projects in order to validate the proposed design.

4 Modeling Drywall Construction Process

Partition drywall assembly involves many components, including gyprock, metal (or woods) studs, insulation, electrical wiring, and telecommunication wiring. After laying the drywall, the gyprock needs grouting and then a finish coat, such as painting, wallpaper or ceramic. For the envelope, in addition to these components may be added several exterior finishing works, including, the vapor barrier, sheathing (or bracing), air barrier, battens, and sidings. Sidings also come in many types, including masonry, glass curtain walls, aluminum, vinyl, wood, fiberboard, or fiber cement. Each of these components has a wide variety of types, sizes, or other technical specifications.

While it is optimal to create typical partitions on the architectural drawings, it is not the same for construction site operations. For the design phase, it is simpler and more efficient to do groupings, which will lighten the plans and estimates of grades C and D. Note that modelling software such as Revit also promotes this technique by creating product families. For the construction phase, each component is carried out by a different subcontractor. Construction contracts are based on materials (wood, plastic, metal, etc.) and not on construction elements (walls, floors, doors, windows, etc.). For example, wood, steel, and aluminum windows are not manufactured by the same supplier. On the other hand, a supplier, who works with steel, will be able to manufacture doors, windows, cabinets, and even stairs in steel. The same logic is applied for wood, vinyl, and ceramic floors, for which different subcontractors will be hired to do the installation on site. So, while groupings by type are excellent for the design phase, they fail for site work planning.

The Chronographical method graphically models the sequences of operations on the construction site by subdividing the construction site into zones. Areas over which crews move to perform work in different emplacements of the site. To do this, the modeling creates a dynamic hierarchy of spaces, a Location Breakdown Structure (LBS). The LBS is structured into project components (different buildings); vertical levels (floors); and horizontal spaces (zones). The LBS identifies, for the zones, the seven (7) major successive stages in the implementation of the construction phase of a building project, namely the creation of spaces (e.g., addition of new floors); systems (e.g., ventilation ducts); envelope (e.g., exterior walls and roof); division of spaces (e.g., partitions); finishing (e.g., painting); closing of spaces (e.g., carpeting); and outdoor facilities and exterior landscaping. The Chronographical method graphically models these stages by creating seven levels of graphic layers. Each is subdivided into zones according to the stage of construction, creating a dynamic hierarchy of spaces.

As mentioned before, for the envelope and the division of spaces, work is done linearly. Spatial divisions of the site must therefore be adapted to this reality. The novelty of this publication is that it proposes a new way of dividing spaces, and it demonstrates this through a practical example. To date, the site decomposition systems offer work surfaces, which are appropriate for many specialties, such as floor installation. However, for linear work, such as partition installation, the site breakdown into areas is an approximation that can hardly be used to establish a good crew rotation. Thus, the new way of dividing the spaces into linear strips according to the different specialties of the subcontractors, represents a good solution. The principal strength of this method is related to its modelling ability that facilitates communication of information between the site stakeholders on the construction site. The dynamic representation of the occupancy of the site using adapted artifacts will improve the visualization of the schedule, ensure a good balance of the use of spaces throughout the project, and will act as a decision-making support system.

5 Applied Example for Scheduling Drywalls Construction

The following example (Figs. 2, 3 and 4) shows the preparation work for drywall assembly for a three-story building. The work includes metal studs, drywall installation (Gyprock), insulation, electrical wiring and telecommunication wiring. Grouting, and painting are not included in this example.

The graphical visual model designs the concept of artifacts that express the objects on the two-dimensional plan. These artifacts demonstrate the modeling of walls components and their sequences to facilitate team rotation, but not as an execution

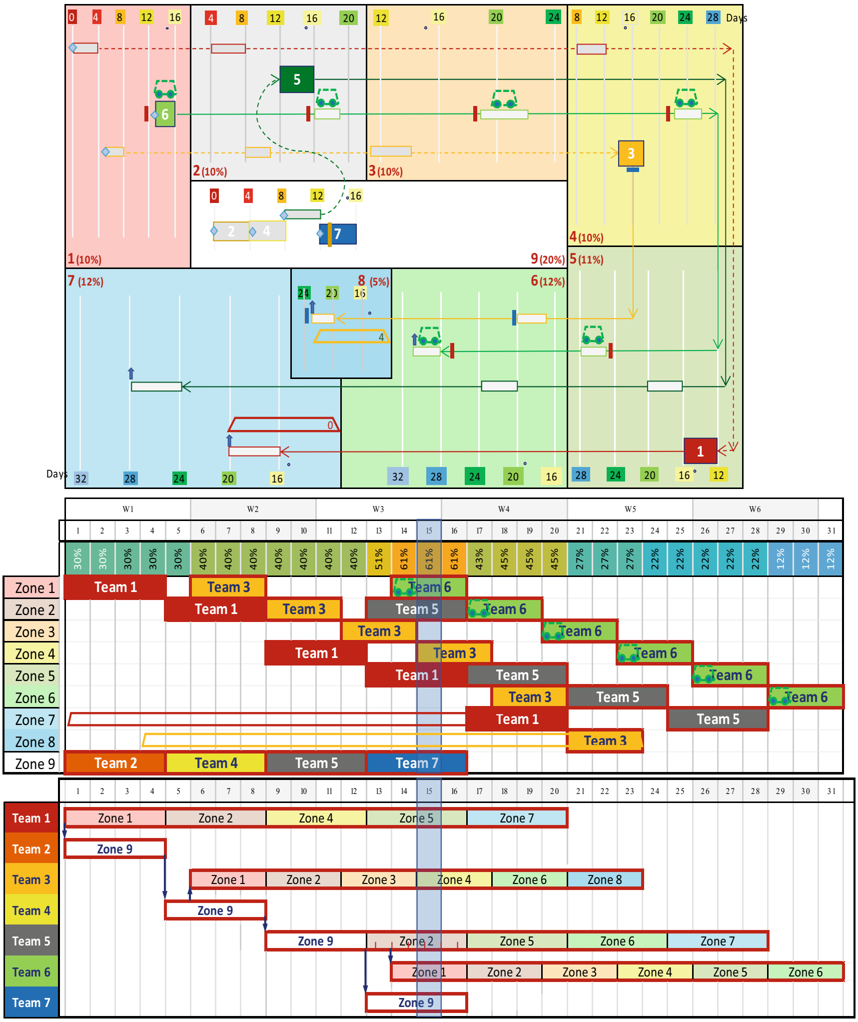

Fig. 2. Applied example for the site-spatial–temporal scheduling [6]

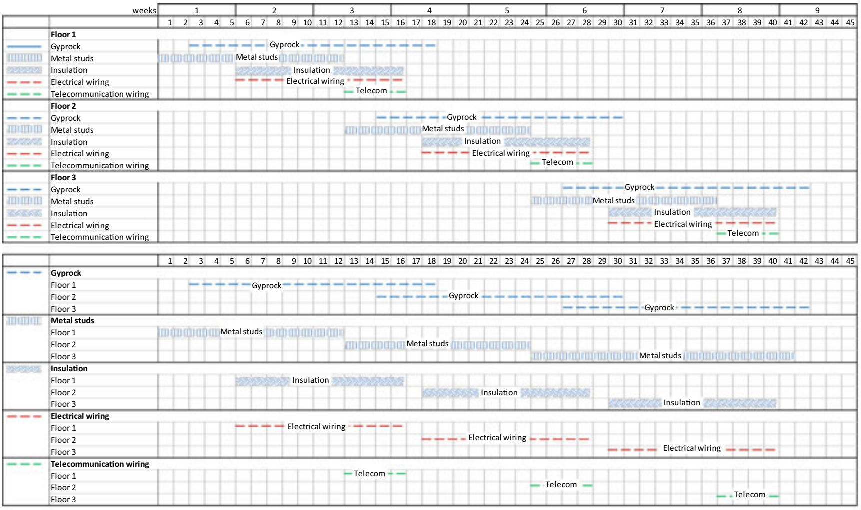

Fig. 3. Project planning grouped by floors and by specialties

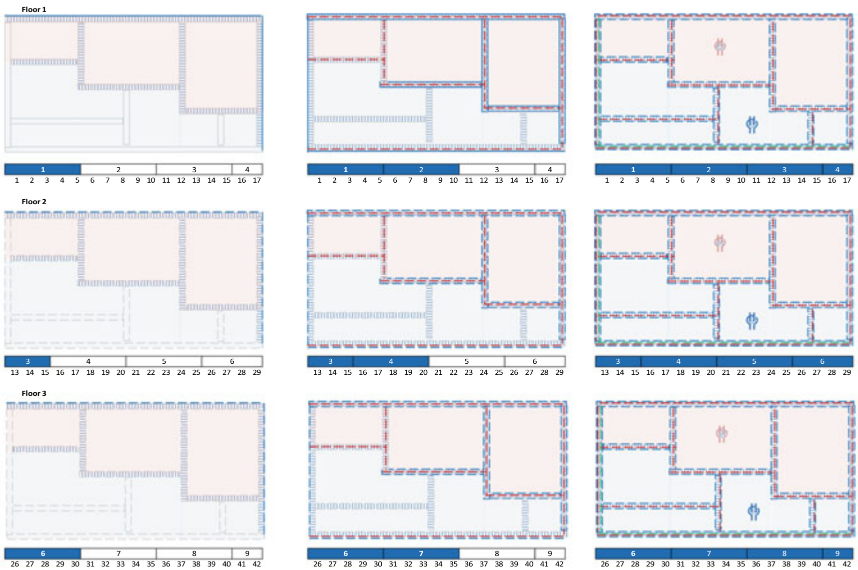

Fig. 4. Project planning and grouped by floors and by specialties.

Fig. 4. Project planning using site-spatial-temporal modeling

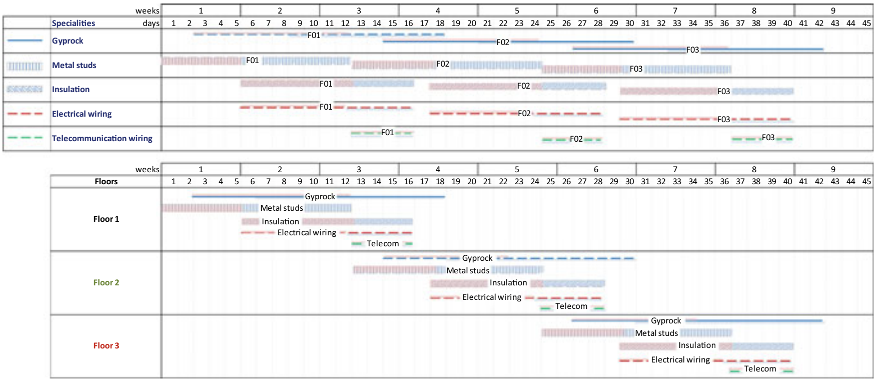

Fig. 5. Project planning and grouped by specialities or by floors

process. For the wall construction process, the model allows the planner to formulate his execution strategies according to the site architecture. This strategy is usually coordinated with the site workers in a Last Planner planning logic.

Figure 2 shows the planning of this project in two forms: i) The upper part shows the specialties grouped by floor. This facilitates the coordination of the work on each floor; and ii) the lower part shows the floors grouped by specialty. This shows the sequence of each specialty on the different floors.

Figure 3 shows the same planning of the same project. The only difference with Fig. 2 is that each floor is divided into two zones shown by the blue and pink colors.

Figure 4 shows this planning on the floors. It is a 2D+1 planning (a simulation similar to the 4D planning, but with a 2D plan + time). In this figure, the evolution of the construction is demonstrated, on each floor, on a weekly basis. Thus, the first section of the figure (top left) shows the progress of the first floor during the first week (days 1 to 5), while the section of the figure (bottom center) shows the progress of the third floor during weeks 6 and 7 of the project (days 26 to 35).

Figure 5 shows the same groupings as Fig. 2, namely, specialties grouped by floor, and floors grouped by specialty. The difference, as mentioned, is related to the distinction between the work progress in each zone.

6 Conclusion

In conclusion, spatiotemporal models are considered more appropriate to model the construction of building projects. These models model the sequences of operations on the construction site by subdividing the site into zones to define the work areas. Although this type of division is well suited to most stages of construction implementation, it is less suitable for the envelope and space division. The process of building the envelope and drywall is done linearly. The spatial divisions of the site must therefore be adapted to this reality. This paper develops artifacts that demonstrate the linear and dynamic evolution of the occupation of these types of structures. The use of these artifacts improves the visualization of the schedule and ensures a good balance in the use of spaces. The novelty of this publication is that it offers a new way of dividing spaces, and it demonstrates it through a practical example. Its main asset is linked to its modeling capacity, which facilitates the communication of information between the actors of the construction site on the construction site.

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Towards Increased Situational Awareness at Unstructured Work Zones: Analysis of Worker Behavioral Data Captured in VR-Based Micro Traffic Simulations

Julia Qin, Daniel Lu, and Semiha Ergan

Abstract In 2020, the Federal Highway Administration (FHWA) reported 857 fatalities due to crashes at roadway work zones, 117 of which were construction workers. Current practices to protect the personal safety of workers, such as stationary sound and light-based work zone intrusion alarms, are frequently disregarded since their alarm characteristics (e.g., volume, duration, frequency) are not well suited to work zone environments. Such alarm devices are also rarely deployed at unstructured (i.e., mobile and short term) work zones. There is a need to identify optimal alarm characteristics that can effectively notify workers of incoming hazards at unstructured work zones without alarm fatigue. This paper is part of a larger research vision, where an integrated platform of virtual reality (VR), micro traffic simulations, and wearable sensors is used to capture workers' physiological and behavioral response to alarms. This platform enabled analyzing behaviors during dangerous traffic scenarios that are not feasible to test in real world settings. The captured data will be used as a dataset to build reinforcement learning (RL) based calibration models to optimize the frequency, modality, and duration of alarms that workers are more attentive to. Towards this goal, this paper provides the results of initial data analysis on how workers responded to alarms sent to wearable devices with different modalities (e.g., sound, vibration), durations, and frequencies. Effect of different alarms on worker behavior and physiology has been measured with metrics that rely on workers' positional changes, head movements and what they see in their field of views, heart rate changes, and acknowledgement of alarms on wearable interfaces. Results indicate that alarms with shorter durations and repeated less frequently can lead workers to react faster by detecting vehicles and acknowledging the wearable warning device. Findings from this study can serve as benchmarking data for the design of effective alarm systems for work zones and be utilized as a dataset for RL models for training agents for such systems.

J. Qin (✉) · D. Lu · S. Ergan
New York University, Brooklyn, NY 11201, USA
e-mail: jq676@nyu.edu

D. Lu
e-mail: dbl299@nyu.edu

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Keywords Wearable devices · Situation awareness · Virtual reality · Worker safety

1 Introduction

Latest figures from the United States (US) Federal Highway Administration (FHWA) and Department of Labor report that vehicle crashes led to 857 fatalities, 117 of which were construction workers, and resulted in 44,000 injuries at roadway work zones in 2020 [1, 2]. These metrics have either increased or remained at similar levels in the last five years. While roadway work zones employ a variety of safety measures to alert vehicle drivers approaching a zone, including layout of traffic control devices (i.e., cones, barrels) and signage, recent work zone intrusion alert (WZIA) systems have been developed to warn workers with sound and light-based alarms after sensors detect potentially hazardous vehicles [3, 4]. Research has begun to understand how these alarm systems can impact workers' safety behavior, such as how responsive they are to alarm characteristics and their resultant situational awareness (SA), the perception of their surrounding elements and ability to project the status of safety hazards in the near future [4–6]. Most WZIA systems emit a fixed set of light and sound-based alarms from a stationary location in the work zone. Consequently, these fixed alarm characteristics (e.g., volume, frequency) are difficult for workers to perceive, either due to environmental conditions (e.g., construction noise, foggy weather, night time) or simply because workers are positioned farther away from the alarm devices. Studies have shown that workers farther away from alarm sources are less likely to notice the alarms and react slower to them, decreasing their SA of hazardous vehicles [5].

Some WZIA systems attempt to counteract the effects of workers' distance from alarms with personal alarm devices carried by the worker [5]. This system feature points to the potential of wearable alarm devices to improve worker's perception of alarm characteristics and improve their resultant SA of nearby traffic. Such wearable alarm devices are especially useful for short-term and mobile roadway work zones, where relatively few traffic control devices are used in layouts [5]. However, there is limited information on what wearable alarm characteristics, such as modality (e.g., sound, vibration), are more effective at evoking a worker to physically react [8]. This paper analyzes data obtained from virtual reality (VR) simulations of urban short term and mobile roadway work zones to examine how workers react to varying alarm characteristics emitted by wearable devices (i.e., a smartwatch).

Improvements in VR and wearable sensing technologies have enabled researchers to more precisely analyze worker behaviors in roadway work zone hazard scenarios without endangering human participants in physical testbeds and real work zones. In order to determine which alarm characteristics more effectively notify workers of incoming hazards, the research team developed a hardware-in-the-loop (HIL) experiment platform integrating virtual reality (VR), calibrated micro-traffic simulations, and wearable sensors [7, 9]. Participants were invited to a visualization lab to perform tasks in virtual work zones while wearing a smartwatch with an application that emitted a random pattern of sounds and vibrations every time a hazardous vehicle (e.g., speeding, work zone collision) approached the work zone. The data obtained from the integrated platform was analyzed to evaluate how varying an alarm pattern's characteristics impact different worker behaviors (e.g., acknowledging alarm, turning head, positive body movement). This data also forms the basis for developing reinforcement learning (RL) controls for the alarm patterns in response to how quickly workers react to the alarms and maintain their safety.

2 Related Work

2.1 Previous Research Studies on Understanding Worker Reactions to Alert Systems

Numerous studies have examined the reactions of workers to alarms in other domains such as firefighting and medical settings (e.g., nurses) [10]. Within the construction industry, however, studies have mainly focused on how workers respond to proximity-based alarms, where alerts are raised to a person when they walk too close to a hazardous object on construction sites [10]. Relative to vertical construction sites (e.g., high-rise buildings), horizontal roadway work zones face a unique risk from passing vehicles. With the commercial development of various WZIAS, research studies have sought to compare their effectiveness in preventing accidents in real-world roadway work zones or physical testbeds involving predetermined vehicle driving trajectories. For example, Gambatese et al. compared how well different work zone intrusion alarms could be heard amidst heavy construction noise in real-world construction work zones [4]. Both construction workers and research staff onsite were given clicker remotes to record when they heard an alarm. Remote clicker reaction times range from 2 to 6 s. Thapa and Mishra utilized physical testbed simulating vehicles and workers in the real-world to evaluate the effects of different work zone layouts and different WZIA systems on worker reaction times, defining reaction specifically as when a worker started to move away from the hazardous vehicle. Mean reaction times were observed to be around 2 s [5].

In these studies, reaction times were a key metric in evaluating WZIAS and were measured using either a remote clicker for each worker to press after noticing an alarm, or a research team member reviewing video recordings for when workers physically moved away from vehicles. In the case of the remote clicker measurement method, a reaction time can be quantified but does not capture specific aspects of a worker's physical reaction (e.g., head turn, body movement). In the case of video recordings, researchers seemed to only focus on a specific physical reaction of body movement, excluding other physical reactions and aspects of a worker's SA that ultimately improve their life safety. Did the worker turn their heads before moving their body away from the vehicle? Did the worker notice the vehicle before the alarm? Furthermore, none of the aforementioned studies employed biometric sensors (e.g., heart rate, respiration sensors) to measure if workers' physiology indicated that they perceived either the alarms or the approaching hazardous vehicles. With the research team's previous work on an integrated VR, traffic simulation, and wearable sensor platform, results discussed in this paper will discuss the many ways participants reacted to the alarm, beyond when they acknowledged the alarm on a remote device and physically moved their body. These forms of reaction times were all quantified by wearable sensor measurements, rather than based on qualitative measures.

2.2 Previous Research Studies on Traffic Safety Using Wearable Sensors and Virtual Reality

To analyze worker's behavior and SA more closely, wearable sensors have been tested in various field studies, examining workers' visual attention (i.e., eye-tracking) and physiological state on real-world construction sites [11, 12]. Meanwhile, many VR-based approaches have been developed for the purposes of worker safety training, but few focus on using virtual simulations for the purposes of testing alarm devices [13]. Most notably, Kim, et al. evaluated risk habituation among human workers after multiple exposures to backup alarms from construction vehicles, and a work zone traffic accident [14]. Their user study protocol had participants wear VR and perform construction tasks in two separate sessions. During each session, VR-based sensors measured how often participants looked up towards a construction vehicle backing up towards them. An accident occurred when participants frequently did not look up at the construction vehicle, causing it to dramatically accelerate towards and collide with the participant. Risk habituation was measured by counting how often workers gaze direction was towards the construction vehicle, and how this "checking rate" changed between the participants' first and second sessions. This measure of worker vigilance appeared to improve with more VR sessions and exposure to an accident. Rather than focusing on how worker behavior is impacted by increased time spent in the VR work zone environments, this paper examines the specific impact of wearable alarm characteristics. Overall, this work focuses on how wearable alarm devices can promote worker safety, rather than use of VR-based safety risk exposure methods.

3 Methodology

In order to analyze the effects of varying alarm characteristics on forms of worker reactions, user studies were conducted on an integrated platform of VR, microscopic traffic simulations, smartwatch applications, and wearable sensors. User study participants wearing a VR headset performed simulated construction tasks near traffic flow. Hazardous vehicles (e.g., speeding vehicles, vehicles colliding with the work zone) approaching the work zone triggered alarms of random characteristics (e.g., duration, frequency, modality) on a smartwatch on the participant's wrist. A suite of wearable biometric and locomotion sensors recorded different forms of the participant's response to the different alarms and dangerous vehicles: watch acknowledgment time, body movement reaction time, vehicle detection reaction time, head turn reaction time, and heart rate percent change. The following subsections describe the aforementioned simulation and data collection methods in more detail.

3.1 Integrated VR-Traffic Simulation Platform

Previous work by the research team led to the development of an experiment platform that integrated VR environments with traffic simulations to realistically model work zones along urban streets [7, 9]. Real-world work zones were reconstructed as VR environments using 3D laser scanning and Unity3D game engine, while traffic patterns along the work zone were modeled with the open-source software Simulation of Urban Mobility (SUMO). SUMO has been validated to replicate traffic flow, helping to ensure realistic vehicular trajectories in the simulation of a roadway work zone. To further increase the realism of the work zone traffic simulation, a customized application programming interface (API) was created to enable bi-directional communication of traffic control devices (e.g., cones, barrels) and vehicle locations in both the traffic simulation and VR environment (Fig. 1). An ultrasonic sensor was also placed around the perimeter of the VR experiment area, creating a hardware-in-the-loop (HIL) system that connected external monitoring of the participant's physical location to the VR environment. Three virtual environments were created on this platform to simulate a variety of work zone scenarios on different urban roadway conditions: (1) placing cones to define a mobile work zone in an urban street, (2) installing a traffic sensor on an urban highway, (3) surveying across an urban intersection. These scenarios were developed for the platform after review of traffic safety literature revealed mobile and short-term construction zones may be more accident prone due to lack of traffic control devices [9]. This paper provides preliminary analysis of how users of the VR-traffic simulation platform reacted to smartwatch alarms in the first work zone scenario.

Traffic simulation also enabled modelling of hazardous vehicle behavior, such as speeding vehicles and vehicle intrusions or collisions at the work zone perimeter (see Sect. 3.3). When these hazardous events occur in traffic simulations, alarm data is sent to a cloud server to pass to wearable devices, such as a smartwatch, to emit an alarm for the worker (Fig. 1). When the VR participant's physical location is also near the edge of the work zone perimeter, the ultrasonic sensor's RaspberryPi control board would also send data to the server to trigger the wearable alarm. Overall, this integrated VR-traffic simulation platform served as a virtual testbed for simulating hazardous vehicle events around a work zone and collecting data on precise changes in workers' physiology and behavior when responding to different alarm patterns and work zone scenarios.

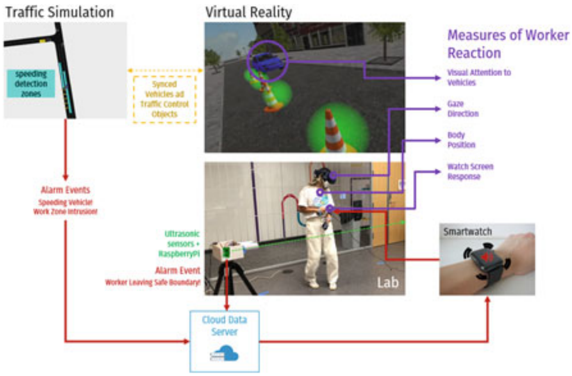


Fig. 1. Integrated VR and traffic simulation platform for evaluating smartwatch alarm characteristics' impact on worker reactions

3.2 Smartwatch Alarm Characteristics

The smartwatch application for the Apple Watch was developed to emit different alarm patterns of randomized characteristics during VR-traffic user studies. Due to the gap in the literature on worker alarm responses, the research team tested a wide variety of alarm characteristics to notify users of dangerous vehicle events. The Apple Watch used in this study already had built-in alarms types of various sounds and vibrations, each lasting around 0.8 s. Alpha tests of smartwatch alarms found that Apple Watch's built-in "Retry" notification sound and vibration was found to be most noticeable and was therefore used to create different alarm patterns. Each alarm pattern is defined by a combination of characteristics: (1) alarm durations, ranging from 1.8 to 3.8 s (2) number of repetitions, ranging from one to three times, (3) frequency of repetitions, ranging from 0.5 to 1 Hz and (4) modality, including tactile vibrations and vibrations combined with sounds. In our study, "alarm duration" is defined as the total length of time of continuously emitted built-in alarms. For example, a built-in alarm duration of 0.8 s that was emitted three consecutive times was considered to have an effective alarm duration of 2.8 s for this study. The continuous duration of built-in alarm could be repeated once or twice, and the repetitions could be spaced apart by a pause of one or two seconds (i.e., a frequency of 1 Hz or 0.5 Hz). The "total notification period" of an alarm was defined as the length of time of the selected alarm pattern, or the sum of the associated alarm durations and pause periods and is shown in Fig. 2 below. The resulting 30 combinations of all possible alarm pattern characteristics had total notification periods ranging between 1.8 to 15.4 s.

In terms of alarm modality, the Apple Watch is able to emit alarms with vibrations and sounds, or alarms with vibrations only. To switch between these two modalities, it was necessary to enter the Apple Watch's system-wide settings and turn on or off Silent Mode. As a result, the smartwatch application was unable to change alarm modalities automatically during a single VR user study trial. In order to test worker responses to both alarm modalities, each participant in the VR user studies conducted at least two trials of the same virtual work zone scenario with each alarm modality

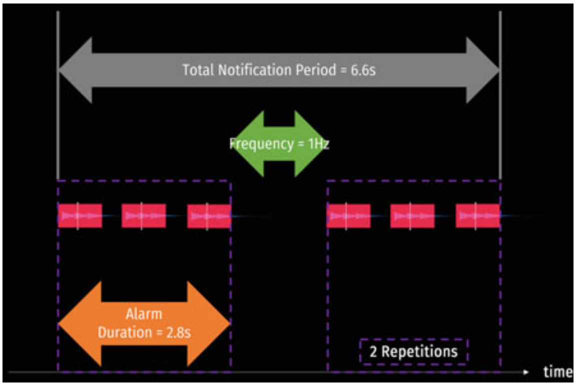


Fig. 2. Illustration of an alarm pattern with duration and frequency between two repetitions with respect to total notification period

characteristic (sound with vibration alarms, or vibration only alarms) fixed during a single trial.

3.3 VR Experiment Design and Procedure

In each trial of the VR user studies, a single participant was asked to establish a work zone perimeter by moving six cones onto blinking white lights (Fig. 3). Cones placed in the correct location turned the white light green and were registered by the traffic simulation. Subsequent vehicles in the simulation treated the properly set up cones as obstacles to avoid. Each trial concluded when all six cones were placed by the participants in the correct location. At least two trials were conducted for each user to monitor how each participant conducted this sequence of work tasks while experiencing the two alarm modalities: vibration only, and sound with vibration combined. The order of modalities was randomized among participants. New York University's IRB approved human subject experiments on the integrated VR-traffic platform (IRB-FY2020-3946). Thirty-five (n = 35) participants were recruited for user studies involving this scenario.

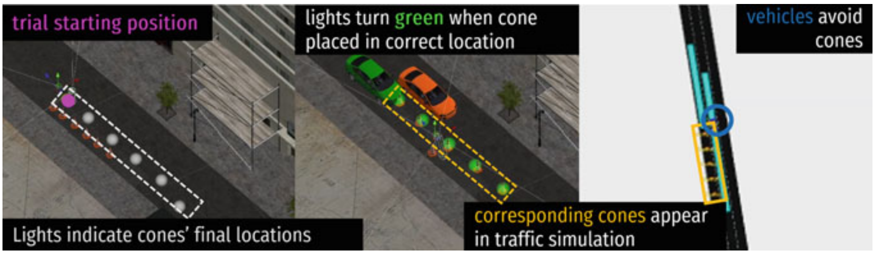


Fig. 3. Work zone scenario for participants in VR user studies

Three possible events in the VR user study were able to trigger alarms on the smartwatch during the trials: work zone collision vehicles, speeding vehicles, and the participant leaving the work zone perimeter. A "collision vehicle" was preset to ignore obstacles, thereby intrude the work zone and collide with the cones or the worker. The Scenario 1 traffic simulation was set up to send a colliding vehicle to the work zone 10 s after each trial began. Traffic simulation was also preset to include three of five cars defined as "speeding vehicles" and were spaced such that the speeding alarms would be raised at least 15 s apart in order for participants to experience the full range of alarm total notification periods. Speeding vehicles were defined as any vehicle which exceeded 25 miles per hour (12 m/s) in the area surrounding the work zone. Participants could also trigger a smartwatch alarm by passing the edge of the virtual work zone perimeter into the area for incoming traffic. The ultrasonic sensors were set up to raise an alarm when the participant's physical location in the lab environment corresponded to the work zone perimeter in the VR environment.

When a speeding vehicle, collision vehicle, or work zone perimeter event occurred, the time stamp of each alarm event along with the smartwatch's randomly picked alarm pattern ID was recorded for analysis of participants' reactions to the alarm.

In order to measure how participants reacted to the alarm, various sensors were worn by the participants during the VR user studies. Two wearable sensors, an Apple Watch and a photoplethysmography (PPG) wristband (Empatica E4), were worn by participants' nondominant wrist to monitor their responses to the VR environment and traffic simulation. The Apple Watch alarm application registered whether and when a user chose to acknowledge or ignore the alarm. The PPG sensor monitored physiological reactions by recording data on participants' heart rate (HR) at a rate of 1 Hz. The VR headset also served as a sensor for recording the participants' head position, orientation at a rate of 50 Hz. together for statistical analysis. Custom raycasting scripts in Unity3D were also written to record when a hazardous vehicle (speeding or collision) was inside the participant's VR field of view. Together with timestamp records of alarm events' pattern IDs, these sensor recordings served as the basis for statistical analysis of worker reactions to alarm characteristics.

3.4 Measuring Workers' Alarm Reactions

For the purpose of quantifying each user's response to the different alarm patterns, multiple aspects of worker reactions were examined: (1) acknowledging the alarm on the smartwatch interface, (2) moving their body in a safe direction, (3) turning their head, (4) detecting a hazardous vehicle in their field of view, and (5) heart rate change. These reactions were analyzed with respect to the timestamp of each alarm event. If the user tapped the watch screen to acknowledge the alarm, the time stamp of the user's response was recorded as well. In analyzing the user studies data, the smartwatch response time, tack, was calculated as the difference between the alarm and screen tap time stamps. The body movement reaction time, tbody, calculated as the time elapsed between the alarm event and when the participant initiated the maximum change in their perpendicular position on the road afterwards. The user's head movement was tracked by analyzing the orientation of the VR camera, recorded as the 3D unit vector gaze direction of where the user is facing. The head turn reaction time, thead, was defined as the time elapsed between the alarm event and when the participant initiated the maximum angular change in gaze direction afterwards. When a collision or speeding vehicle entered the participant's VR field of view, the time stamp was recorded as vehicle detection event. The vehicle detection reaction time, tveh, was calculated from the time elapsed between the alarm event and when the participant first saw the hazardous vehicle in their field of view. This study also examined how participants' physiological factors changed in response to alarms. The PPG wristband sensor recorded heart rate (HR) in beats per minute (BPM). The heart rate percent change was defined as the percent difference between the average heart rate over 2.5 s time interval before and after each alarm. The time frame of 2.5 s was selected based on the literature review of general reaction times to alarms.

3.5 Evaluating Impact of Alarms on Worker Reactions

Each form of worker reaction was analyzed for average reaction times with respect to alarm pattern characteristics (i.e., alarm modality, duration, repetitions, and frequency). Average reaction times were analyzed with respect to each alarm pattern characteristic independently for evaluating any positive or negative correlation between a particular form of worker reaction's speed and a specific alarm characteristic. Nonparametric analysis of variation statistical tests were also conducted to determine the impact significance of different alarm characteristics as sources of variation, without having to assume the reaction times followed a particular family of distributions in statistical tests. For each alarm characteristic in this study (modality, duration, frequency, number of repetitions), a Kruskall-Wallis H-test was used to determine if the distributions of sample groups of worker reaction times (e.g., head turn reaction times grouped by duration = 1.8 s vs. 2.8 s vs. 3.8 s) for analysis have significantly different distributions. The null hypothesis for each test is that all sample groups were drawn from the same distribution, meaning that worker reaction times are not significantly different with respect to different alarm characteristic values. Statistical tests with significance levels of $p < 0.05$ would indicate the alternative hypothesis is true at 95% confidence, meaning that variation in a specific alarm characteristic correlates with significantly different worker reaction times.

4 Results and Discussion

The thirty-five (n = 35) participants recruited for the VR user studies consisted of affiliated faculty and students. Only a select fraction (29%) of participants had previous construction and road work experience, ranging between 2 months to 6 years. Results presented here are not representative of the roadway construction workforce. That said, the task of placing cones in the VR environment was well understood by all participants, and lack of construction experience was not expected to impact the participants' behavior in the VR traffic simulation. A total of 251 alarms were experienced by all participants. Only 3 of those alarms were triggered by a participant stepping outside the work zone perimeter. Of the remaining 248 alarms, 179 resulted from speeding vehicles and 69 resulted from collision vehicles. Results discussed in the following sections pertain only to speeding and work zone collision vehicle alarms.

4.1 Worker Reaction Benchmarks

The average reaction time across worker response types for each alarm modality (sound with vibration, or vibration only) are shown in Table 1. The sample sizes used to determine mean reaction time for each response type and alarm modality are also presented. Alarm reaction times two standard deviations beyond initial analysis of mean reaction time are omitted from these results. In terms of watch alarm acknowledgement, Table 1 indicates that only around 22% of alarms were acknowledged on watch by participants. This low response rate could be attributed to the general inconvenience of tapping the watch screen rather than a sign that most people did not notice the alarms. Sound and vibration alarms were nearly twice as likely to be acknowledged as vibration only alarms. Additionally, participants were faster (5.95 s) on average in acknowledging their watch in response to sound and vibration alarms than in response to vibration only alarms (6.56 s). Given the low rate of watch acknowledgement, the other forms of reaction may be more useful in evaluating which alarm patterns may be more effective in evoking a physical reaction from the worker. Table 1's mean reaction times indicate that on average, participants may have first seen a vehicle in their field of view before turning their heads or moving their body. This could imply that most participants noticed the vehicle in their peripheral vision after the alarm before physically moving out of the way. is may also explain for the low rate of watch acknowledgement. If most participants quickly noticed the hazardous vehicle and moved in some way within the first 3 s, they may not have felt the need to acknowledge the watch alarm.

Mean and quartile reaction times are illustrated in box plots in Fig. 4, with individual subplots showing a single form of worker reaction time compared with independently varying a specific alarm characteristic. Subplots in Fig. 4 for body movement and head turn reactions show mean reaction times generally hovering around

Table 1. Statistics for worker reaction times for each response type across all alarms

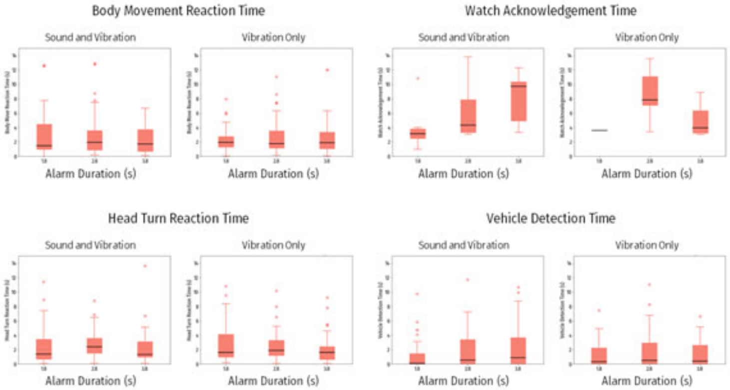
	Sound + Vibration Alarms		Vibration Only Alarms	
	n	Mean Reaction Time	N	Mean Reaction Time
Total Alarms	125	n/a	123	n/a
Watch Acknowledgement	20	5.95	13	6.56
Vehicle Detection	114	1.36	118	1.49
Head Turn	120	2.19	114	2.01
Body Movement	119	2.46	118	2.19

2 s regardless of variations of alarm characteristics of duration, number of repetitions, and repetition frequency. On the other hand, plots of watch acknowledgment time reveal that workers tended to acknowledge the watch alarm more slowly with increasing durations of sound and vibration alarms (Fig. 4a, upper right). Similarly, workers tended to acknowledge the alarm more slowly with increasing repetitions and increasing frequency of repetitions. (Fig. 4b and c, upper right). Closer inspection of vehicle detection time plots reveal that workers also tend to take more time to look and see the hazard vehicle as sound and vibration alarm duration increases. While these findings can change as more data is collected in future VR user studies, preliminary results indicate that shorter durations and less frequently repeating alarms may encourage workers to react faster.

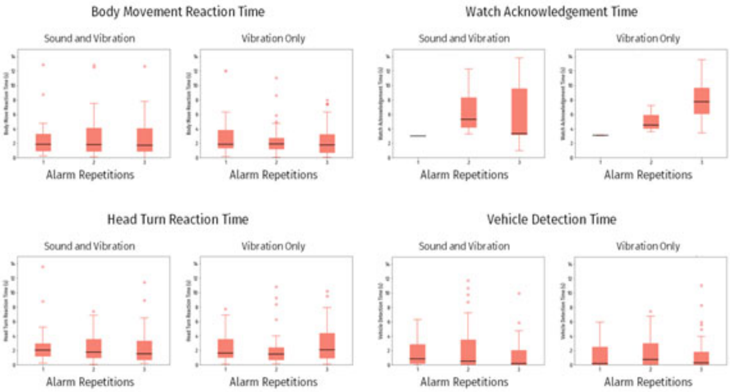
4.2 Analysis of Variance

Table 2 shows the analysis of variance results for the different sources of variation and measures of reaction. Each row is a different alarm characteristic or number of previous alarms experienced in a single trial. Each measure of reaction column has both the test statistic and p-value for the corresponding source of variation. Both $p < 0.05$ and $p < 0.10$ levels of significance were considered in evaluation of the tests, as indicated by the respective dark and light green highlighted boxes in Table 2.

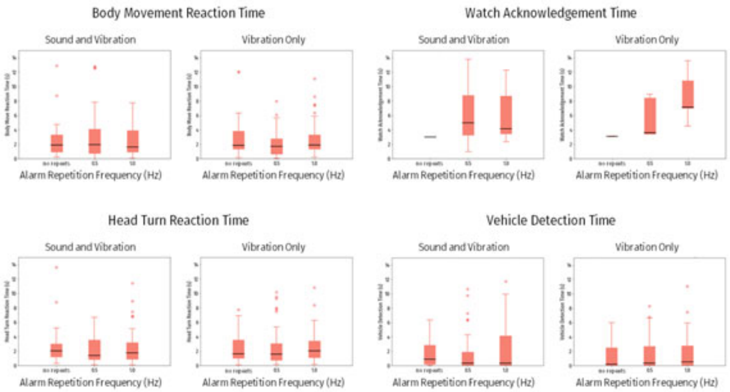
Formally, the Kruskal–Wallis H-test analysis of variance statistical tests indicate whether distributions of workers' reaction times grouped by an alarm characteristic belong to different populations. Informally, these statistics show if a worker exhibited a significantly different reaction after experiencing different alarm characteristics, without indicating whether that reaction was faster or slower relative to an increase in an alarm characteristic value (i.e., suggests impact of an alarm characteristic with no indication of positive or negative correlation). For example, the last row of Table 2 suggests that the most significant characteristic is the number of alarm repetitions, as watch acknowledgement times grouped by alarm repetitions appear to belong to significantly different distributions ($H = 9.07$, $p = 0.011$). In other words, workers with two very different watch acknowledgement times likely experienced different



(a)



(b)



(c)

Fig. 4. Plots of different forms of worker reaction time with respect to different alarm characteristics: a) alarm duration, b) alarm repetitions, c) alarm repeat frequency

Table 2. Kruskal–Wallis H-test analysis of variance in different measures of reaction based on alarm characteristics as potential sources of variation. Bold text in dark green boxes and italics text in light green boxes denote significance levels of $p < 0.05$ and $p < 0.10$, respectively

	Measures of Reaction									
	Watch Acknowledgement Time		**Vehicle Detection Reaction Time**		**Head Turn Reaction Time**		**Body Movement Reaction Time**		**Heart Rate Change**	
Alarm Characteristics	Stat	p	Stat	p	Stat	p	Stat	p	Stat	p
Alarm Modality	1.44	0.230	0.000	0.988	0.00	0.975	0.00	0.974	*2.73*	*0.098*
Alarm Duration	3.886	0.143	0.96	0.620	*4.93*	*0.085*	1.00	0.607	2.48	0.290
Alarm Frequency	3.65	0.161	0.344	0.842	0.94	0.626	0.81	0.666	1.47	0.479
Alarm Repetitions	**9.07**	**0.011**	1.27	0.529	1.54	0.464	0.30	0.863	1.79	0.408

alarm repetitions. At the higher significance threshold of $p < 0.10$, alarm duration also appears to have a significant impact on head turn reaction times ($H = 4.93$, $p = 0.085$). Alarm modality also appears to correlate with high variation in the percent change in heart rate ($H = 2.73$, $p = 0.085$) immediately after alarms (i.e., different heart rate changes observed among participants are likely associated with alarms of different modality). Overall, alarm characteristics of vehicle detection and body movement appeared to have little impact on worker reactions. These results indicate that alarm modality, alarm duration, and repetitions that have the potential to significantly impact worker behavioral measures. These characteristics need to be further investigated across the measures of reactions.

5 Challenges and Future Work

One of the first steps is to focus on the alarm characteristics that highly correlate with response measures. Two additional VR work zone scenarios that were developed by the research team will focus on these characteristics among all we identified. Future work will also focus on the time sequence of physical reactions by workers (i.e., turning their heads then moving body or some other sequence of reactions) in evaluating how alarm systems can improve worker safety. As previous alarm-related fatigue studies may suggest, further analysis may reveal that workers exhibit the strongest reaction after their first alarm, with diminishing reactions thereafter. This study did not employ a VR headset with built-in eye tracking, and was therefore unable to assess whether people saw the vehicle in the center or periphery of field of view.

Additional visual analysis methods will be employed in future studies to obtain detailed data on workers' situational awareness of hazardous vehicles. While alarms appear to have little effect on participants' heart rate changes, other physiological measures (e.g., EEG, respiratory rate) could be considered. More VR user studies will be conducted for different scenarios (night-time highway sensor installation, afternoon surveying on urban intersections) which can yield more data on worker reactions and reveal the effects of different worker environment and nature of the work performed. With more experiment data, a training environment can be developed for a reinforcement learning model that can potentially optimize alarm characteristics to improve worker attention and reaction to safety alarms.

6 Conclusions

This study presented an approach for measuring different forms of worker reaction and evaluating how alarm characteristics affected those reaction times and types with in an integrated VR traffic simulation platform. Preliminary analysis of average reaction times indicate that workers tend to react faster at detecting vehicles and acknowledging the alarms on the warning device when alarms are shorter in duration and repeated less frequently. Nonparametric statistical tests on data from 35 participants within a simulated urban mobile work zone indicate some variation in worker's watch acknowledgment, head turn, and heart rate reactions in response to an alarm's number of repetitions ($p < 0.05$), duration ($p < 0.10$), and modality ($p < 0.10$), respectively. Given the low rate of watch acknowledgement, this study indicates that the use of remote clickers or similar devices may not be the best method of evaluating worker reactions to alarms, especially when other forms of physical reaction such as head turn and body movements are more important to a worker's situational awareness and overall safety. Second-order or time-dependent effects are worth investigating, since the number of previous alarms experienced by participants may induce alarm fatigue (i.e., slower responses, lack of response to alarms). Findings from this study begin to contribute to the limited understanding of how alarm system features can improve workers' situational awareness in roadway construction work zones. The approach presented here for analyzing the effects of varying alarm characteristics on worker reactions will serve as a basis for future investigations in reinforcement learning-based optimal control of alarm patterns on wearable devices.

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Resilient and Sustainable Urban and Energy Systems

How Can Digital Twins Support the Net Zero Vision?

Eleni Papadonikolaki and Chimay Anumba

Abstract Net Zero relates to decarbonisation efforts to tackle climate change by not adding new emissions to the atmosphere. Reaching Net Zero depends on datafication and digitisation as data on carbon emissions collected across assets' lifecycle are important for neutralising them. This study aims to understand how technological ecosystems such as Digital Twins – that connect physical and digital artefacts – can support a Net Zero vision in the built environment, in an industry-agnostic way to transfer any relevant lessons from other sectors. The method is a systematic literature review that structures new knowledge on the topic. The study showed that environment sustainability has been an overused idea in scientific literature, yet rarely operationalised. A scarcity of studies utilising the potential of digital twins for Net Zero was found. The emergent themes are: overreliance on technocratic solutions at the expense of systems thinking, proliferation of renewable sources and misunderstandings regarding visualisation necessity, and showing pathways for future DT system design for Net Zero.

Keywords Digital twins · model-based systems engineering · sustainability · net zero · review

1 Introduction

In 2019, the United Kingdom (UK) became the first G7 country to legislate for Net Zero, recommending a 2050 Net Zero carbon emissions target (CCC, 2019). Construction is a key contributor to emissions, as buildings and construction accounted for 36% of final energy use and 39% of process-related carbon

E. Papadonikolaki (✉)
University College London (UCL), Gower Street, London WC1E 7HB, UK
e-mail: e.papadonikolaki@ucl.ac.uk

C. Anumba
University of Florida, Gainesville, FL 32611, USA
e-mail: anumba@ufl.edu

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dioxide (CO2) emissions in 2018. Digitalization has become a key trend in innovating construction projects to meet Net Zero target and improve sustainability. For example, digital transformation through the power of data science has the potential to monitor and evaluate and, ultimately, cut emissions to facilitate a more sustainable footing for the world economy.

Current and emerging digital technologies have the capacity to support sustainability efforts and enable corporations and firms to meet their sustainability goals. Technologies such as Building Information Modelling (BIM), wireless sensing, Internet of Things (loT) and blockchain have shown their potential in connecting with building Digital Twins (DTs) for making construction processes more efficient, faster, safer, and cheaper, globally attracting attention. Similarly, DTs, originally defined by Grieves (2014), pave the way to cyber-physical interaction and convergence between the physical world and the cyber world of production. To this end, DTs bring together data from all aspects of product lifecycle, laying the data foundation that enables traceability and better control of sustainability objectives. This paper draws upon a systematic literature review to identify the potential of digital twins for sustainability and in particular meeting the Net Zero vision. Whereas this paper is industry agnostic, it aims to provide some recommendations for the built environment.

A recent study in digital technologies in the built environment (BE) found that the main technologies discussed in the literature were: BIM, augmented reality, virtual reality (VR), Internet of Things (IoT), cloud computing, and big data (Papadonikolaki et al., 2022). Papadonikolaki et al. (2022) argued that the concept of digital evolves toward connected technologies such as BIM and big data and smart cities/big data. This trend shows that the BE finds solutions to its problems in the use of technologies that rely on big data. Unlike other sectors where big data is available, the BE is behind the curve in terms of asset digitization, usage, and labor (Agarwal et al., 2016). However, the BE sector is slowly picking up.

This paper systematically first reviews policy and industry agendas, best practice and various digital technologies that support digital twins to identify how they can accelerate insight and enable the Net Zero vision. Afterwards, the paper is built upon a Systematic Literature Review (SLR) aiming to document the state-of-the-art, structuring disparate knowledge around Digital Twins and Net Zero and synthesize a new perspective addressing the following Research Question (RQ):

> *How can Digital Twins support a Net Zero vision in the built environment and what lessons are there to learn from other sectors?*

This review aims to transfer lessons across sectors and enhance cross-disciplinary and cross-industry learning beyond silos. The contribution of the paper is the provision of a practical guide to support the sustainability and corporate social responsibility agendas of construction businesses by providing a summary and outlook of how digital twins contribute to the Net Zero vision.

2 Theoretical background

2.1 Origins of Digital Twins

Originally developed to improve manufacturing processes, Digital Twins (DTs) were defined in a white paper in the early 2000s as a "virtual representation of what has been produced" (Grieves, 2014). Grieves (2014) argued that DTs consist of three components: (a) physical asset, (b) virtual asset and (c) bi-directional data connecting the physical and virtual asset. The term digital twin is used to describe a digital replication of a physical asset and additionally, the process of seamlessly transmitting data between the physical and the digital twin (El Saddik, 2018).

In theory, digital twins can update data in real time, so that virtual models can undergo continuous improvement through comparing the virtual asset with physical asset (Tuegel et al., 2011). Digital twins shorten the product development cycle, improve the build efficiency and guarantee accuracy, stability, and quality. Furthermore, the use of digital twins promotes efficient synergies between the different stages of a product lifecycle (Qi and Tao, 2018).

2.2 Types of DT technologies

There are three main types of DT technologies: (a) input technologies, for sending data from the physical world to the machine, (b) processing technologies, for analysing the data and (c) output technologies, for sending information from the machine back to users and/or to the physical world. Therefore, DTs relate to a whole interlinked ecosystem of technologies to deliver a DT.

First, during the input stage, DTs focus on modelling the behavior of the physical asset or product accurately over an entire lifetime. To do this, DTs use data from input devices such as sensors installed on physical assets, e.g., through the Internet of Things (IoT), a foundational technology for DTs, to follow their real-time performance, operating conditions and changes over time.

Second, during the processing stage, DTs demonstrate the impact of live changes, evaluating scenarios, external environmental conditions and other endless variables by incorporating multi-physics simulations, data analytics and Artificial Intelligence (AI) including Machine Learning (ML) data analytics approaches. This data-intensive stage completely eliminates the need for physical prototypes, reduces modeling and simulation time but specifies the need for high-spec digital infrastructures, including cloud and edge computing to deal with massive (big) data.

Third, as the DTs evolve, they are continuously updated to reflect changes to their physical twins across the product lifecycle, feeding back through output technologies into a virtual environment that enables users to monitor and continuously optimize the product or asset. Visualization opportunities through Augmented Reality (AR) and Virtual Reality (VR) usually make the top-most layer of a DT that combines the data and insights to present, advise and interact with users or other machines.

DTs have various usages across the product lifecycle as they have the potential to link production and product and its performance. According to Siemens, the applications of DTs depend on the product lifecycle, identifying three types of DTs: (i) product, (ii) production and (iii) performance. When these three DTs are integrated, they can support real-time and dynamic cyber-physical connectivity across all stages of the product and production lifecycles.

2.3 Application areas of DTs

Aerospace: DTs originated from systems engineering and in particular in Model-Based Systems Engineering (MBSE) (Madni et al., 2019). Various current initiatives in the aerospace and defense industry are the continuation of work by NASA in the 1960s that later formed the basis of NASA Technology Roadmap (Shafto et al., 2012). The NASA Apollo project entailed the creation of two identical space vehicles built to allow mirroring the conditions of the space vehicle during the mission (Rosen et al., 2015). After the one vehicle was launched, another vehicle remained on earth and was called the 'twin' This 'twin' which was not yet digital but a physical prototype was used extensively for training during flight preparation and afterwards, during the mission to simulate real-time alternatives on the earth-based model, fed with data on the flight conditions to assist the astronauts. In aircraft manufacturing DTs are responsible for asset performance benefits of 30% increase in aircraft uptime (Grieves and Vickers, 2017).

Automotive: The automotive industry has been traditionally credited for various innovations in not only business, (see Taylorism, Fordism, Lean thinking) but also production technology. Such a disruptive industry is leading the DT developments from manually-operated cars to fully autonomous vehicles leveraging automated control systems. Rudimentary developments of DTs in the automotive include simple computer simulations of cars' braking systems to simulate how they would perform across various real-world scenarios and weather conditions (Madni et al., 2019). Schleich et al. (2017) describe how through DT technologies, Tesla advances car automation, through sensors, IoT, AI, ML and simulation tools. TESLA aims at developing a DT for every car, hence enabling real-time data transmission between car and factory. Other automotive manufacturers focus on AR and VR applications for the vehicle's DTs.

Plant Management: MBSE has been applied apart from aerospace and automotive also in plant manufacturing, not only during design but also during the back-end of the life cycle for diagnosis and optimized operations ((Rosen et al., 2015). In MBSE, the role of modeling, simulation and optimisation are inter-connected as only after accurate data is fed into the system to produce robust simulations, optimisation can take place to increase the competitiveness of the product or asset as to energy and resource efficiency, short production time-to-market and enhanced control. Relevant developments in logistics and warehousing are also revolutionalised through industry leaders such as Amazon and IBM for scenario-live-simulations and digital shop floor management (Brenner and Hummel, 2017).

Medical: Digital twin technologies have also been pioneered in medical science. By creating a human digital twin, clinicians can follow the performance of human and artificial organs (Barricelli et al., 2020). Other applications include fitness trackers that with very simple sensors can monitor patients' health and performance and even schedule medical tests when needed. In cardiovascular medicine, DTs can draw diagnosis and prognosis to tailor future treatments based on health status and data through cyber-physical synergies (Corral-Acero et al., 2020).

Infrastructure and Buildings: In construction, DTs are defined as "a realistic digital representation of assets, processes or systems that is distinguished by the data connection between the physical and virtual asset" (Bolton et al., 2018) and their visual properties are accentuated. Whereas DTs can be developed at any project stage, Sacks et al. (2020) argued that in order to have a fully mature DT, its implementation should start during the conceptual design and thereafter the information from the design and construction stage of the physical asset, including as-planned process, as-designed product, as-built product, as-preformed process information about the physical asset, connected to the digital asset real-time to monitor the physical asset and start adding as maintained/renovated asset information. While DTs may be used in isolation without the need to engage with other technologies, their real value is realized when they are used for asset management. For example, Love and Matthews (2019) found that DTs were linked to a suite of technologies such as Building Information Modelling (BIM), Geographic Information Systems (GIS) and supervisory control and data acquisition (SCADA) systems to enable a digital twin during operations and maintenance. Akanmu et al. (2021) explore the development of next-generation cyber-physical systems (CPS) and digital twins (DTs) for the construction industry.

2.4 Sustainability

Triple Bottom Line (3BL): Sustainability in business has been defined as the 'triple bottom line' (3BL) of people, planet and profit (or societal, environmental and economic sustainability). However, CEOs and business leaders predominately focus on economic sustainability for business, profit and markets and less on environmental and social sustainability. Elkington (2018), who developed the 3BL term, notes that success or failure on sustainability goals cannot be measured only as profit, but instead as wellbeing of billions of people and the health of our planet. Whereas there have been improvements, our climate, water resources, oceans, biodiversity and wellbeing are all increasingly threatened. There is a need to understand how digital technologies can support people and planet targets.

Net Zero: Net Zero relates to decarbonisation efforts to tackle climate change by not adding new emissions to the atmosphere according to the United Nations. There are many similar terms around carbon, emissions and climate, such as: carbon neutral, climate neutral, climate positive, zero emissions, and so forth. Net Zero carbon emissions describe an activity that releases net zero carbon emissions back into the atmosphere and is essentially similar to 'Carbon Neutral'. Net Zero relates to carbon or emissions. For example, when a building is powered by solar power using zero fossil fuels its energy is labelled "zero carbon" and as no carbon was emitted from it, no carbon needs to be captured or offset. Likewise, Net Zero emissions are when there is a balance of the overall greenhouse gas emissions (GHG) produced and taken out of the atmosphere. Net Zero Energy (NZE) building, is a building with net zero energy consumption, that is the total amount of energy used by the building on an annual basis equals the amount of renewable energy created on the site or by renewable energy sources offsite. To this end, Net Zero describes manmade activities that stop adding climate-heating gases in the atmosphere.

2.5 Synthesis of Research Gap

Digitalisation has been promoted as a means of achieving sustainability goals. However, sustainability goals, especially as outlined in the United Nations' Sustainable Development Goals (SDGs), are too broad and usually misplaced, given the far-reaching implications of sustainability (Kirchherr, 2022). This study focuses on narrowing down (mainly environmental) sustainability regarding reaching the Net Zero vision as an end-goal of digitalisation efforts and, in particular, the deployments of digital twins, which is the next frontier in intelligent data collection, analysis and simulation aiming to provide real-time behaviour and performance information.

Any system that mirrors the operation of another different system is defined as a model. A model in turn is an abstraction from the structure and processes that define the mirrored system (Batty, 2018). In this sense, an immediate question is to define the differences between a real system and any computer model of that system, and thus it is worth noting the conundrums that this raises with respect to the arguments about what constitutes a digital twin. The main research aim is to understand how DTs can support a Net Zero vision in the built environment and transfer lessons from other sectors to structure knowledge on the potential of Digital Twins for delivering a Global Net Zero vision and provide insight informing policy or practice, and developing a new theoretical model or framework.

3 Methodology

3.1 Systematic Literature Review

Drawing upon the research gap described above, this paper conducts a Systematic Literature Review (SLR) to synthesize and compare findings from studies and answer specific research questions (Klein and Müller, 2020). This study aims at synthesizing a new perspective and structuring disparate knowledge around Digital Twins and Net Zero. The main research aim is to structure knowledge on the potential of Digital Twins for delivering a Global Net Zero vision.

SLR as a methodology was originally developed in the medical sciences to consolidate information from several sources in a transparent, rigorous and detailed manner (Tranfield et al., 2003). SLRs can produce new knowledge (Tranfield et al., 2003) or document the state-of-the-art (Lockett et al., 2006) providing a better understanding of the phenomenon in question for practitioners and scholars. Through these research instruments, SLRs guide the building of theory accumulating knowledge and evidence after analyzing a large number of studies and methods, thereby increasing consistency in the results and conclusions (Akobeng, 2005).

3.2 Data Collection

The sample consists of research articles on the broader area of Net Zero, that is sustainability and digital twins without any time or industry/sector restrictions, in order to have a holistic view of the phenomenon. Most papers of this SLR were published in 2018, that echoes the timing of the 2016 Paris Agreement. One of the largest academic online databases, Scopus was used to sample articles and in the future that might be complemented by Web of Science (WoS), although no significant discrepancies are expected. The sampling was limited to refereed journal articles. Books and book chapters are typically excluded from SLRs, as they are often categorized into grey literature (Adams et al., 2017) or not considered to be subject of the robust review process journal articles go through (Clemens et al., 1995). We excluded conference papers as many do not undergo peer review. The sampling string on Scopus was as seen in Fig. 1 below:

```
( TITLE-ABS-KEY ( "digital twin*" ) OR TITLE-ABS-KEY ( "model-based systems engineering" ) AND TITLE-ABS-KEY ( sustainab* ) OR TITLE-ABS-KEY ( "net zero" ) ) AND ( LIMIT-TO ( SRCTYPE , "j" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )
```

Fig. 1. Keyword search in Scopus database

A key decision was using both 'Sustainab*' and 'Net Zero' in the sampling, as the latter is a recent concept and only a few results were relevant to 'Net Zero' according to the indexing keywords, although more papers were relevant to it. The term 'Carbon Neutral' was also added to show the relevance to 'Net Zero' visions. This search returned 258 document results (September 20th, 2022).

3.3 Data Analysis

The data analysis contained three sequential main parts as seen below.

Step 1: Descriptive analysis: After collecting the sample of paper, the first step of the analysis was descriptive in order to understand some initial trends appearing in the sample.

Step 2: Content analysis: Afterwards, an extraction form was created in Excel including various categories of additional categorical data. The abstracts of the whole sample were read and categorised. (n = 258). This approach was preferred to bibliometric approaches of analysing large bodies of literature because it could give granularity to the findings and possibilities for customized analysis. The chosen categories for this analysis part were:

- Technologies discussed (free code)
- Processes (if applicable, free code))
- Target improvement (free code)
- 3BL category (societal, environmental or economic sustainability)
- Net Zero vision applicability (Yes/No)
- Sector (free code)
- Sub-sector (if applicable, free code)
- Paper type (empirical, review, position)

Step 3: Thematic analysis: Finally, after evaluating the relevance to the RQ a final sample of 16 final articles were isolated for full reading and deeper analysis.

4 Results

4.1 Descriptive Results

The resulting literature was a sample of 258 articles published between 2012 and 2023. Whereas there was no limit in the publication date, the sample consisted of mostly recent literature that remained stable between 2012–2018 with 0–4 publications annually and a steep trajectory starting in 2019 (20 published documents). This increased steep trajectory resulted in a marked increase in 2022 (111 published documents).

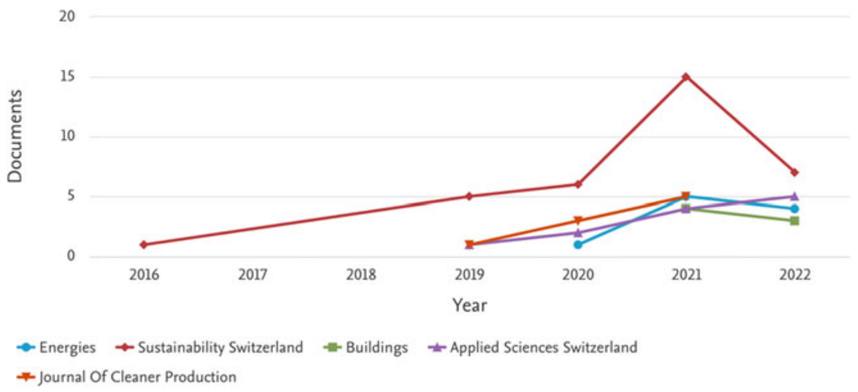

Fig. 2. Description of the literature sample (n = 258) per year by source

Some publication outlets were more prolific than others. Key outlets are: (i) Sustainability Switzerland (34 published documents), (ii) Applied Sciences Switzerland (12 published documents), (iii) Energies (10 published documents), (iv) Journal of Cleaner Production (9 published documents) and (v) Buildings (7 published documents). Figure 2 shows in greater details how these trends are emerging the recent years across these different outlets. Notably, outlets dedicated to energy sectors, manufacturing and the built environment are most represented in this.

The literature was from a variety of research fields, revealing the inter-disciplinary nature of the phenomenon. Most studies were multi-disciplinary and were categorised in more than one subject area. In particular, although most literature stemmed from engineering (144 published documents) and computer science (80 published documents) areas, these were followed by energy (79 published documents), environmental science (64 published documents), social sciences (59 published documents) and business, management and accounting (37 published documents) among others. It is important to note that these categorisations are not representative of the application areas and the industries that the empirical nature of applicable studies relates to. Figure 3 below summarises the above areas and shows further areas relative to the sample.

4.2 Content Analysis

The content analysis was based on screening (reading) all the abstracts of sample (n = 258). This approach was preferred to bibliometric approaches because it could give granularity to the findings and possibilities for customised analysis.

Triple Bottom Line (3BL): The first 'code' studied in this step of the analysis was aiming to understand how sustainability was used in these studies and to what extent the resulted literature related to the areas of the 3BL: societal, environmental and

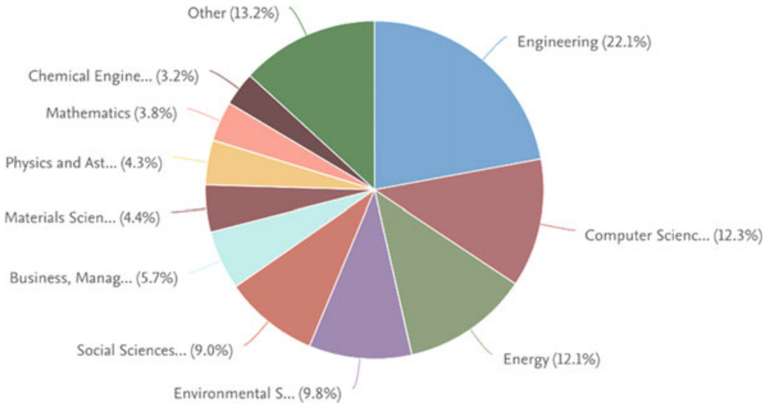

Fig. 3. Description of the literature sample (n = 258) per year by subject area (based on the Scopus database index)

economic sustainability. As expected, due to the keywords used, the majority of the studies were related to the environmental sustainability (213 published documents), followed by social sustainability (36 published documents) and economic sustainability (10 published documents). Naturally, there were instances were more than one aspect of 3BL was relevant to the study, nevertheless, the main idea is that sustainability and Net Zero as well as their relation to digital technologies is approached more from an environmental perspective, rather than socio-economic, with implications for organising and implementing relevant digital transformation initiatives. To this end, there were little works on stakeholders, requirements and policy. Figure 4 shows the analysis of this data.

Relevance to Net Zero: As this study looks in particular at the links to Net Zero, apart from general sustainability ideas, it was important to understand the nature of the extant literature on the topic. Surprisingly, only 16 out of the 258 abstracts of the

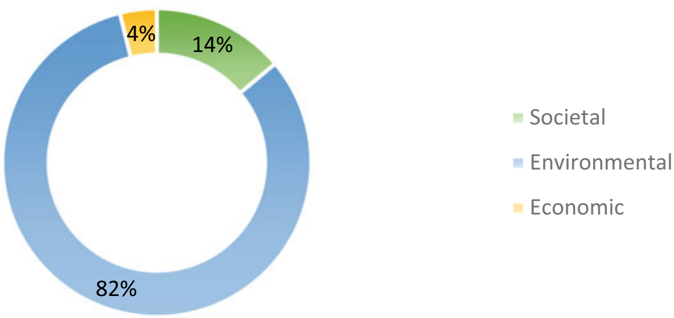

Fig. 4. Content analysis of the literature review sample based on relevant to the triple bottom line aspects

published documents reviewed were clearly related to the Net Zero vision. This observation reveals the popularity of the concept of sustainability but also the lack of its operationalisation in research. Sustainability is typically seen as an all-encompassing and transferable approach to show improvement from research and linkages to social and environmental impact and benefit. However, most of the times these claims are not substantiated. However, looking at Net Zero is a tangible approach to showcase the said impact.

Associated Technologies and Processes: As the reviewed literature was already captured from a scientific database (Scopus) it had already assigned author keywords. To understand the sample better in a more systematic and coherent manner, additional keywords related to associated technologies and processes, or initiatives discussed in the studies were added. In total, a maximum of three keywords were assigned to reveal new patterns in the sample. From these, most of the reviewed literature related to smart manufacturing approaches (34 published documents), Industry 4.0 (27 published documents), smart cities and lifecycle thinking (19 published documents each). Regarding technologies, most of the studies related to Artificial Intelligence (AI) (33 published documents), Internet of Things (IoT) (29 published documents) and Building Information Modelling (15 published documents) among others. Figure 5 illustrates the most frequent of these associated technologies and processes. The former is show in green in the bar chart and the latter in blue colour. Figure 6 shows more keywords containing the associated technologies and processes in relation to DTs for sustainability in a Word Cloud format.

Application Areas: Another important aspect of this initial analysis was focused on identifying the application areas of the relevant literature as regards to industry and sub-sector. The majority of the sample concerned applications in the manufacturing industry (84 published documents). From this, the applications areas were either in optimising machinery, machine tools and production methods, or less so looking at optimising plants, industrial sites, creating smart factories, followed by a smaller sub-set of studies where the DTs were used in optimising the performance and sustainability of materials and material properties. This massive application area was followed by applications in construction (33 published documents). Most of the applications of the reviewed literature in the construction area were related to housing and larger complexes in the form of smart campuses where DTs could provide improvements in the management of energy, maintenance and performance.

Construction as an application area was purposely distinguished by urban planning applications and infrastructure, to provide greater granularity to the findings. Infrastructure was another application area related to several studies (28 published documents). These applications were mainly on water systems (8 published documents), rail (4 published documents), roads (3 published documents) and less so in bridges and ports. Applications as a larger urban planning scale were also a significant number (24 published documents) with specific applications areas at neighborhood levels. Other applications concerned energy (18 published documents) with applications in energy production, power grids, battery optimisation, geothermal and other sources of energy, as well as agriculture (14 published documents), e.g.,

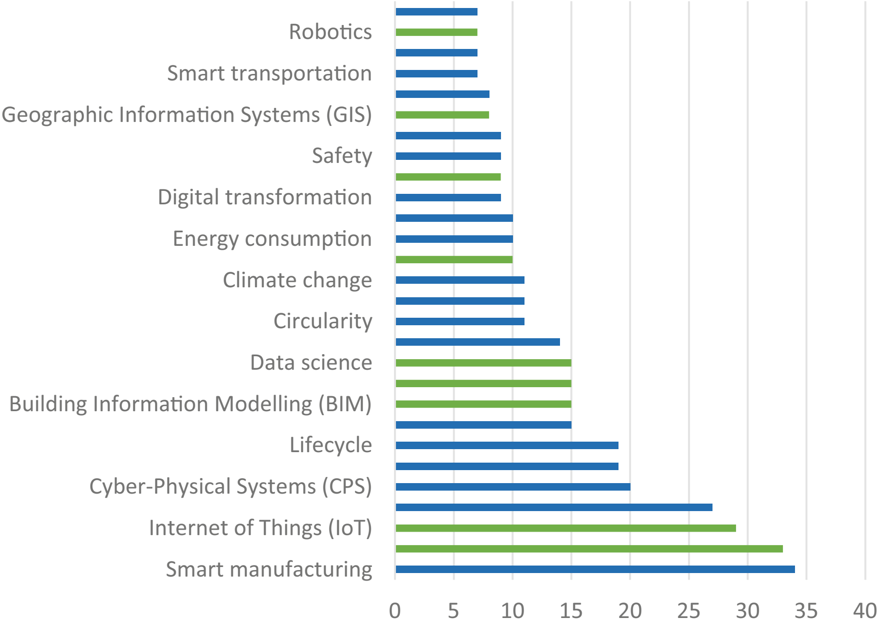

Fig. 5. Associated technologies (in green) and processes or initiatives (in blue) in the reviewed documents

Fig. 6. Word cloud with the associated technologies and processes to digital twins for meeting sustainability visions goals

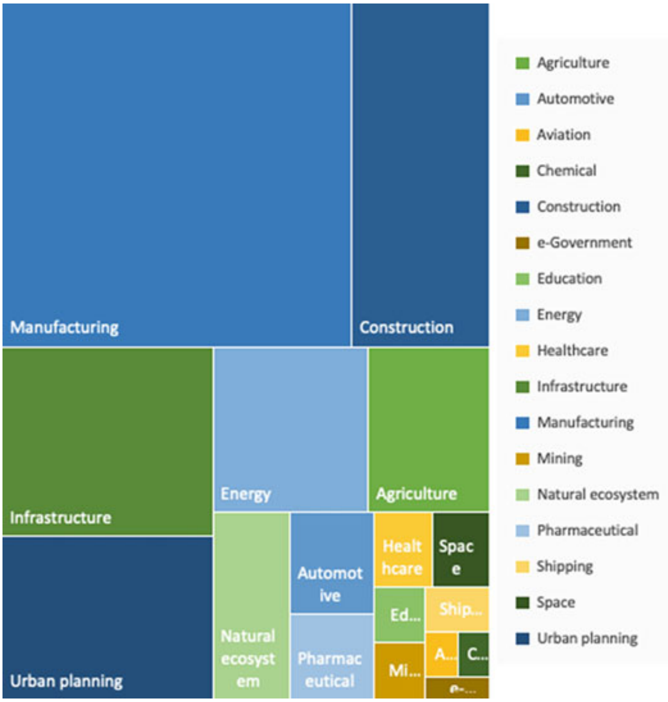

Fig. 7. Analysis of application areas of literature on digital twins for meeting sustainability

in farming, livestock management, food production and greenhouse. Figure 7 shows the application areas.

Paper Type: Finally, the content analysis focused on the exact type of each piece of the reviewed literature. Although bibliographic databases such as Scopus already have categorisations of 'document type', the preliminary analysis in this study showed that these categorisations are, in some instances, flawed. Therefore, in this step, the abstracts of the published studies were reviewed and showed that only 168 published documents were empirical studies, followed by 47 review papers, 22 position papers and 4 editorials. This shows that the topic is new and there is a lot of interest in understanding the state-of-the-art of this novel field. This step is important for understanding which studies have empirical basis before proceeding to the thematic analysis. Figure 8 shows this information.

4.3 *Thematic Analysis*

The thematic analysis investigated closely the sub-set of the data on Net Zero, which was a sample of 16 final papers mainly consisting of empirical (n = 14) and review

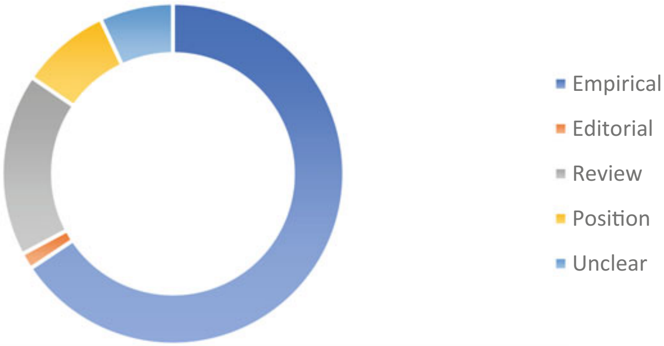

Fig. 8. Analysis of document type in the literature review sample (n = 258)

(n = 2) papers. It is worthy to mention that some papers outside this sample studied low-carbon emissions and efforts to reduce carbon emissions but not reaching Net Zero and neutrality yet, despite being an effort towards that direction.

Renewable Sources: A considerable number of studies looked at Net Zero through the lens of renewable systems, such as wind energy systems (Fahim et al., 2022), Photovoltaic systems (PV) (Bartie et al., 2021) and geothermal energy systems (Khanmohammadi et al., 2022). Even though a renewable energy system does not have carbon dioxide emissions during the operation, it is marked with environmental emissions embedded in their implementation. However, these were not covered in these studies, nor any attempts were made to shift them.

Visualisation Capability: Another key theme emerging from the data was the emphasis on the visualisation potential of the studied DTs for meeting Net Zero. This trend was particularly present in studies coming from the wider area of the built environment, such as construction of buildings and infrastructure, ranging existing buildings (Kaewunruen et al., 2018), townhouses (Kaewunruen et al., 2019) and rail station buildings (Kaewunruen and Xu, 2018). Equally, in this category of studies, data derived from BIM, especially proprietary applications such as Autodesk Revit was the norm.

Technocratic Solutions: One of the main themes of this investigation was the linkages to data science and in particular Artificial Intelligence (AI) and Machine Learning (ML) methods in order to deal with large sets of data points and make predictions to reach carbon neutrality (Tariq et al., 2021). However, from these technical solutions, there was little consideration to wider workflows and policies. Most of the studies showed a lack of systematic views of the problem of addressing Net Zero.

Systems Thinking: Especially in the review papers, but also in some of the empirical papers, there was a better linkage to system thinking and stakeholder engagement. In these studies, there were attempts to link to policies and existing workflows, or create new ones. These approaches considered both policy instruments and technological methodologies. For example, in the effort to develop Positive Energy Districts (PED) as energy-efficient and energy-flexible urban areas with surplus renewable energy production and Net Zero greenhouse gas emissions, active information exchange and analysis, as well as stakeholder engagement was seen as paramount for reaching Net Zero (Zhang et al., 2021). Similarly, Howard et al. (2021) envisaged an ecosystem of DTs in a distributed approach of "system of systems" interconnecting them in a production facility of greenhouses to simulate all aspects of the production chain, from production to supply.

5 Discussion and Conclusions

This study undertook a systematic literature review to answer the RQ of how Digital Twins can support a Net Zero vision in the built environment, and showed, first, that in terms of application areas, there is a lot of development in the manufacturing, especially machinery and operations, and construction, especially at an urban level and infrastructure. However, although most of the relevant advancements focus on the environmental sustainability aspect of the 3BL, there is a scarcity of studies on Net Zero and in general operationalisation of environmental sustainability for neutralisation of carbon emissions. The investigation also showed that apart from DT technologies, other associated technologies, such as AI, IoT and BIM and associated processes, such as lifecycle thinking, and Industry 4.0 are complementing DT solutions for environmental sustainability.

The thematic analysis of the sub-set explicitly targeting DTs for Net Zero goals, showed several emergent themes. First, there was a proliferation of studies on renewable sources that are per se carbon neutral in their operation. However, the carbon emissions during their implementation were not considered, signalling a need in shifting these. Second, there were several studies focusing on visualisation properties of DTs that showed a superficial approach and missed opportunity in exploiting heterogenous types of data. Finally, the study revealed an overreliance on technocratic solutions in addressing the topic, but at the expense of systems thinking. In such a complex topic with political implications, only a couple of studies approached it from a systems thinking approach, attempting to connect DTs together in a "system of systems" approach to meet Net Zero. These systems were of both hard (e.g., DTs) and soft (e.g., stakeholders) nature, showing pathways for future DT system design for Net Zero.

Whereas there is a popular belief that digitalisation and datafication can support the green or sustainability transition in our society, this paper is the first study explicitly connecting the developments in the field of Digital Twins with the potential to achieve Net Zero. The practical implications of this work are on identifying key themes on the topic, for further analysis and stepping stones for developing a framework or roadmap for researchers, practitioners and policy-makers in the area. Naturally, this work has some research limitations, especially located at the small data sample in this niche field. Future studies in this direction can work towards revisiting the sample and expanding it with more document types and broad definitions of environmental sustainability so as to capture findings towards the preceding stages of research investigations around the Net Zero vision.

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A Review of Smart City Maturity Assessment Models

Pavan Kumar, Aritra Pal, and Shang-Hsien Hsieh

Abstract The urban population is expected to increase from 56.61% (2021) to 68% (2050), hinting at an enormous population inflow in urban areas across the globe. As governments worldwide toward a sustainable way of life with sustainable development goals (SDG), today's urban areas encounter challenges such as pollution, overcrowding, housing, traffic, and poor infrastructure. Smart Cities intends to identify an intelligent and efficient way of facing these challenges and reducing the complexity of challenges in urban areas. Although the implementation of Smart-cities worldwide is increasing with the support of policies, smart cities tend to mature in multiple directions at their own pace at different levels, attributed to the uniqueness of the cities in a particular geographical area. Consequently, tracking a trail of the smart city's holistic maturity advancement becomes crucial. Therefore, this paper reviews the existing smart-city maturity assessment models and proposes an outlook of a well-defined holistic smart-city maturity assessment model, which is expected to aid the implementation and efficient management of smart cities across the world.

Keywords Smart city · maturity models · maturity frameworks · assessment methods

1 Introduction

1.1 Smart city origin and definition

Urban spaces have always been a crucial dimension of civilization and cities across the globe have grown at different rates in multiple directions. According to the United Nations, Cities stage more than half of the world population, and further growth in the urban population is predicted. With such an extraordinary growth, city

P. Kumar (✉) · A. Pal · S.-H. Hsieh
Department of Civil Engineering, National Taiwan University, Taipei, Taiwan
e-mail: d10521028@ntu.edu.tw

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municipalities have always aimed to find a feasible solution to urban challenges. Time-lapse of the growth of cities across the globe portrays the advancements in the process of management of cities, as cities choose to inculcate novel methods in the functioning of cities by replacing laborious ones.

Digitization initiatives by the local government and existing initiatives around innovation and technology have become one way for cities to be called smart [1] boosting the implementation of smart cities. Digitization of processes and services in cities, and developing the capability to work with data in the city organization as a core component has solidified the concept of smart cities. The inclusion of innovation and experiments in pursuit of solutions to the challenges of urban spaces portrays the growth of the smart city concept. Walravens N et al. [1] highlight the cities that strongly embraced innovation and experiments with technology can often be titled smart cities. The origins of Smart city concepts are attributed to the fundamental improvement and offering of a better quality of life and enhance the ease of living for its citizens, simultaneously improving the information system for citizens [2]. Maestre G et al. [3] discusses the emergence and the purpose of smart cities are to fill the void of energy-efficient and sustainable urban spaces with better interaction between inhabitants, city municipalities, and the environment.

Several attempts have been made to define smart cities in literature. Walravens N et al. [1] identifies technology, service of citizens, efficiency, and effectiveness as main goals in several smart city initiatives. Several studies find the integration of information and communication technology (ICT) into existing cities' structures, enabling sustainable living in the city is a crucial characteristic of the smart city. Although the smart city concept often tends to hover between several elements such as ICT, economy, governance, mobility, environment, and living, there is obscurity in the definition [4]. The void for a shared and holistic definition of smart cities can be attributed to the wide diversity in cities across the globe.

2 Methodology

Keywords "smart AND city* AND maturity models AND "maturity frameworks" AND "assessment" were used to accumulate the resources from the Scopus database. The search resulted in 234 papers in total, Mendeley, and Spreadsheets were used to sort and avoid duplication. Screening with a focus on a maturity assessment, 23 papers that discussed the maturity assessment of the smart cities, written in English were filtered.

3 Assessment Methods

Discussions on smart cities often raise questions regarding measuring the city's success in terms of its smartness, progress tracking, and timely human intervention. Assessment plays an important role by providing useful insights into answering these questions and assisting the implementation of policies. Assessment of the city aims to guide city municipalities to identify crucial areas to be improved [5] and plan and execute timely required interventions. Several organizations have put forward different ways of assessing smart cities, such as ranking metrics, standards, and assessment frameworks.

The use of a ranking system in the context of a smart city is widely used. Ranking cities enables positioning cities in a hierarchy based on indicators, such as city infrastructure and technology services to city inhabitants. Orlowski A [5] Lists the following widely accepted smart city rankings mechanisms.

- IESE Cities in Motion Index
- Top 50 smart cities governments (2020)
- 2020 smart city index by the institute for management development, in collaboration with the Singapore University for technology and design
- Smart cities index by 2019 by EasyParkGroup (Easypark 2019)

This method of putting cities to assessment not only impacts the inhabitant's social attention but also often simulates the discussion on city development strategies [6] and their implementation. Although the ranking method is significant in logically placing the smart cities in the hierarchy, it skips providing a holistic approach and brings the city municipalities into ambiguity. For example, Orlowski A [5] attempts to highlight the usual occurrence of different positions in multiple rankings at the same time, this eventually impacts the decisions of city municipalities. Furthermore, the usefulness of the information provided by the ranking system is limited as it only succeeds in providing city municipalities with information for comparing smart cities in the hierarchy and not in the city's progression [5]

Other assessment methods of smart cities such as the use of standards also pose challenges that are rightly pointed out by Orlowski A [5] as standards tend to impose a rigid framework of indicators that often succeeds on specific cities. As mentioned earlier, various cities around the globe have been using an assessment tool at city levels, subsequently, helping city municipalities find efficient methods to counter the challenges of cities and improve living. Maturity models are extremely popular and many cities are put to use maturity frameworks to assess growth.

4 Smart City Maturity Models

The process of evolution of the smart city, from its concept to its implementation, assesses cities in different aspects often these aspects are named differently such as dimensions, elements, or field of action. Several maturity models have identified various dimensions based on their requirements and purpose. Maturity models that attempt a holistic assessment of maturity identify dimensions that are not necessarily focused solely on Information and communication technologies, but rather consider other crucial verticals of smart cities such as education, innovation, and governance. For example, Afonso RA [7] identifies domains for a smart city such as water, education, energy, governance, housing, environment, health, security, technology, and transport, however, a few domains such as governance may tend to overlap with other domains as governance can be measured in every other domain. Mohsin BS et al. [4] highlighted two major domains of smart cities that can be noticed in literature, the hard domain focuses on the significance of ICT, its importance in the functioning of other smart city sectors, and the soft domain, where ICT application is not critical. Nevertheless, technology and its applications remain the least unfocused subject of research when it comes to smart cities. Few maturity models have considered untapped specific areas of smart cities and attempted maturity assessments in those domains. A few areas are worth mentioning as follows.

4.1 Strategy, Planning, and Citizen Participation

The introduction of technological interventions in the city certainly aids the better functioning of smart cities. However, this technological advancement can turn into a challenge without proper citizen involvement. Thus, posing the requirement of understanding the citizen's level of maturity towards participatory planning. Bouzguenda I et al. [8] identifies the level of maturity towards the introduction of digital participatory planning (DPP) in small European cities and proposes a framework that would allow local governments to assess their level of maturity of sustainable smart cities through DPP. Lack of strategy before embarking on the smart city implementation journey can be disastrous as a strategy provides a structure to follow. Kapkaev Y et al. [9] identifies strategy void as a major problem in the journey of digital transformation of territories. Korachi Z et al. [10] offers a methodology to formulate a strategy for the implementation of a smart city. Understanding the requirement of smart city transformation Identifying the stakeholders, and method of collaboration, and defining strategic goals and challenges for the smart city are crucial milestones in the development of smart city strategy. The novel smart city maturity model proposed by Moustaka V et al. [11] stresses citizen involvement but claims real-time data and privacy concerns are major challenges that must be addressed.

4.2 Mobility

[12–14] discusses the maturity assessment of specific dimensions of smart cities related to mobility which focuses on transportation and ICT. Warnecke D et al. [13] proposes a web-based self-assessment tool called SCMAB that attempts to enable stakeholders to measure the impact of smart city initiatives in the context of the mobility dimension. The tool is based on 36 indicators spreading across six themes: Policy and planning, ICT integration, Intermodal integration, public transport performance, environmental impact, and social impact. SCMAB maturity levels are score based, categorized into five stages with descriptions concerning the inclusion of ICT. However, the SCMAB tool fails to approach the holistic assessment of the smart city and claims the void of policy coherence across different levels of government as one of the major challenges. Visan M et al. [15] proposed and defined a cooperative intelligent transport system (C-ITS), a mobility-specific maturity model with five stages of maturity characterized by description focused on processed-oriented rather than outcome-oriented. Furthermore, it emphasizes the relevant technologies to implement C-ITS.

4.3 Data Transparency and quality

Data in the context of a smart city is another area where several maturity assessments often seem to take place. Data management becomes extremely crucial as cities embrace technology as a major enabler in the transition into smart cities. Technology is an inseparable element in making smart cities as every smart city initiative looks toward technology deployment to carry out the existing services and unlock efficient ways to perform activities. Nearly every maturity model proposed and used data for maturity assessment of the smart cities, for example [5, 16, 17] used data as a fundamental unit of the entire assessment framework. As studies like [5, 8, 18–20] are based on qualitative and quantitative methodologies, they naturally tend to lack the measure of data transparency and ignore the capability of an open data ecosystem in smart cities. Lnenicka M et al. [21] stresses on assessing the level of maturity of open data transparency in a smart city context, by examining 34 portals representing 22 European cities. Factors such as data understandability, usefulness, ease of user interaction, data quality, and accessibility impact the transparency of the open data ecosystem. The study identifies five types of ecosystems for open data each representing a variation of Open Government Data deployment for smart cities. It defines an open data ecosystem as "systematic efforts to integrate ICT and technologies into city life to deliver citizen-centric, better-quality services, solutions to city problems with open data published through the data-centric and data-driven infrastructure" In addition to the transparency of the open data ecosystem, the quality of the data impacts the results of the assessment of a smart city, eventually reflecting in smart city implementation initiatives. Data Quality Driven Smart Cities Maturity

Models (DQSC-MM) attempt to assess the maturity of smart cities with a focus on the quality of data generated and used. The model identifies connectivity, data centers, data analytics, application, and end users are five leverage domains that are further broken down into key domain areas [20]. Unlike Jāmiʿat al-Baḥrayn [21], Rotta MJR et al. [19] examines the maturity of eGov platforms as digital commons and presents Municipal eGov Platform Assessment Model (MEPA) to assess 903 municipal websites' maturity to aid the understanding of the promotion of commons and citizen participation and cites digital commons as a "resource based on information and communication technology, shared by groups and integrated into a value chain, under principles of equity, coproduction, and sustainability". As MEPA concerns factors like data openness, transparency, and civic engagement, it also attempts to stage the maturity levels that map with the commons-principles. MEPA adds to another specific dimension aiding the maturity assessment of smart cities.

Smart city maturity models are established by various cities with diverse specifications and definitions. They often are staged at multiple levels with each level portraying its characteristics. The characteristics often tend to differ from one maturity model to another, hinting towards uncommonness in consideration of the fundamental definition of maturity, and sometimes acceptance of capability in the basic assumptions in the maturity models. For instance, the maturity levels, provided by Nuraeni A et al. [17] are characterized based on the output of the task with a description of various stages of achieving the task ranging from 0 to 100%. On the contrary, maturity levels proposed by Bernal WN [18] are characterized by the nature of performing the activity i.e., integrated, analytically managed, and automated optimization. Although the formation of the maturity stages differs from the context it rests in, the fundamental assumption of the definition of maturity and capability remained a void to be filled. It can also be highlighted that the definition of maturity and capability in the formation of maturity models in an attempt to assess the smart city varies and remains unshared across maturity models of smart city maturity assessment.

Maturity assessment of domains such as transport and digital implementation is crucial, however, consideration of sustainability as a domain is rarely seen in the literature. Shen L et al. [16] introduces a methodology to assess low-carbon cities (LCC) using the capability maturity model. The model helps city municipalities to determine the maturity of LCC. However, like several other attempts, the model is specifically tested only in Beijing. Jāmiʿat al-Baḥrayn [22] highlights the concern over the applicability of maturity models is limited.

5 Proposed Smart City Maturity Assessment

The proposed smart city assessment consists of multiple layers as illustrated in Fig. 1. The top layer will account for domains or dimensions of the smart city and are characterized by not being common with each other. For instance, the mobility domain is easily distinguishable from the city's environment domain. City municipalities can choose the domains of their priority-based consideration using the Lens layer, thus allowing the maturity model to tend to be more holistic in nature.

The stack of layers below the lens layer represents the process and outcome-oriented sectors whose characteristics highlight commonness among all domains. For instance, governance is a sector that can be common in the mobility and the environment domain of the smart city. These layers shall represent the smart city path as it considers the processes required for selected domains. For example, digital participator planning proposed by Bouzguenda I [8] might happen to be the first step for the particular city to embark on the smart city journey followed by strategies for smart city implementation as proposed by Korachi Z [10]. These layers are outcome-oriented and answer the question of achievement of the task at multiple levels such as incomplete, managed, and performed. The layers represent the capability of the smart city and its status of achievement framework, each capability is measured to assess the efficiency with which it is performed. Maturity can be staged with a focus on each capability as structured, integrated, and optimized. Upon putting all the elements together, the proposed framework presents a holistic approach to assessing of maturity of the smart city, allowing city municipals to focus on required priority domains, and simultaneously provide the smart city path and its maturity assessment. This also characterizes the framework to be more dynamic in nature as it provides the flexibility for city municipalities to follow their maturity assessment.

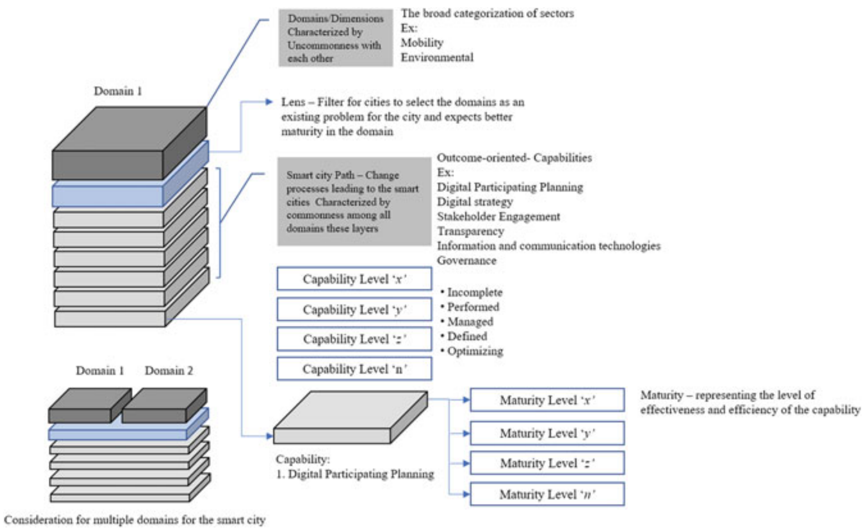

Fig. 1. Proposed conceptual smart city maturity assessment framework

6 Conclusions

To support the maturity assessment of the smart city, this study highlights the recent developments in strategy, planning, citizen participation, mobility, data transparency, and quality that aid the smart city assessment. Smart cities at their strategic phase clearly require an agreeable understanding of the capabilities they are there to achieve within a specified time frame. Maturity is the method to achieve those capabilities. Clearly distinguishable consideration of the definition of capability and maturity in the assessment framework is needed as they impact the staging strategy of maturity. Considering the capability as the necessary task that smart cities can achieve and the maturity as the effectiveness and efficiency with which the capability is achieved are the definitions considered in the proposed smart city maturity assessment framework. The presence of the lens layer makes the framework more flexible and dynamic in nature for cities as it allows city municipalities to choose the required domain specific to the city to achieve the capability for the city and higher maturity. Further, the details of the framework are to be considered to be developed in future attempts to establish a systematic maturity assessment model for the smart city.

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Challenges for the Implementation of Sustainable Construction Practices in Developing Countries: A Bibliometric Review

Motheo Meta Tjebane, Innocent Musonda, Adetayo Onososen, and Molusiwa Ramabodu

Abstract Developing countries face the constant challenges of implementing sustainable practices in their construction industry. However, a literature review is still needed to bring together the disaggregated studies and determine the development status of the sustainable construction research field. This study explores the challenges the construction sector faces in developing countries in integrating sustainability practices into infrastructure delivery. Through a bibliometric review, this study analyses articles from the Scopus database published between 2011 and 2021. The bibliometric analysis focused on analysing sustainable construction research publications and citation patterns, while content analysis was used to identify the primary levels of analysis and topical focuses. Emerging trends in the sustainable construction research field are reported. The study also determined the most productive authors and collaboration among authors, most productive journals, and most active countries and publications with the highest impact on sustainable construction research. The study's findings reveal the level of interest in sustainable construction by academics and industry practitioners in developing countries. This also informs on the level of awareness on sustainable development in developing countries. Challenges identified and discussed explore themes on institution support, stakeholders' role, lack of regulation and legislation, and building standards and guidelines. The results are imperative for improving the understanding of challenges to sustainable development, which is vital to policy formulation and decision-making. The discussions also provide solutions to sustainable development challenges and offer strategies to drive adoption.

M. M. Tjebane (✉) · I. Musonda · A. Onososen · M. Ramabodu
Center of Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: tjebane.motheo@mut.ac.za

M. M. Tjebane
Department of Construction Management and Quantity Surveying, Mangosuthu University of Technology, Durban, South Africa

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Keywords Sustainable Development · Developing Countries · Resilient · Responsive · Infrastructure

1 Background

Sustainability has recently gained popularity due to its positive impact on environmental, social, and economic issues [1]. Within the construction industry, projects embrace sustainability to secure economic improvement while preserving biodiversity and ecology [2]. This is because the construction industry consumes a significant amount of energy and resources, including 16% water, 25% timber, 40% raw materials, and 32% total energy consumption. Furthermore, the industry is responsible for 40% of waste generation, and one-third of carbon emissions [3, 4] noted that the construction industry has a critical role to play in influencing the achievement of Sustainable Development Goals (SDGs).

Even though the construction industry is the backbone of any economy, it still contributes significantly to emissions by consuming energy and producing the majority of waste [5]. Given the global climatic challenges, sustainable construction practices are the only solution. Many sustainable construction projects are being built worldwide, mainly in developed countries, because of their enormous benefits [6]. However, in developing countries, implementing sustainable construction poses numerous challenges.

Various studies have been conducted on the challenges and barriers of sustainable construction practices in various countries using different methods [7]. Looking at green building barriers in Taiwan using a mixed approach of questionnaires and case studies. [8]conducted a quantitative study on Barriers to Sustainable Management of Construction and Demolition Waste in Developed and Developing Countries. The study Ranking of the barriers was carried out using the Relative Importance Index (RI), and the results were statistically analysed using Statistical Package for Social Sciences (SPSS). [9] study looked challenges of sustainable construction delivery in the United Arab Emirates (UAE). A quantitative approach questionnaire survey was developed and distributed to construction professionals in the UAE to evaluate the significance of sustainable construction project delivery challenges.

These studies provide insight into the challenges of sustainable construction. Few have a quantitative impact regarding the amount of work conducted worldwide on the challenges and barriers. Thus, this study aims to conduct a bibliometric analysis of the challenges of sustainable construction practices in developing countries. This is accomplished through a bibliometric review of articles published and indexed on Scopus between 2011 and 2021. The following is how the article is structured: Sect. 2 discusses the research design and methodology, while Sect. 3 discusses the bibliometric findings. The findings are discussed in Sect. 4. Finally, Sect. 5 contains the conclusions.

2 Research Design and Method

This study used a quantitative bibliometric approach to fulfill the research objectives. A systematic approach was used in scoping and selecting publications. The flowchart in Fig. 1 below shows the research method used.

A bibliometric visualisation is a useful tool for visualising the domain of information as well as the relationships between papers, and journals, among others [10]. Based on established literature, bibliometric mapping is used in this study to classify knowledge domains and research patterns for challenges of sustainable construction in developing countries. in the AEC industry. [11] noted that bibliometric survey aids in understanding globally published research by storing information such as publication year, country, author, journal of publication, and affiliation in a single database. Meanwhile, a systematic analysis was conducted to include a holistic view of current research to assess knowledge gaps and predict future research directions

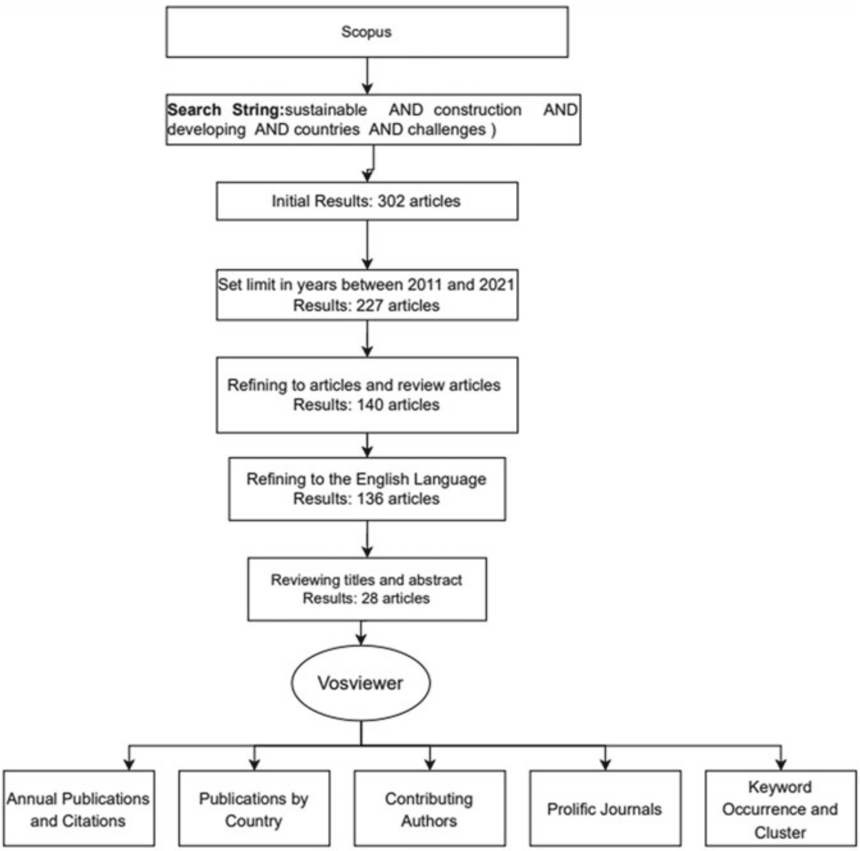

Fig. 1. Research flowchart

[12]. Scopus database was used as the platform to source publications. Scopus is the most widely used database in science mapping due to the belief that it contains higher-quality data [13]. Scopus, which includes over 23,500 peer-reviewed journals. It has over 75 million records dating back to 1788 in various subject areas such as [14].

2.1 Inclusion and Exclusion Criteria

The articles were selected an inclusion and exclusion criteria. This eligibility criterion determines whether the titles, abstracts, years, and keywords of the publications read are part of the required set for this review [15]. [16] noted that researchers avoid bias by establishing exclusion and inclusion criteria in advance. In general, inclusion criteria serve as the foundation for including articles that provide the information needed to answer the research question. While exclusion criteria include the basis for excluding non-relevant articles, duplicate articles, and articles with no available full-text. The inclusion criteria looked at the following:

- Publications made between 2011 and 2021
- Articles and review articles
- Published in the English language

2.2 Search String

Because of the rapid advancement of technology, bibliometric analysis can now be performed using various existing software. A list of keywords relevant to sustainable construction practice was created. The query string was: sustainable AND construction AND developing AND countries AND challenges. The Boolean operator AND ensured that every publication containing the keywords was extracted from Scopus [15].

2.3 Data Analysis

Because of the rapid advancement of technology, bibliometric analysis can now be performed using various existing software. VOSviewer is a free visualisation software based on the Java platform that can be used to create accessible maps using bibliographic data. It is far more effective and powerful in data processing and map generation than other visualised tools. It allows researchers to quickly identify hotspots and developments in their research field of interest [17]. VOSviewer was chosen for this study to draw science mappings because it has exceptional text-mining capabilities and is well-suited for dealing with larger networks. VOSviewer

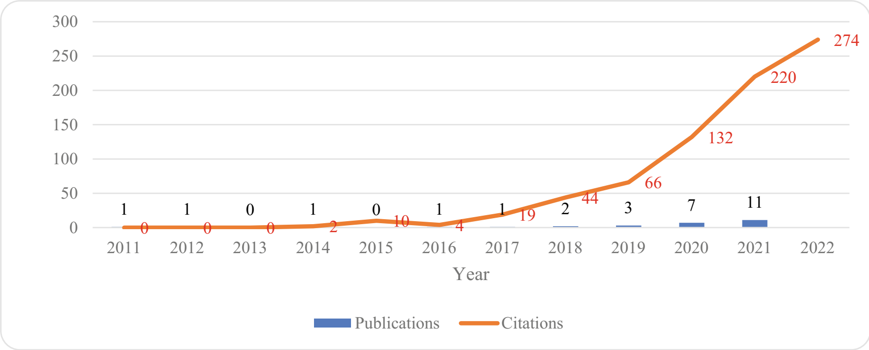

Fig. 2. Publication verses Citation from 2011 to 2021

is currently being used in construction industry research to create science mappings for various topics [15] and analyse the mapping analysis, bibliographic coupling, keyword co-occurrences analysis, and co-authorship [18].

3 Results

3.1 Descriptive Analysis

From 2011 to 2021, 28 documents on sustainable construction practices in developing countries were published on Scopus. The distribution of publications and citations by year. This is shown in Fig. 2 below. Five papers on sustainable construction practices in developing countries were published in the first seven years. The rate of article publication has increased at a faster rate since 2018. Overall, the annual publications on SEC in machining operations have been steadily increasing since 2020.

3.2 Country Analysis

China accounted for the greatest number of publications with six articles. Australia followed this with five and the United Kingdom with four. Six countries had only one publication each. In terms of citations, India had the highest with 298, this is followed by China with 240 and Australia with 99. Ghana accounted for the lowest, with 14. Figure 3 Australia has the most collaborations, followed by Iran and Saudi Arabia (See Table 1).

Fig. 3. Country collaboration network

Table 1. Country Analysis

Country	Documents	Citations	Total Strength
India	1	298	0
China	6	240	4
Australia	5	99	8
united states	2	74	1
Germany	2	67	0
Denmark	1	64	1
Iran	3	39	6
Kazakhstan	1	27	0
New Zealand	1	27	0
Norway	1	27	0
Malaysia	2	26	0
Egypt	3	24	0
Saudi Arabia	1	20	0
United Kingdom	4	18	6
Ghana	3	14	0

3.3 Authorship Analysis

Table 2 shows the top authors in terms of number of citations. From the list of 16 authors, 6 authors have 298 citations from publishing 1 article. Furthermore, 3 authors had 99 citations from 1 published article. Figure 4 below shows the lines of collaborations being clustered among authors.

3.4 Journals

Table 3 shows the top 22 most cited journal articles in sustainable construction practice by total publications and citations. Construction and building materials had the highest number of citations, with 298 citations from 1 article. The journal with the second highest number of citations was the journal of environmental management, with 99 citations from 2 published articles. The lowest citations came from advanced sustainable systems, with seven citations.

Table 2. Author Analysis

Author	Documents	Citations	Total Strength
Ansari M	1	298	0
Dutta S.C	1	298	0
Joshi H	1	298	0
Kisku N	1	298	0
Nayak S	1	298	0
Panda S.K	1	298	0
Aslam M.S	1	99	4
Cui L	1	99	4
Huang B	1	99	4
Tam V.W.Y	2	82	5
Duan H	1	64	3
Liu G	1	64	3
Miller T.R	1	64	3
Manowong E	1	63	0
Kumanayake R	1	31	1
Luo H	1	31	1

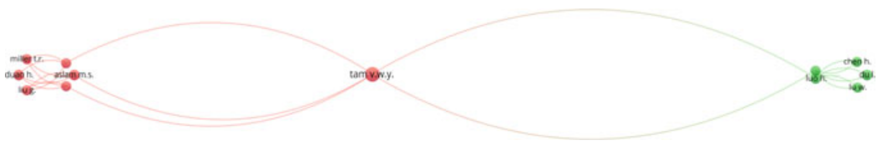

Fig. 4 Author collaboration network

3.5 Keyword and Cluster Analysis

A keyword frequency visualisation sustainable practice research in contraction was generated by VOSviewer as seen in the Table 4 and Fig. 5 Among the most frequently mentioned keywords were developing countries (occurrence = 17), sustainable development (occurrence = 15),construction industry (occurrence = 13), sustainability (occurrence = 12), developing world (occurrence = 9), sustainable construction (occurrence = 9), surveys (occurrence = 5), waste management (occurrence = 5), construction (occurrence = 4), construction and demolition waste (occurrence = 4), developing country (occurrence = 4). Five clusters of 66 keywords were grouped.

Table 3. Journal Analysis

Journal	Documents	Citations	Total Strength
Construction and Building Materials	1	298	0
Journal of Environmental Management	1	99	1
Waste Management and Research	2	70	0
Waste Management	1	64	1
Sustainability (Switzerland)	3	32	0
Building and Environment	1	31	1
Environment, Development and Sustainability	1	27	0
Sustainable Cities and Society	1	26	0
Administrative Sciences	1	24	0
Engineering, Construction and Architectural Management	2	22	1
Journal Of Engineering, Design and Technology	1	20	0
Smart and Sustainable Built Environment	2	11	1
Case Studies in Construction Materials	1	10	0
Natural Resources Forum	1	10	0
Advanced Sustainable Systems	1	7	0

4 Discussion

4.1 Content Analysis

4.1.1 Cluster 1

This cluster comprised 16 keywords, including building industry, demolition, and waste disposal, among others. From the content analysis, [19] the concept of sustainable cities is mainly about neutralising and conserving resources and maximising economic benefits with minimal investment and pollution. This includes paying attention to waste management and material utilisation with all "new" buildings, regardless of their class. In the case of "old" buildings, the highest priority is waste management, use of materials, energy consumption, and sustainable use of ecosystems [3].

Construction and demolition waste, produced by rising demand for infrastructure and municipal growth, has expanded due to urbanisation's effects on the population and economy. With such a large amount of construction waste, environmental challenges are created, such as resource depletion, loss of green space, increased air and land pollution, and hazardous waste discharge [8]. The majority of developed countries have environmental sustainability laws that direct infrastructure design and force design teams to take environmental sustainability into account at the design stage. Contrarily, insufficient ecological regulatory frameworks and a lack

Table 4 Keyword cluster analysis

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Building Industry	Affordable housing	Architectural design	Article	Assessment method
China	barriers	carbon	construction activities	Building
circular economy	challenges	carbon dioxide	construction materials	Costs
cities	construction industry	carbon emissions	construction waste materials	life cycle
city	construction sectors	construction	construction wastes	life cycle analysis
construction and demolition waste	decision making	design/ methodology/ approach	developing country	life cycle assessment (LCA)
demolition	developing countries	environmental technology	economic and social effects	material selection
developing world	drivers	global warming	economics	scales (weighing instruments)
economic conditions	framework	green building	environment	social aspects
environmental protection	green projects	green buildings	numerical model	surveys
municipal solid waste	knowledge	intelligent buildings	strategic approach	
recycling	project management	sustainable development	urbanisation	
refuse disposal	stakeholders	sustainable practices		
solid waste	sustainability			
waste disposal	sustainable construction			
waste management				

of standards for designers to follow regarding environmental sustainability goals are prevalent in developing countries [20].

4.1.2 Cluster 2

This cluster comprised 15 keywords, such as construction sector, drivers, sustainability, and stakeholders, among others. From the content analysis, [20] found the infrastructure design stage in developing countries is where technical, functional, and aesthetic factors take precedence over environmental considerations. Moreover,

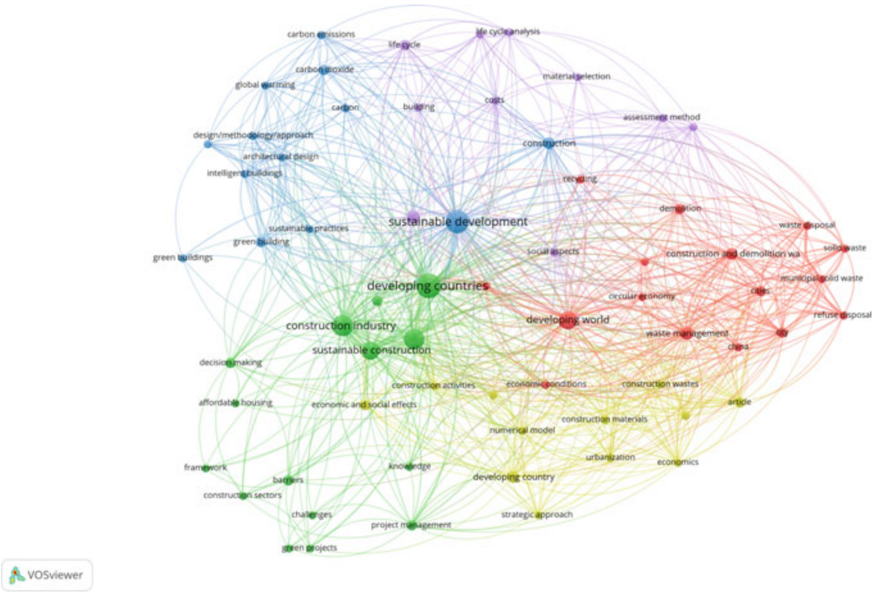

Fig. 5 Keyword cluster network

[2] found that the economic and regulatory-based hurdles more heavily influence the failure of a change to sustainable practices in Iran. The major barriers to incorporating sustainability into construction projects are: (1) a lack of knowledge about the potential benefits) a lack of collaboration between practitioners, research institutions, and environmental organisations, and a lack of a systematic strategy for pursuing sustainability goals.

The difficulties in choosing acceptable materials for sustainable construction projects are caused, among other things, by the high cost of construction materials in developing nations like Ghana. This indicated the need for a proper selection of sustainable construction materials that can promote a better quality of construction structures, ensure faster construction solutions and foster new economic development at better cost offers. The "sustainability" of energy efficiency and environmental techniques for specific local situations, such as the social, economic, and ecological components of sustainable practices, will be addressed in this choice [1]. Similarly to a study by which found [21] most of the highly ranked barriers, such as "high-interest rates," "high inflation rate," "high upfront cost of materials and sustainable technologies," and "high cost of serviced land.

However, developing countries can overcome this through government subsidising small contractors to offset premiums, encouraging sustainable construction in public projects, and hiring or engaging sustainability experts, among others [22]. Despite the well-known benefits of sustainable construction methods, adopting them widely will take a lot of time and effortespecially in developing nations where the presence of hurdles makes adoption difficult or unprofitable [3].

4.1.3 Cluster 3

This cluster comprised 13, including architectural design, construction, intelligent buildings, and sustainable development. Highlighting critical design factors for infrastructure, such as functionality, aesthetics, and construction cost, is important when designing with sustainability [20]. Project management key stakeholders must proactively identify and overcome the adoption hurdles if sustainable practices are to be incorporated into construction projects. This is due to the critical role that project management plays in the planning, development, and execution of construction projects [2]. Also, sustainable construction practices should occur at every stage or step. Better material selection is required to realise sustainable building practices for project delivery and achieve the desired sustainable results. This includes using automation, energy utilisation and intelligent buildings to accelerate issues in sustainability [23]

4.1.4 Cluster 4

This cluster comprises 12 keywords such as article, construction wastes, developing country and urbanisation [9]. The quantity and complexity of the construction industry's projects are growing, leading to increased environmental degradation and greenhouse gas emissions. This has increased awareness and helped several nations, even developing ones, act. This is due to increased construction-related issues brought on by sustainable construction, making projects more complex. As a result, it's important to recognise and classify the difficulties in completing sustainable construction projects.

The management of sustainability comes at an additional expense. Cost-saving measures include finding the optimal routes, using waste transportation, recycling resources, and improving quality to realise economic and environmental gains while using less fuel [8]. [24] also noted that the primary force behind the guiding standard for decision-making in its development is the economy of sustainability. Where the potential financial savings can be made—in the initial investment in sustainability, later operation expenses, or reduced resource use—is still up for debate in the economics of sustainable construction. These could all be influenced by the nation and its stakeholders.

However, developing countries frequently struggle to achieve sustainable development due to balancing economic development and environmental quality while simultaneously enhancing social welfare. Because of benefits like lowering greenhouse gas emissions and energy consumption, especially in developing countries where environmental pollution has been a big issue, sustainability will undoubtedly become increasingly popular in the future [7].

4.1.5 Cluster 5

Cluster 5 comprises 10 keywords, including life cycle assessment (LCA), material selection, scales (weighing instruments) and social aspects. [20] found the main barrier to using sustainable building methods is their higher cost as compared to conventional ones. Along with other elements like the absence of historical data or information, the method used to choose a pricing strategy, the possibility of unexpected costs, the level of staff training and development, and others, this is one of the contributing factors [1].

Infrastructure operation and maintenance will be more sustainable if a sustainable material selection is used. This maximises the sustainability of the whole project life cycle [25]. The necessity and value of sustainability reside in the fact that construction managers are the ones who make most choices throughout any infrastructure project. Together with other experts, they choose the specific design and/or building technique to apply. Therefore, recognising the larger, system-based picture is crucial to successfully barriers and incorporating sustainability drivers into construction projects [3]. Moreover, life cycle assessment is done mainly in old infrastructure and not newly built. This is considering the high number of old buildings in urban areas [26]

4.2 Implications

The construction industry is among the many sectors adopting sustainability practices for economic, social and economic benefits. This article assessed the current research status of sustainable construction practices in developing countries. Scientometric methods were used to accomplish this, specifically downloading metadata information from the Scopus index for more than 28 publications published between 2011 and 2021. The resulting dataset was examined in terms of the sources and research areas associated with it and the affiliation between countries and international collaboration.

The initial search results of 302 results to 28 articles after applying inclusion and exclusion criteria. Moreover, within the ten years, the most significant jump in publications was made in 2020, when seven articles were published. This shows little research linked to sustainable construction practices in developing countries.

From the research on sustainable construction, the practice has grown within the last four to 5 years, as shown in Fig. 2. Moreover, the analysis of the keyword frequently mentioned words was developing countries, sustainable development, construction industry, and sustainability. According to [27], to avoid subsequent processes for managing construction projects in developing countries with limited financial resources and limited construction management initiatives on sustainability. Strategies should be established to take proactive steps and pay attention to existing and anticipated conditions for construction sustainability practices. Moreover, the sustainability criteria among developing and developed countries must be different.

Regarding country analysis, China accounts for the most publications, with 6, while India has the most citations, with 298 [28]. China and India appear to be in a severe position from the viewpoint of environmental issues. [28] had 298 citations; this accounted for the highest citations for country, authorship, and journal.

This article had some limitations. Only Scopus was used to gather the bibliometric data. We also used inclusion and exclusion criteria which might have left out some relevant articles.

5 Conclusion

This study examined the challenges of implementing sustainable construction practices in developing countries. This study provided a state-of-the-art bibliometric review through bibliometric review. This was on the challenges of implementing sustainable construction practices in developing countries. Future research should expand the number of databases and publications despite the study's limitations. Moreover, the bibliometric review advances the body of knowledge on sustainable construction practice.

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Robotics, Automation, and Control

Structural Health Monitoring of Civil Infrastructure using Mobile Robots

Kay Smarsly, Kosmas Dragos, Jan Stührenberg, and Mathias Worm

Abstract With the advancements in information, communication, and sensing technologies, structural health monitoring (SHM) has matured into a substantial pillar of infrastructure maintenance. In particular, wireless sensor networks have gradually been incorporated into SHM, leveraging new opportunities towards reduced installation efforts and enhanced flexibility and scalability, as compared to cable-based SHM systems. However, wireless sensor nodes are installed at fixed locations and need to be employed at high density to reliably monitor large infrastructure, which may cause high installation costs. Furthermore, the limited power autonomy of wireless sensor networks, installed at fixed locations for unattended long-term operation, still represents a significant constraint when deploying stationary wireless sensor nodes for SHM. To resolve the critical constraints stemming from costly high-density deployment and limited power autonomy, a mobile structural health monitoring concept based on legged robots is proposed in the feasibility study reported in this paper. The study explores the feasibility of deploying legged robots for wireless SHM of civil infrastructure, aiming to achieve insights into realizing the advantages of mobile wireless sensor nodes in general and of legged robots in particular. As will be shown in this paper, the legged robots, as compared to stationary wireless sensor nodes, require a smaller number of nodes to be deployed in civil infrastructure to achieve the same sensor information, entailing more cost-efficient – yet accurate – SHM. In conclusion, this feasibility study represents a first step towards autonomous robotic fleets advancing structural health monitoring.

Keywords Structural health monitoring (SHM) · quadruped robots · legged robots · wireless sensor networks · infrastructure maintenance

K. Smarsly (✉) · K. Dragos · J. Stührenberg · M. Worm
Institute of Digital and Autonomous Construction, Hamburg University of Technology, Hamburg, Germany
e-mail: kay.smarsly@tuhh.de

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1 Introduction

The US Federal Highway Administration estimates a US$ 125 billion bridge repair backlog in the United States [1]. The situation in other industrial countries is similar. In Germany, almost 700 bridges are more than 100 years old, and more than 10% of highway bridges are deficient [2]. The vulnerability of civil infrastructure due to aging is being further exacerbated by climate change, thus highlighting the need for timely structural maintenance, which has been increasingly relying on structural health monitoring (SHM) [3].

Over the years, the SHM community has witnessed gradual transitions in strategies and equipment adopted, following the advances in sensor technologies. Early SHM case studies have been limited to civil infrastructure of high importance or of strong academic interest, due to the dependence of SHM instrumentation on relatively expensive cable-based sensors and data acquisition units. In recent years, however, developments in sensor technologies have been offering cost-effective alternatives for SHM, usually consisting of wireless sensor nodes [4]. Since the merits of wireless technologies have been apparent from the very first "wireless" strategies in SHM, practitioners have sought, on the one hand, to exploit the scalability of wireless sensor networks towards deploying SHM systems of increasing density, in an attempt to obtain spatially rich information on structural conditions [5]. On the other hand, misuse of scalability of wireless SHM systems may result in particularly dense sensor networks. Dense sensor networks, in turn, may raise questions regarding the eventual cost-effectiveness of dense SHM deployment, the robustness of the SHM system, and the conformity of the SHM strategy with aesthetic and operational requirements.

In recent years, representing the middle ground between obtaining spatially dense information and utilizing the convenience of wireless technologies with minimal deployment of equipment, the SHM practice has been drawing from the field of robotics. At first, the notion of mobility in SHM systems had materialized in mobile robots facilitating powering embedded remote sensors and retrieving data with close-proximity telemetry, as reported by Huston et al. [6]. Furthermore, solutions based on non-stationary wireless sensor nodes have sporadically been proposed in the form of mobile SHM systems employing wheeled robots [7]. Examples include the "robomote" introduced by Dantu et al. for augmenting static sensor networks [8], and the prototype mobile SHM system, capable of navigating structures using ferromagnetic materials, designed and validated by Zhu et al. [9]. The efficiency of mobile robots for SHM lies in the capabilities of a minimum deployment of robots (i) to scan relatively extensive areas on structures and (ii) to form ad-hoc wireless networks for exchanging information to collaboratively analyze the structural conditions [10]. However, state-of-the-art approaches on mobile SHM systems largely rely on wheeled robots, which, in complex structures, may be unable to access areas with impediments. In this regard, legged robots may offer an attractive alternative for SHM, in terms of maneuverability and transversability, following up on recent research advances in bionics [11].

This paper reports on a feasibility study, proposing a mobile structural health monitoring concept based on legged robots, extending preliminary work published in [10] and in [12]. Legged robots exhibit enhanced mobility, compared to wheeled robots, and are able to access extensive locations on structures by traversing impediments, such as stiffening plates, pipelines and electrical installations [13]. The feasibility study essentially seeks to validate the mobile SHM system presented in the studies mentioned above in real-world conditions, i.e. implemented in robust legged robots and applied on a real-life pedestrian bridge. The mobile SHM system consists of legged robots, featuring (i) a locomotion component, (ii) a processing component, and (iii) a sensing component. The goal of the feasibility study is to showcase that the mobile SHM system is capable of yielding the same level of information on structural conditions as a stationary wireless SHM system when applied on a real-life pedestrian bridge. In the rest of the paper, Sect. 2 describes the mobile SHM system, and Sect. 3 covers the validation tests conducted on a pedestrian bridge in Hamburg, Germany. The paper concludes with a summary and an outlook on potential future research efforts that may be undertaken to advance the concepts presented herein.

2 A Mobile Structural Health Monitoring System Based on Legged Robots

Considering the refinement characterizing modern structural analysis methods, e.g. using finite element models with fine meshes, it is reasonable to pursue SHM-derived information that would at least spatially envelope structural analysis results. In this context, the motivation behind the mobile SHM system, presented in this section, is to maximize the information on structural conditions, while employing a SHM strategy that is efficient, cost-effective, and least invasive. The capabilities of legged robots to navigate extensive areas on structures and to reach locations that may be hardly accessible to humans allow collecting elaborate fields of structural response data that can help stakeholders make educated judgments on structural conditions. In addition, elaborate fields of structural response data enable comparisons with structural analysis results, which can be used for system identification and (finite element) model updating.

From a budgetary perspective, for a mobile SHM system to be viable, only a small number of legged robots should be used. Particularly considering the unit price difference between legged robots and wireless sensor nodes, it follows that the cost-effectiveness of a mobile SHM system can be ensured only if the number of legged robots is kept to the minimum necessary for fulfilling the SHM objectives. Drawing from common SHM practice, which largely involves analyzing acceleration response data and computing experimental mode shapes, SHM objectives frequently require simultaneous data acquisition from at least two locations. As a result, for the mobile SHM system proposed in this feasibility study, two legged robots will be deployed. Apart from collecting acceleration response data, the legged robots are capable of communicating with each other and of collaboratively analyzing the data to extract information on the structure, e.g. in the form of experimental eigenfrequencies. In what follows, the hardware and software specifications of the mobile SHM systems are described.

2.1 Hardware Design and Implementation

The type of legged robots used for the mobile SHM system in this feasibility study are "intelligent documentation gadgets" (IDOGs), built around Unitree's A1 robot model [14]. In accordance with the mobile SHM system requirements previously described, the IDOGs are capable of multi-direction locomotion, of data acquisition, and of on-board data processing. The hardware design implementation follows the same reasoning as in [10] and is shown in Fig. 1.

The "locomotion component" of the IDOG, shown in Fig. 1, consists of four legs driven by motors at three points ("hip", "knee", "thigh"), thus providing twelve degrees of freedom for locomotion and ensuring advanced maneuverability. The locomotion component enables the IDOG to assume the "measuring posture", essentially lying down for conducting measurements, and the "walking posture", i.e. standing up and moving from one location to the other. The locomotion control is computed and provided by the "locomotion board", which resides in the "processing component". Apart from the locomotion board, an on-board computer, designated as "computing board", is included in the processing component for reading and analyzing data from the sensors attached to the IDOG (included in the "sensing component").

In this feasibility study, the sensing component encompasses a "light detection and ranging" (Lidar) sensor that enables the IDOG to perceive its environment. In future

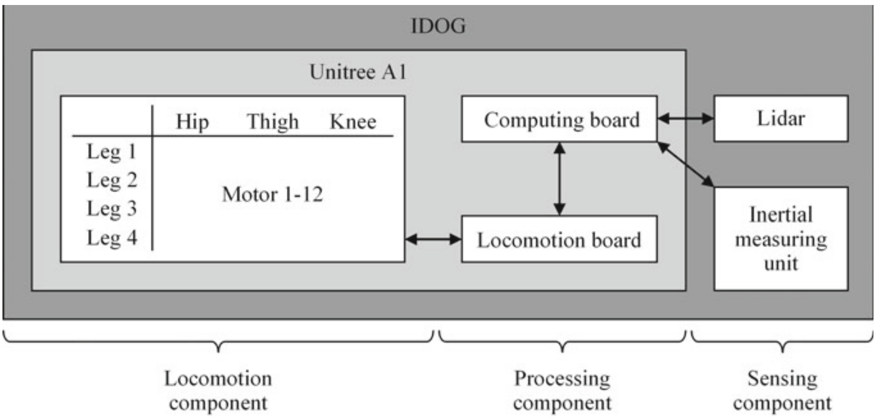

Fig. 1. Hardware components of the IDOG

work, the Lidar sensor will enable the IDOG to autonomously navigate to measurement locations. Moreover, a Bosch BMI055 inertial measuring unit (IMU) with an integrated accelerometer is included in the sensing component for collecting acceleration response data. The IMU measures at a range of ±4 g, at a sampling frequency of 250 Hz, and with a minimum detectable acceleration of 0.98 mg [15]. As will be shown in the validation tests, the measuring posture that the IDOG assumes ensures that the measurements of the IMU correspond to the acceleration response data of the structure being monitored. As a result, the acceleration response data collected by the IDOGs are suitable for vibration-based SHM tasks, such as operational modal analysis, using embedded software, which is described in the following subsection.

2.2 Software Design and Implementation

The IDOG leverages embedded software, flowcharted in Fig. 2 by means of the process conducted by the mobile SHM system, designed around the "robot operating system" (ROS) framework. The embedded software enables collecting, processing, and analyzing acceleration response data. When beginning operation, a ROS process is started that starts the accelerometer. Next, the IDOG assumes the measuring posture at a measurement location, the acceleration response data is collected and stored in a local file. Subsequently, the acceleration response data is analyzed by performing fast Fourier transform (FFT) and peak picking, i.e. detecting "modal peaks" in the frequency-domain representation of the acceleration response data that essentially are frequency components exhibiting maximum amplitude in the FFT.

For perceiving the environment, two ROS processes are started. The first process collects Lidar scan data in the form of a point cloud. The second process subscribes to the scan data and executes a "simultaneous localization and mapping" (SLAM) algorithm. In this study, the Google cartographer is used for creating a 2D grid map [16]. The grid map is devised for visualization purposes, highlighting the positions of the acceleration measurements. As discussed previously, in future work, the grid map will be integrated into the mobile SHM system to provide perception for autonomous locomotion of the IDOG.

3 Field Validation Tests at a Pedestrian Bridge

Validation tests within the framework of the feasibility study are conducted on a pedestrian bridge. The purpose of the validation tests is to showcase that the mobile SHM system is applicable in real-life conditions. Serving as a benchmark system for comparison, a wireless SHM system comprising stationary wireless sensor nodes is installed on the bridge. In the remainder of this section, the pedestrian bridge and the experimental setups are described, and the test results are presented and discussed.

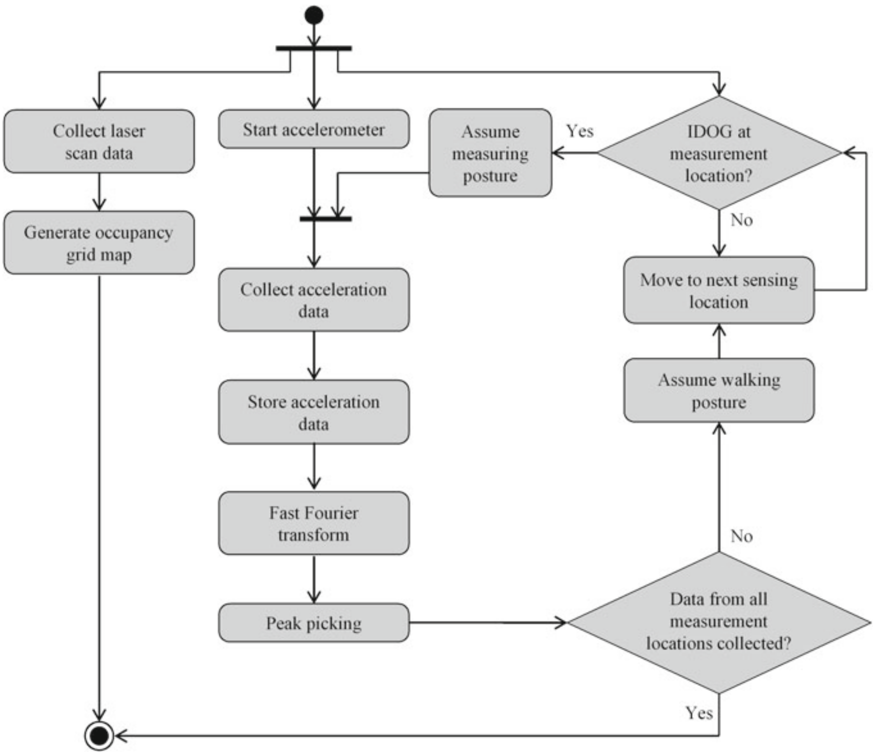

Fig. 2. SHM process conducted by the embedded software designed for the IDOGs

3.1 Description of the Pedestrian Bridge and the Benchmark SHM System

The pedestrian bridge used for the validation tests is the "Citadel Bridge" (German: "Zitadellen-Brücke"), which spans the Lotse Canal at Hamburg, Germany. The pedestrian bridge, shown in Fig. 3, is a relatively new structure, opened to traffic in 2016. The main deck of the bridge comprises a welded steel trapezoidal hollow "box" section of variable dimensions. The deck has a length of 45.5 m and a width that varies from 3.25 m to 5.65 m. In the vertical direction, the main deck rests on two reinforced concrete piers, and, at its ends, abuts the quay walls on each side of the canal, essentially forming one middle span, between the two piers, and two side spans, each between one pier and one abutment. The main part of the main deck is capable of revolving around one of the piers, functioning as a swing bridge, to facilitate traffic of canal vessels.

The benchmark system includes eight wireless sensor nodes of type Oracle "Sunspots" [17]. The microcontroller of each sensor node features an ARM processor running at 400 MHz, volatile memory of 1 MB, and flash memory of 8 MB. The

Fig. 3. Views of Citadel Bridge, Hamburg, Germany

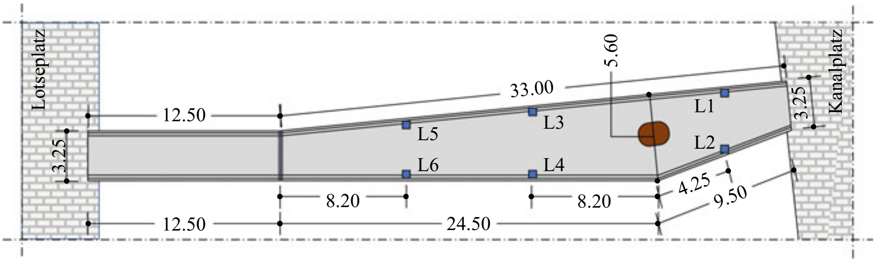

Fig. 4. Plan view of the measurement locations on the pedestrian bridge

sensing component of each sensor node integrates a 3-axial accelerometer, of type MMA7455L, measuring at a selectable range between 2 and 16 g with a selectable sampling rate up to 250 Hz. The analog-to-digital conversion supported by the accelerometer is of 8-bit resolution. For the purposes of this study, the accelerometers are placed along the longitudinal edges of the main deck, as shown in Fig. 4. In particular, four sensor nodes are placed on the middle span, and two sensor nodes are placed on each side span. The purpose of placing the sensor nodes along the edges of the deck is to capture both translational and torsional vibrations. Due to the swing function of the bridge, the left-hand side of the main deck, as shown in Fig. 4, is separated by a full-depth gap from the rest of the deck, and, thus, exhibits independent dynamic behavior from the rest of the bridge. Therefore, the measurements are restricted to the middle part and the right-hand side of the deck. The wireless sensor nodes are tasked to collect acceleration response data in the vertical (z) direction with a measurement range of 2 g and a sampling frequency of $f_s = 125$ Hz for a duration of 120 s.

3.2 Validation Tests

The benchmark system and the mobile SHM system are compared on the basis of information extracted from acceleration response data. As mentioned previously, the information translates into "modal peaks" in the FFT amplitude spectra of the

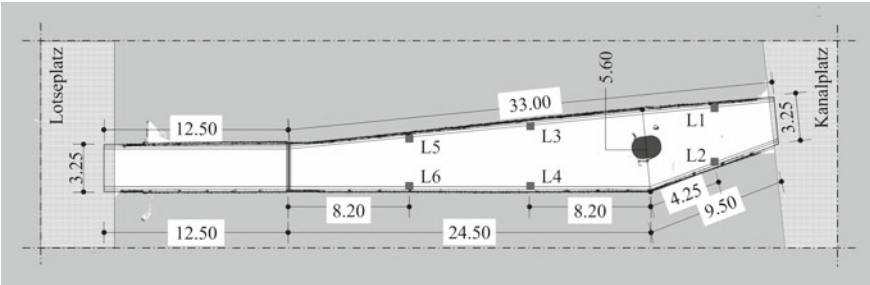

Fig. 5. Visualization of the pedestrian bridge using Lidar data

acceleration response data. For the benchmark system, the wireless sensor nodes autonomously estimate modal peaks and communicate the respective frequencies to a centralized server. For the mobile SHM system, a minimum deployment of two IDOGs is adopted to progressively access all measurement locations of the benchmark system in pairs and to collect acceleration response data. The reasoning behind using at least two IDOGs is to ensure that the modal peaks detected in the FFT amplitude spectrum are confirmed by two independent IDOGs from two separate locations, thus avoiding false positive detections of modal peaks, given the output-only nature of the SHM approach. Although the measurement locations are accessed manually in this study, since autonomous navigation is part of future work, the visualization of the pedestrian bridge by the SLAM algorithm showcases that the IDOGs are capable of perceiving the surroundings of the structure through the Lidar sensors. The measurement locations (L1…L6) are illustrated in Fig. 5. In each pair of measurement locations, the IDOGs collect and analyze the acceleration response data in the frequency domain to obtain modal peaks, which are wirelessly communicated to a centralized station.

The IDOGs are positioned at the abutment on the right-hand side of the main deck. Since the analysis of one of the IDOGs serves as confirmation of the modal peaks, one of the measurement locations is selected as a "reference point", against which the analyses from the rest of the measurement locations are compared. Location L4 is selected as reference point based on engineering judgment, because most vibration modes are expected to exhibit discernible amplitudes. One of the IDOGs ("IDOG 1") is placed at the reference point, and the other IDOG ("IDOG 2") progressively accesses the rest of the measurement locations by assuming the walking posture, shown in Fig. 6 (bottom left). Upon reaching a measurement location, the IDOG switches to measuring posture, as shown in Fig. 6 (bottom right). Simultaneously, the IDOG at the reference point switches to measuring posture, as shown in Fig. 6 (top), and both IDOGs collect acceleration response data for a duration of 120 s at a sampling frequency of f_{so} = 250 Hz. Next, each IDOG transforms its acceleration response data into the frequency domain and detects modal peaks, using the embedded FFT and peak-picking algorithm. Finally, the IDOGs exchange the modal

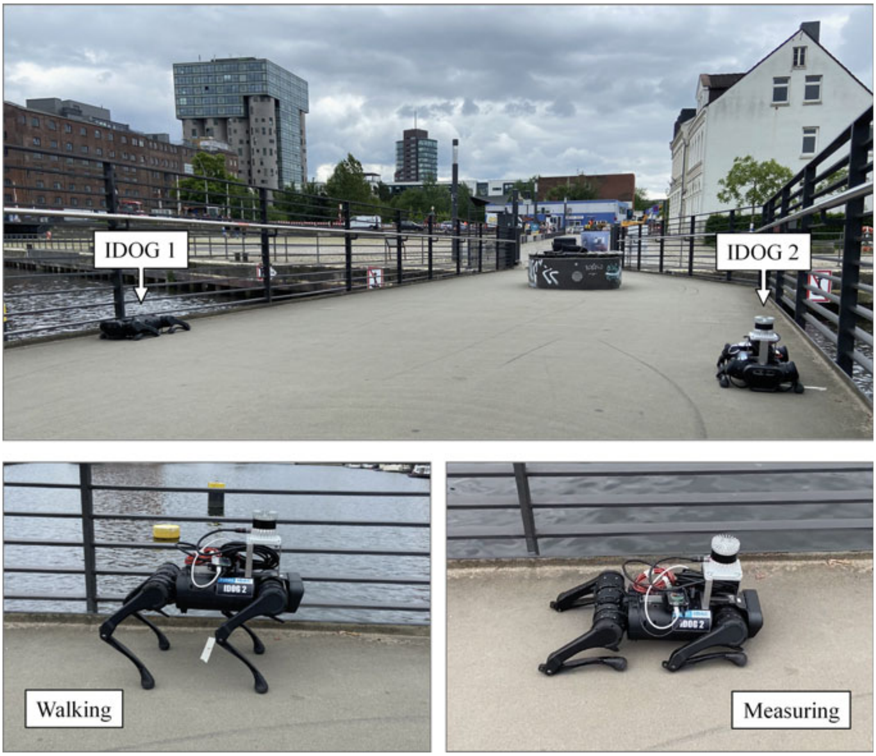

Fig. 6. Simultaneous collection of acceleration response data at measurement locations L3 and L4 (top), walking posture of the IDOG (bottom left), measuring posture of the IDOG (bottom right)

peaks to confirm that the eigenfrequencies of the modal peaks detected by each individual IDOG match.

3.3 Results and Discussion

The results of the embedded peak-picking algorithm, executed autonomously by each IDOG, are summarized in Tables 1, 2 and 3. First, the results of IDOG 1 are presented, next, the results of IDOG 2 are provided, and, finally, the results from applying peak picking at the acceleration response data of the benchmark system are tabulated for comparison purposes.

As can be seen from Tables 1, 2 and 3, the embedded peak-picking algorithm of the IDOGs is capable of yielding 2–3 modal peaks at the same frequency components as the benchmark system. Minor discrepancies between the modal peaks detected by IDOG 1 and IDOG 2, as well as between the IDOGs and the benchmark system, are attributed to interference of noise and to the approximative character of the FFT.

Table 1. Peak picking results from IDOG 1

Setup	Location	Modal peaks (Hz)		
		1	2	3
1	L4	3.082	4.333	10.544
2	L4	3.067	4.318	10.590
3	L4	3.052	4.303	10.544
4	L4	3.082	4.288	10.437
5	L4	3.082	4.257	10.483

Table 2. Peak picking results from IDOG 2

Setup	Location	Modal peaks (Hz)		
		1	2	3
1	L1	3.113	4.303	-
2	L2	3.082	4.349	-
3	L3	3.113	4.303	10.620
4	L5	3.098	4.318	10.590
5	L6	3.113	4.303	10.590

Table 3. Peak picking results from the benchmark system

Location	Modal peaks (Hz)		
	1	2	3
L1	3.036	4.356	-
L2	3.029	4.333	-
L3	3.044	4.356	10.544
L4	3.036	4.341	10.597
L5	3.044	4.349	10.437
L6	3.036	4.326	10.597

Exemplarily, the FFT amplitude spectra computed by both IDOGs for setup 3 are plotted in Fig. 7a. Furthermore, Fig. 7b illustrates the FFT amplitude spectra between IDOG 1 and the corresponding sensor node of the benchmark system at location L3. In both plots, the proximity between the FFT amplitude spectra is evident.

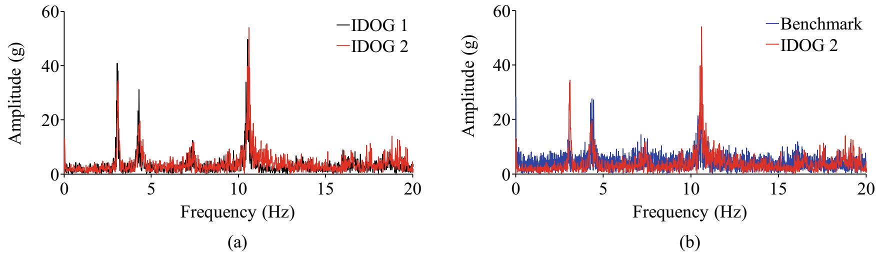

Fig. 7. Comparison between FFT amplitude spectra of IDOG 1 and IDOG 2 for setup 3 (a), and comparison between FFT amplitude spectra of IDOG 2 and the benchmark system at location L3 (b)

4 Summary and Conclusions

The advantages of wireless sensor networks for structural health monitoring, in terms of cost-efficiency and flexibility, may be easily nullified by designing particularly dense wireless SHM systems consisting of stationary wireless sensor nodes. As alternatives, approaches proposing mobile wireless SHM system have been sporadically proposed. Nevertheless, since the concept of mobile SHM is still in its infancy, this feasibility study has focused on highlighting the applicability of mobile SHM in real-world conditions. Specifically, building upon previous work of the authors, a mobile SHM system, comprising legged robots, which can advantageously navigate areas with impediments that are hard to reach by wheeled robots, has been tested on a pedestrian bridge. The purpose of the feasibility study has been to investigate the capability of the mobile SHM system to (i) perceive its surroundings and (ii) yield information on the structural condition similar to the information obtained by a benchmark system, consisting of stationary wireless sensor nodes. On the one hand, the juxtaposition of the visualization of the pedestrian bridge with the actual geometry of the bridge has showcased the capability of the legged robots to perceive the surroundings. On the other hand, the comparison between the outcomes of the mobile SHM system, in the form of eigenfrequencies obtained through peak picking, and the corresponding outcomes of the benchmark system have proven the capability of the mobile SHM system to provide rich information on the structural condition. Future work will focus on using the mobile SHM system to obtain elaborate information on the structural dynamic behavior, such as mode shapes, and on implementing autonomous navigation of measurement locations.

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Bottlenecks to the Implementation of Automation and Robotics in the Construction Industry

Ayanda Boya, Opeoluwa Akinradewo, Clinton Aigbavboa, Andrew Ebekozien, and Molusiwa Ramabodu

Abstract South Africa is increasing its use of technological innovation in the construction sector. Given the recent advancements, understanding how technology affects the construction industry is crucial. Industry related concerns include decreased quality and productivity, wastage, accidents, project delays, and unfavorable working conditions. A solution to these issues is the adoption of the implementation strategies of automation and robotics technologies, which have the potential to increase productivity, safety, and quality in the construction industry. However, there are barriers that hinder the progression of this implementation. This study aimed at evaluating the challenges of the implementation strategies of automation and robotics in the South African Construction industry. Corresponding literatures were reviewed, and a quantitative research methodology was adopted to extract information about the research question. To achieve this, a cluster sampling technique was used, and a survey questionnaire was distributed to 111 construction professionals, who were situated in the Gauteng province of South Africa. The data collected presumed that the most impactful challenge to the implementation of automation and robotics in the construction industry is the high costs of acquiring technologies. This could be based on existing corroborations that SMME's and other small organisations struggle to obtain technologies due to lack of funding, and technologies are generally deemed to be very costly. The study concluded that innovative technologies are generally expensive and not easily attainable.

Keywords Automation · Construction Industry · 4IR · Robotics · Technology

A. Boya (✉) · O. Akinradewo · C. Aigbavboa · A. Ebekozien
Cidb Centre for Excellence and Sustainable Human Settlement and Construction Research Centre, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa

C. Aigbavboa
e-mail: caigbavboa@uj.ac.za

M. Ramabodu
Department of Construction Management and Quantity Surveying, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: molusiwar@uj.ac.za

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1 Introduction

Automation and robotics in construction is the mechanization and digitalization of human skills to aid in productivity as well as to resolve issues related to labor scarcity, safety factors etc. [1]. The rise of the industrial revolution 4.0 (4IR) has assisted in making people more mindful of the convenience of implementing automation and robotics in their daily tasks [2]. Aghimien [2] stated that the implementation of automation and robotics in the building industry has been deemed non-progressive, considering the fact that it has the ability to mitigate the dangers posed to human health and safety. Without the use of building technologies, efficiency is minimal [3]. Construction has been described as an industry with a higher rate of workplace injuries and fatalities with building collapse and falls from great heights being the leading cause of deaths. Furthermore, construction automation has shown to be necessary for carrying large materials thus leading to injury prevention [4]. Thoroughly embracing technologies such as robotics and building automation is the solution to labour shortages, workplace health and safety, and a decline in efficiency and productivity [5].

Conversely, robotics necessitates the ability of technicians to handle or monitor the robots, so expertise of robots would be essential in order to work with them. This implies that any time new equipment is introduced to the site; the operators will need to be professionally trained to run the equipment. Automation is the process of digitizing machines to execute certain tasks, thus academic knowledge would be needed for the user to comprehend the equipment's functionality [6]. Opposition to robotics and building automation is also associated with a high installation cost, as well as the cost of operating machinery. Construction expectations, such as improved job efficiency, necessitate the operation of hefty materials or heavy-duty machines, which, when influenced by the job description, can be quite costly [7]. Labourers fear job loss as a result of the introduction of robotics and automation in the construction industry [8]. As a result, automation becomes a deterrent because if robots are the new construction technology, job loss is inevitable.

Although there are many benefits of automation and robotics, there are still numerous implementation challenges. The main objective of this study is to investigate these implementation bottlenecks within the construction field. This research will expose professionals and students to the barriers of implementing automation and robotics in the South African construction industry. The findings that have been presented will assist in creating strategies to mitigate these barriers.

2 Automation and Robotics in the Construction Industry

Automation and Robotics is the application of self-controlled mechanical and electronic machines with smart regulatory systems to automate building tasks and processes [9]. The words and terminology are used interchangeably; and they comprise systems ranging from human-operated mechanical machinery to partially autonomous or autonomous equipment that are remote controlled, to automated robotics with additional sensors and automatic monitoring functions. With regards to this research, construction automation and robotics depicts a broad category of machinery and applications used to automate construction-related tasks across the project's life cycle [9]. As maintained by some scholars, "construction automation" depicts the use of designs assisted by computers and worksite technology handled by robots to simplify all-inclusive tasks [10]. Currently the phrase "digital fabrication" in substitution for "construction automation" is used when discussing the customization of building construction. Construction robotics is explained as "a re-programmable, multifunctional manipulator designed to move materials, parts, tools or special devices through variable programmed motions for the performance of a variety of tasks occurring in production processes of the building industry" [11].

2.1 Bottlenecks to the Implementation of Automation and Robotics in the Construction Industry

Model Constraint

Due to automation still prevailing in the beginning stages of design and development, there is a designer-operator divide in application [12], and there is a scarcity of certified and relevant models that constitute the foundation of the structure of computative networks and hardware components. There is a lack of globally approved and validated models that can be used to a variety of enterprises with diverse IT enabled applications and operational capabilities [13]. The automation restrictions are determined by unstructured government mechanisms, non-existing government policies, initiatives, and studies. Furthermore, models that are approved across a sector must be reconditioned and adjusted in accordance with the types, stages, and degrees of automation, i.e. including industry-approved manuals [14].

Money Constraint

The combination of hardware, software, and human-resource expenditures is referred to as the monetary costs of automation. The fundamental expenditures of planning automation are lack of funding for automation or significant capital investment for formalization, servicing, personnel training, professional partnership, specialist teams for organizing periodic tasks and activities, computational (hardware) facilities, and software development [15, 16]. In general, automation finance is too difficult to grasp and implement due to the numerous expenses connected with automation testing [17]. There is resistance for building automation by entrepreneurs or small businesses since they are not acknowledged by the market, meaning that stronger businesses have a better chance of buying or hiring heavy equipment [18]. Some studies go as far to say that the problems of robotic and automated installations include expensive updates as technology improves as well as developing modern technologies to complement the task since not all construction methods are the same [19].

Management Constraint

There is a deficit in managerial initiative to bring about the breakthrough incorporated in the automation process from conception to application [20]. In addition, managerial reluctance and openness towards change are the missing connection with ever-changing businesses and competitive markets [21]. A few of the management-oriented limitations of automation implementation include a lack of trust in automation systems, machine-managed operations imposed by political, legal, moral, and societal pressures [22], privacy and security issues, lengthy difficulties of men-machine task synchronization, and ever transpiring machine errors [23]. In contrast with manual labour, construction automation and robotics cannot accept true ownership and accountability for tasks, particularly in cases of incidents or error, which is also a major management challenge, because of its "unstructured" and "uncontrolled" characteristics [24].

Men-Machine Interaction

Operators must reskill in certain areas to transition from leading machines to working on them as assistants or supervisors [25, 26]. The willingness of human operators to employ the "learn-unlearn-relearn" methodology through comprehensive training courses can minimize automation problems and further develop the performance of the operator [27]. In addition, the connection between human and machines is often mentioned as the main limitation accelerating automation system failures since development engineers have never foreseen complicated system interactions [28].

Measurement Constraint

The lack of tools and methodologies for analyzing the effectiveness that automated processes, functionalities, and operations have on organizational workers and revenues is a measurement restriction of automation. Several studies have studied the costs assigned to automation stakeholders by automation equipment, employee restructuring and training, software upgrades, as well as the contribution or benefits each of these changers makes to companies [29]. The lack of effect measuring tools against the starting automation process seems to be the most significant absent link between automation idea and adoption, as well as post-implementation [30].

Mechanism Constraint

This constraint of automation leads us to the lack of literature on "who, when, where, why, and how" following the automation process, as well as which processes must be implemented for effective deployment or operation, which appears to be either non-existent or unverifiable [31]. The lack of knowledge exchanging conferences, forums, conventions on automation also limits business fraternity. Automation initiatives are very complicated, requiring planning and management on several levels, including technological, administrative, clinical, social, and economical [32]. The lack of support for government changes and cooperative machinery from the framework of specialized automation stakeholders is even more concerning. The mechanism for effectively testing and implementing automation is hampered by firms' policies of concentrating their technological resources for operational efficiency alone rather than generalizing them towards widespread benefits and influence [33].

Employment

According to James [34], the construction industry employs a substantial number of people in the country. Majchrzak [8] stated that employees are afraid of job loss potentially caused by the construction sector robots and automation, which makes it a challenge to automation, because robots are the future construction technology they would presumptuously create job losses. Full adaption of robotics in construction will affect most jobs, since the accessibility of work will be reduced. Only occupations of the people who perform robotic tasks will be lost, as machines may undertake special tasks with the advantages of higher production and improved output. The implementation of robots will substitute skilled people and employees impacted by use of robots and automation will have to alter the occupation in which they are familiar with, for instance with bricklayers, because it is envisaged that robots that lay bricks will be used as a specialty in construction [35].

Robots and Automated Systems

Drones and autonomous vehicles

There are several obstacles that have to be confronted, such as i) high capital cost; (ii) insufficient battery power which limits operations - for example, the majority of drones have a flying time of not more than thirty minutes; (iii) sophisticated hardware and software operational capability that requires considerable training and increases expenses; (iv) apparent mistakes and accidents to the degree of precision and acceptance; (v) strict restrictions that raise acquisition costs; and (vi) extra health and safety hazards caused by drones [38, 39].

Exoskeletons

The perceived challenges to employing exoskeletons in the construction business include i) concerns about safety and health, since exoskeletons might raise "catch", "snag", and "fall" hazards; cleanliness difficulties and a false feeling of safety; (ii) issues about usability, that include lifespan, robustness and adaptability; iii) The failure to integrate additional protective equipment (PPE); (iv) the adoption's capital costs and the necessity for a speedy rate of return; (v) a key obstacle is the possibility of poor worker acceptance rates [40].

New Work Methods

Most construction workers do not get advanced learning, they are taught to become experts in particular craft on the job. The majorities of construction employees are trained in single craft and have been specializing in this craft for years, making training difficult for employees because they have limited academic foundation. Managers might consequently distrust the competence of personnel to manage new robots and building automation [35]. Automation is all about computerization for specific operations and the operator needs educational training to comprehend the operation of the machine [6].

3 Research Methodology

The quantitative research approach was used for this study. A deductive logic approach was implemented where surveys/questionnaires were gathered and issued to collect data. The explorative technique was most suitable with comparing the relationship between variables. The research was conducted in Gauteng, South Africa. Construction organizations as well as professionals (Quantity Surveyors, Construction Project Managers, Civil Engineers and Architects) in the engineering and construction sector were targeted respondents. The type of sampling employed for this research was random cluster sampling. Surveys were distributed to the above-mentioned professionals in Gauteng. They represented organizations familiar with automation and robotics in the construction industry. This random sampling technique was used because it was not feasible to sample the whole population of construction professionals in South Africa. A total of 111 valid responses were obtained and the data collected was examined using Microsoft Excel and Statistical Package for Social Science (SPSS). MIS – "Mean Item Score" and SD – "Standard Deviation" were used to analyse the data that was collected. The study encountered limitations due to the fact that the targeted number of professionals did not attend to the survey and some individuals did not accurately complete the surveys. The reliability of the results was tested using Cronbach's Alpha coefficient, which amounted to 0.903, meaning the findings of this study can be relied upon.

4 Findings and Discussion

4.1 Findings

The background data that was collected from the targeted respondents was analysed. Results showed that 18.9% hold a post matric certificate or Diploma, 41.4% hold a bachelor's degree, 29.7% hold an honour's Degree, 8.1% hold a master's Degree, and 1.8% hold a doctorate. Results also indicated that 8.1% are Architects, 49.5% are Quantity Surveyors, 11.7% are Civil Engineers, 0.9% are Industrial Engineers, 10.8% are Mechanical Engineers, 8.1% are Construction Managers, 8.1% are Construction Project Managers, and 2.7% fall under other professions in the built environment.

Through the application of the 5-point Likert scale of ‘Strongly Disagree’ (SD) – ‘Strongly Agree’ (SA), the respondents were required to specify the extent at which they agree with regards to the benefits of the strategies adopted in the implementation of automation and robotics in the industry. Table 1 indicates the respondent’s rankings of the challenges to the strategies adopted. The results reveal that “High costs of acquiring technologies” was ranked first position, with a MIS of 4.50 and a SD of 0.712; “Risks of job loss caused by technologies” was ranked second position, with a MIS of 4.35 and a SD of 0.931; “High costs of maintaining and updating technologies” was ranked third position, with a MIS of 4.30 and a SD of 0.848; “Resistance to implementation of technologies by workers” was ranked fourth position, with a MIS of 4.09 and a SD of 0.968; “Lack of funds required to implement technologies” was ranked fifth position, with a MIS of 4.07 and a SD of 1.024. Additionally “Lack of knowledge on how to operate technologies” was ranked sixth position, with a MIS of 3.87 and a SD of 0.964; “Difficulty to acquire technologies due to unavailability” was ranked seventh position, with a MIS of 3.77 and a SD of 1.128; “Difficulty to understand and operate technologies” was ranked eighth position, with a MIS of 3.74 and a SD of 1.015; and lastly “Inadequate compatibility of technologies with current practices” was ranked ninth position, with a MIS of 3.72 and a SD of 1.105.

Table 1. Bottlenecks to the implementation of Automation and Robotics

Challenges to the strategies adopted	MIS	SD	R
High costs of acquiring technologies	4,50	0,712	1
Risks of job loss caused by technologies	4,35	0,931	2
High costs of maintaining and updating technologies	4,30	0,848	3
Resistance to implementation of technologies by workers	4,09	0,968	4
Lack of funds required to implement technologies	4,07	1,024	5
Lack of knowledge on how to operate technologies	3,87	0,964	6
Difficulty to acquire technologies due to unavailability	3,77	1,128	7
Difficulty to understand and operate technologies	3,74	1,015	8
Inadequate compatibility of technologies with current practices	3,72	1,105	9

Mean Item Score (MIS); Standard Deviation (SD); Ranking (R)

4.2 Discussion

On the basis of the previously mentioned findings, it can be concluded that 'High cost of acquiring technologies' is the most significant challenge of the implementation strategies. This conclusion is congruent with findings from [41], who according to their literature 'High cost of acquiring the construction robotics technologies' was ranked third out of a total of ten. The 'Risks of job loss caused by technologies' ranking is in agreement with literature presented by [8] that employees fear job loss potentially caused by the construction robots and automation. 'High costs of maintaining and updating technologies' is congruent with literature proposed by [19] which relates the challenges to robot and automation installation as being expensive to update as technology advances.

'Inadequate compatibility of technologies with current practices' was ranked least. This corresponds with the literature of [41]. In this literature, the findings concluded that "Workers are more prefer the traditional method and proven solution instead of modern methods" was ranked least. It can be deduced that technologies are compatible with current practices/modern methods. 'Difficulty to understand and operate technologies' was ranked as one of the least significant challenges. This contradicts literature from [36] that the lack of understanding material mechanical function is a significant issue. [27] also stated that comprehensive training programs, which can minimize the complexity of automation and increase the performance of the operator, appear to be challenging and hypothetical.

4.3 Implication of Findings

The reason for 'High cost of acquiring technologies' being ranked first could be based on existing corroborations that SMME's and other small organisations struggle to obtain technologies due to lack of funding and technologies are deemed to be very costly. 'Risks of job loss caused by technologies' by employees may be a concern because of the perception that their day-to-day tasks may be replaced by automation and robotics technologies, and since their skills would not be required this could ultimately result in retrenchment. 'Difficulty to understand and operate technologies' may be considered one of the least challenging strategies due to the probability that employees have sufficient access to training in the workplace.

5 Conclusion and Further Research

This study's research objective was established and met. The survey questionnaire demographic was restricted to professionals in the South African construction industry. As a result, the study's findings reinforced methodological approaches and offered valuable recommendations for automation and robotics implementation approaches. The studies derived from the questionnaire based in Gauteng, South Africa reveal that the challenges to the strategies adopted are: High costs of acquiring technologies; Risks of job loss caused by technologies; High costs of maintaining and updating technologies; Resistance to implementation of technologies by workers; Lack of funds required to implement technologies; and Lack of knowledge on how to operate technologies. A suggestion for further research or recommendation can therefore be increase in exposure with regards to the benefits of using these technologies – further research needs to be implemented to provide more information entailing the importance of implementing automation and robotics in the construction industry.

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Simulation and Process Modeling

Integrating AEC Domain-Specific Multidisciplinary Knowledge for Informed and Interactive Feedback in Early Design Stages

Julia Reisinger, Shervin Rasoulzadeh, Balint Istvan Kovacs, Peter Ferschin, Khrystyna Vasylevska, Michael Hensel, Iva Kovacic, and Michael Wimmer

Abstract In the context of digitalization in the industry, a variety of technologies has been developed for system integration and enhanced team collaboration in the Architecture, Engineering and Construction (AEC) industry. Multidisciplinary design requirements are characterized by a high degree of complexity. Early design methods often rely on implicit or experiential design knowledge, whereas contemporary digital design tools mostly reflect domain-specific silo thinking with time-consuming iterative design processes. Yet, the early design stages hold the greatest potential for design optimization. This paper presents a framework of a multidisciplinary computational integration platform for early design stages that enables integration of AEC domain-specific methods from architecture, engineering, mathematics and computer science. The platform couples a semantic integrative mixed reality sketching application to a shape inference machine-learning based algorithm to link methods for different computation, simulation and digital fabrication tasks. A proof of concept of the proposed framework is presented for the use case of a freeform geometry wall. Future research will explore the potential of the framework to be extended to larger building projects with the aim to connect the method into BIM-processes.

J. Reisinger (✉) · S. Rasoulzadeh · I. Kovacic
Department for Integrated Planning and Industrial Building, TU Wien, Vienna, Austria
e-mail: julia.reisinger@tuwien.ac.at

B. I. Kovacs · P. Ferschin · M. Hensel
Department for Digital Architecture and Planning, TU Wien, Vienna, Austria

K. Vasylevska
Research Unit of Computer Graphics, TU Wien, Vienna, Austria

M. Wimmer
Institute of Visual Computing & Human-Centered Technology, TU Wien, Vienna, Austria

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1 Introduction

Formalizing design intentions is a complex task. Design knowledge is ambiguous, as it is based on both tacit (implicit) aspects that are difficult to codify and explicit aspects that are codifiable (experience- or evidence-based) [1, 2]. Designers are experts at implementing intuitive design knowledge in the process of synthesizing "good design" – yet, it is often difficult to articulate such design decisions in explicit terms [3]. An essential task in design science research is the representation of a design problem and the generation and evaluation of its solutions [4]. Design processes usually consist of two basic activities: Designing an artifact representing an improvement for stakeholders (build), followed by an empirical assessment of the artifact's performance in a specific context (evaluate) [5]. An artifact's performance is strongly influenced by its environment. A lack of understanding that environment can lead to inappropriately designed artifacts or artifacts that have unintended consequences. The evaluation of an artifact can be complicated as its performance is dependent on its intended use, and the intended use can include a wide range of tasks. A general problem solving method can be applied to a wide range of problems, but its performance varies considerably depending on the application domain and the criteria for evaluation must be determined in advance [6]. The AEC industry is characterized by interdisciplinary and multidisciplinary design teams. "Subjective" or non-formalized criteria are often difficult to share with professionals from other disciplines, who do not have the same explicit design knowledge and experience [7]. Explicit codified knowledge has often been developed within a particular discipline and often operates within that discipline [8]. In computer-aided design, a designer's creativity and imagination are often limited by the capabilities of the software used, or designers must construct workarounds or segment their process by switching between different tools [9]. The aforementioned facts often lead to a lack of appropriate feedback mechanisms in interdisciplinary design processes, consequently many promising design ideas are ignored in early design stages. Yet, the early design stage holds the greatest potential for optimization [10] and most crucial decisions are taken when the architectural design is still in its rudimentary draft of a sketch [11].

For powerful communication at the early sketching phase, fast and easy-to-use modeling methods are more important than the accuracy and detail of geometry. Sketch-based design interfaces are an attractive solution for quickly modeling designs to evaluate the overall concept before spending the effort on detailed design as they are intuitive (pen-and-paper metaphor) [12]. Various researchers introduce novel sketching methods for early stage 3D design exploration with sketching and generative design [13] and methods for immersive, freehand or hybrid 3D sketching in virtual reality (VR) [14–17]. Other researchers address the sketch recognition [18] and sketch-based reconstruction and shape inference for 2D or 3D model creation [12, 19, 20]. Such approaches enable the creation of 3D sketches followed by generation of 3D geometries, but do often not integrate interdisciplinary AEC relevant computations or simulation methods to receive relevant performance feedback to sketched designs.

Immediate feedback on the feasibility of a design alternative and the degree to which design objectives are met requires constant computational reassessment of constraints and objectives. Yet, holistic systems integration, connecting software systems of cross-functional domains can be challenging due to numerous independently evolving software systems [21]. Several research efforts address computational design methods for integrated design, performance optimization and decision support using parametric and generative [22–28] or BIM-based [29–31] design tools to improve the economic, environmental or energy performance of buildings at the early design stage. However, such computational methods are rarely suitable for early design sketching, as they require detailed information and modelling. Various researches investigate the application of VR for assisted design exploration in architectural design [11, 32], collaborative structural building and production layout design [33] or present an iterative and interactive user-centered design system for shared realities [34]. These approaches are remarkable but are mainly based on systematic approaches that take into account limited knowledge about the requirements resulting from daily collaboration in interdisciplinary AEC design. Higher efficiency of design processes could be achieved by extending and linking existing methods for different design and simulation tasks at early design stage. To significantly reduce lengthy and costly design and feedback cycles, designers should be able to create and evaluate sketched design variants in real time to develop innovative and well-performing solutions. The development of such a multidisciplinary sketching, simulation and feedback platform, integrating AEC domain-specific knowledge, is the aim of this presented research.

This research is conducted within the ongoing funded special research programme (SFB) "Advanced Computational Design (ACD)". ACD addresses the advancement of design tools and processes through multi- and interdisciplinary basic research in the areas of digital architecture, integrated building design, computer graphics and virtual reality (VR), discrete and applied geometry, and computational mechanics. The primary goal of ACD is integration of digital design tools and domain-specific disciplinary knowledge from architecture, engineering, mathematics and computer science, leading to an expansion of solution spaces and interactive feedback in early design stages.

This paper presents a framework for a digital platform, based on a semantic mixed reality sketching tool, allowing generation of geometry from a 3D sketch and thus bi-directional data exchange with various simulation environments and models. The platform, incorporating the mixed reality sketching app, enables 3D sketching, which is a basic tool of early design; as well as simulation and real-time feedback in the fields of geometrical form-finding, structural and material analysis, lighting optimization, haptic feedback in VR and digital fabrication (see Fig. 1). The overall goal is to provide immediate and informed design feedback in the sketching phase,

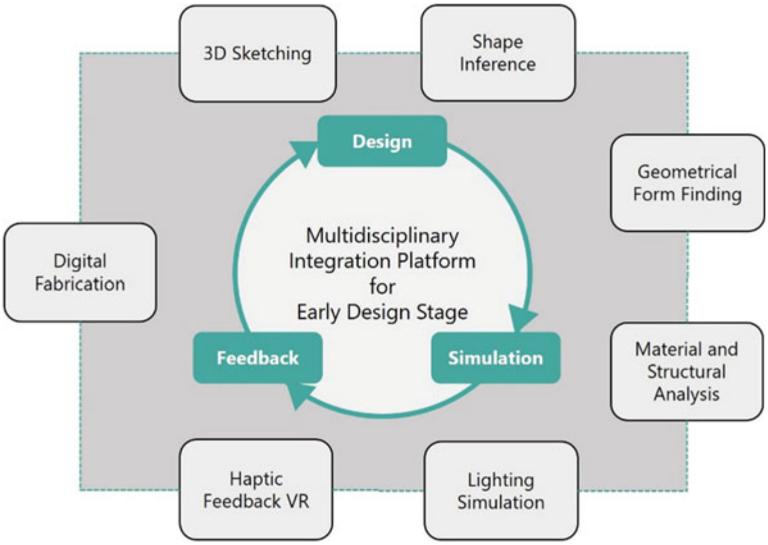

Fig. 1. Diagram showing the main components of the multidisciplinary integration platform and their relationship in a process that links design, simulations and feedback

in order to shorten design cycles and improve design quality at early design stages. The paper provides the first proof of concept of the developed platform, performed on the use case of a freeform geometry wall to verify the efficiency of the workflow, identify the potential for system integration and initiate the next necessary steps.

2 Literature Review

A variety of technologies on integrated design and simulation methods for design-space exploration and evaluation at early design stages have been developed in AEC industry. The following summarizes the state of the art research on informed and interactive design feedback in the early stage of sketching and highlights the new contributions of this paper:

Three critical issues that affect the implementation of the building performance optimization processes in the early design stage can be identified: (1) model integration, (2) real-time performance analysis, and (3) interactive optimization design [23]. In current design practices, ideation is dominated by 2D sketches, while disparate CAD-tools produce 3D concept models [20]. Various researchers have introduced novel sketching methods. Barrera Machuca [14] presented Multiplanes, a VR drawing system combining freehand sketching with the ability to draw accurate shapes in 3D, generating snapping planes and beautification trigger points based on previous and current strokes and the current controller pose. Multiplanes automatically beautifies a stroke in real-time while the user is drawing it. Kazi, et al. [13] developed DreamSketch, a 3D design interface combining free form sketching, 3D model generation and a generative design algorithm for computation. After sketching a design context, the generative algorithm generates optimal solutions for the entire design space using topology optimization. The authors highlight as limitation of the work, that the topology optimization has not taken advantage of parallel or cloud computing for simultaneous optimization. Arora, et al. [16] initiated SymbiosisSketch, combining 3D interactions in the air with constrained sketching in 2D. Users can create canvases and sketch on them using a tablet. The sketches are created in the context of the physical objects in the scene, enabling quick post-processing to seamlessly integrate the virtual objects into the real world. Drey, et al. [17] developed VRSketchIn, an immersive sketching application with unconstrained 3D air sketching with a pen and constrained surface-based sketching on a tablet. Other researchers address the reconstruction and shape inference integrated in sketching methods. Yu, et al. [20] present CASSIE, where AR/VR technology is used to support ideation and concept modeling in a shared immersive space. CASSIE combines freehand sketching with the geometric and aesthetic constraints of 3D modeling to produce 3D models out of surface user strokes with sufficient quality for subsequent applications. Rosales, et al. [19] present SurfaceBrush, enabling to draw 3D strikes using a VR brush. A surface process has been developed that converts such VR drawings into user-intended manifold 3D free surfaces, providing a new approach to 3D shape modeling. Mahoney [11] developed a system called V-Sketch, which employs digital computation, translating from intuitive sketching to 3D geometric elements, decoupling the sketch analysis from the creation of 3D forms by using machine-learning techniques. The reconstruction function and a set of libraries containing different geometric elements enable the designer to refine the solution space and generate different results from the same sketch. A sketch-based system for quad meshes is presented in Sketch2PQ [35], which aims to bridge the gap between concept design and digital modeling of freeform roof-like shapes represented as planar quadrilateral meshes.

Various research projects focus on real-time 3D environments for collaborative design [36] not focusing on the integration of simulation and computation possibilities directly in these environments. Leon, et al. [37] present a computational design application for interactive surfaces within co-located collaborative design teams making use of HCI. They provide an integration of different sensory modalities, including visual and haptic. A computer-mediated environment (M.S.PixelSense) was employed to be a facilitator for collaborative design. Full haptic feedback in immersive VR environments, can enable teams to experience the spatial characteristics of a room-scale design [38, 39]. Vonach et al. suggested a system utilizing the robot actuation for haptics [40]. They showed that employment of the haptic feedback contributes to the naturalness and more convincing experience of touch and thus interaction with simulated virtual environment. Dumont, et al. [38] investigated real-time deformation simulation through haptic interfaces for the purpose of the design evaluation of deformable mechanical parts in the process of industrial product lifecycle management. They develop an interactive mechanical simulation framework for design improvement in virtual reality. Giunchi, et al. [39] present a method for searching 3D model collections using free-form sketches within a virtual environment as queries.

Optimization processes on free-form designs that are not determined a priori by specified performance criteria often result in inadequate solutions. This can often imply limitations in the realization process [41–43]. Regarding paneling of architectural freeform surfaces, freeform panels generated from a set of simple-to-manufacture geometric types have mainly been dealt with from an optimization point of view [44]. A thorough treatment of discrete structures that underlie such arrangements is investigated in various researches [44–46]. Recently, the study of mechanical properties of sub-constructions [47] has added even more complexity to this problem. Rigid-foldable discrete surfaces or origami is an active research area [48]. Integrating such methods in a mixed reality sketchbook could make flexible quad-surfaces accessible for designers. Tachi [49] presented a computational design method using a restricted set of folding patterns. The web-based app "origami simulator" enables to simulate how complicated origami crease pattern will fold in 3D [50], whereas "crane" focuses on design, rigid folding simulation, form-finding and fabrication for origami structures as a plug-in for Rhino/Grasshopper [51]. Recently, a framework for the design of flat-foldable quadrilateral mesh origami approximating a general surface was published [52]. Moreover, Jiang et al. [53] presented an optimization technique to penalize an isometrically deformed surface with planar quads.

There is a scientific gap in linking computational methods of such geometry optimizations to mechanical information of the underlying material as well as to the structural behavior of the design. This has rarely been done yet, as considering material nonlinearity leads to a sharp increase in the computational effort, and appropriate numerical methods [54] are still under development and often not sufficiently stable for linking them with geometric design tools. Furthermore, the non-linear 3D mechanical behavior of complex anisotropic material systems is not predictable to the required extent for 3D form-finding tasks yet. Concerning the sketching systems integrating structural or material analysis, interactive visualizations are being used to a small degree. Murugappan and Ramani [55] present FEAsy, which is a sketch-based interface integrating structural analysis in early design, enabling users to transform, simulate and analyze finite element models quickly and easily through freehand 2D sketching. A computational workflow for structural analysis feedback from architectural design sketches is presented in Rasoulzadeh, et al. [56], using the Points2Surf algorithm for shape inference [57]. Podkosova, et al. [33] present a multi-user VR framework for early-stage collaboration, implementing a real-time bidirectional link between a generative design model created in Rhino/Grasshopper that performs optimized structural calculations of industrial building variants, and an immersive VR environment in which the automatically calculated building variants with ecological and economic performance feedback are visualized.

Interactive visualizations are increasingly employed in visual and haptic planning methods, mostly involving the use of immersive VR environments. Solutions allowing high-quality design interaction [58] are not widely adopted and not unbiased due to the required simplifications. Furthermore, it is desirable to extend the solution space, e.g., by optimizing light placement according to given criteria. This has only been attempted for exterior lighting [59], while indoor lighting optimization, which is more challenging due to diverse requirements, remains unresolved. Offering design variations for editing operations has been shown in the domain of furniture design [60], but not in lighting design. Haptic feedback can significantly improve task performance and the perceived presence in a virtual environment [39]. An immersive 3D sketching system in VR is provided by Oti and Crilly [15], however haptic feedback to the 3D sketches is not included. Tactile interaction could support design interaction through immediate haptic feedback. General-purpose haptic interfaces proposed in literature have significant limitations for fully immersive large scale VR systems, required for designing the extensive environments. In our presented research we seek to improve the situation with a haptic platform employing a mobile robot.

A similar integration goal to the one we take in our research is offered by COMPAS [61], an open-source, python-based framework for computational research and collaboration in architecture, engineering, digital fabrication and construction. The framework provides geometry processing, data structures, topology, numerical methods, robotics, the plugin mechanism, remote procedure calls etc. and can be used independently of CAD systems in any environment that supports python programming.

Several independently working software systems for 3D sketching, simulation, calculation or digital manufacturing have been developed. However, to the best of our knowledge, there is a lack of a cross-functional, multidisciplinary platform that enables early design sketching, while integrating various AEC simulation and computation methods and providing immediate performance feedback on sketched designs.

3 Methodology

This research is conducted within the inter- and multidisciplinary research project SFB – ACD. The SFB is structured into 8 scientific subprojects (SPs), connecting researchers and knowledge from architecture, computer science, mathematics and engineering. This study is conducted within subproject SP2 – Integrating AEC domain knowledge – and explores a new design method that integrates different methods into a digital platform for early design stages. In the following, a short description of the research aim and goals of each subproject is given:

Geometric form Finding Methods. Higher Order Paneling of Architectural Freeform Surfaces (SP6) [46, 62] and Flexible Quad-Surfaces for Transformable Design (SP7):

SP6. Investigation of methods for generation of smooth and discrete surfaces that facilitate interesting panel shapes and/or allow the repetitive placement of congruent as well as bendable panels.
SP7. The goal is to expand the solution space of flexible quad-surfaces and to make it accessible for architectural applications by the development of computational design tools.

Structural and Material Analysis Methods. Linking Mechanics to Form-Finding of Plant-based Bio-Composite Structures (SP8) [63]:

SP8. Development of mechanical models for plant-based building materials, a promising material category for future-proof buildings. The resulting comprehensive understanding of the mechanical performance of these materials should increase the design options and enable efficient integration into design processes through analytical models that can be evaluated quickly, as e.g. [64, 65].

Methods for Visual and Haptic Feedback. Lighting Simulation for Architectural Design (SP4) and Large-Scale Haptic Feedback in Virtual Reality (SP5):

SP4. Development of fast differentiable global illumination solvers for modern GPU hardware, enabling interactive visual feedback and automated lighting design optimization, also aiming to investigate example-based and suggestive lighting design methods.
SP5. This subproject focuses on the development of a natural haptic feedback in virtual environment using a mobile collaborative robot (Cobot). The goal is to provide a real-time haptics for simulation such as representation of mechanical properties of simulated virtual structural elements and support haptic interaction with various design elements at a large scale.

Digital and Rapid Prototyping Methods. Computational Immediacy (SP3) [66], Material- and Structurally Informed Freeform Structures (SP9) [67, 68]:

SP3. The aim is to develop a hybrid workflow for physical/digital modeling of architectural concept models based on 3D point clouds and machine learning. The goal is to enable transfers of design features from learned point clouds via 2D representations onto newly created models in creative design processes.
SP9. The goal is development of new geometrical definitions of freeform surfaces based on their material and functional properties in order to develop strategies to find cost-efficient freeform structures with stay-in- place and/or reusable formwork. This will be achieved through an enrichment of computational geometrical models with material and structural information.

In this paper, we aim to answer the following research questions (RQ) regarding the integration of the aforementioned subprojects:

RQ1: How can different design and simulation methods relevant for the AEC from complex geometry building design, for example for panelization using spherical panels or transformable surfaces made of planar or skew quadrilaterals, be integrated in an early design stage tool to provide informed design feedback?
RQ2: How can a digital tool provide designers with an informed design feedback in regards to computing lighting simulation for architectural design and large-scale haptic feedback in VR so that the designer can still adapt the geometry to provide solutions?
RQ3: How can shape-generation methods regarding geometric, material, mechanical and structural constraints linking mechanics to form-finding of structures be addressed in such digital design methods?
RQ4: How can experimental validation with real-world materials and rapid prototyping methods be integrated into the digital methodological approach to discover unexpected mechanical or geometrical behavior, or verification of the properties of structural simulations?

The methodology employed in this study is based on open-guided interviews and a model and data analysis with the subproject researchers to analyze domain-specific data structures and processes of each subdomain. The analysis served for identification of discipline-specific interfaces and workflows and to express design goals and constraints in a formal and structured way. Based on the interview results, a workflow has been created that integrates knowledge and tools from the different computational domains and enables the link of a semantic integration platform with feedback of design automation, simulation, visualization and prototyping tools from the specific research fields. The results are merged into the framework of the multidisciplinary integration platform, coupling several concepts. The platform framework consists of an interactive mixed reality sketching application for architectural form finding with a shape inference module aided by machine learning enabling automated surface mesh modelling from sketches and the created links to the specific computational design tools. The proposed computational workflow, the integration platform and the domain specific outputs are evaluated in the application area of theater-stage design, using a basic element of a wall as a use case. A wall design is advantageous for testing as it provides freeform structures with flexibility and small scale. The proof of concept evaluates whether the application of the framework enables an adequate data exchange and simulation with real-time feedback, verifies the efficiency of the workflow for discipline-specific system integration and answers the above mentioned research questions.

4 Results – Multidisciplinary Integration Platform for AEC

This section presents the framework for a multidisciplinary integration platform that enables simulation-based feedback on sketched designs in early stages. The integrated methods address research on geometrical form finding, material and structural analysis, lighting optimization, haptic design interaction in VR and digital fabrication.

The platform couples a semantic integrative mixed- reality sketching application with a shape inference machine-learning based algorithm for interpretation of geometry from sketches to link the specific computational tools and methods. The goal is to achieve a bi-directional data exchange for real time feedback and design optimization of sketches in future.

Figure 2 presents the framework of the multidisciplinary integration platform. The core of the framework is the sketching application for mixed-reality design and a machine learning-based algorithm called Strokes2Surface (S2S) for shape inference of sketches. The specific research from the SFB subprojects providing computer-aided simulation and feedback on the sketched designs can be categorized as geometric form finding and material/structural analysis, visual and haptic feedback, and computational immediacy through point-cloud computation.

An Integrative Mixed Reality Sketching application uses mixed reality interaction and enables sketching directly in 3D space, capturing the process as temporal data, and uses simulation feedback in form finding. The sketching application leverages a tablet (Apple iPad Pro (2020)) and pen input (Apple Pencil 2) paradigm, and the sketched designs can be used on systems with VR capabilities (Windows PC

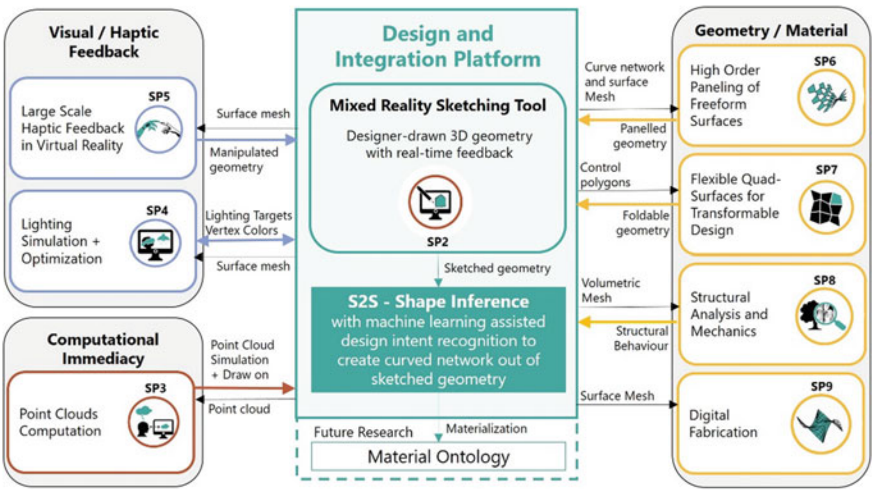

Fig. 2. Framework of the multidisciplinary integration platform, integrating simulation feedback from geometric form finding and material/structural analysis, visual and haptic feedback, and computational immediacy through point-cloud computation

with SteamVR support, Oculus/Meta Quest 2), further enhanced by hand-tracking input modalities. Sketching is aided by geometric objects serving as canvases to draw on. The sketching application forms the starting point of the design process for later real-time simulation and collaboration. The integration platform is a set of tools that integrate software applications or methods that are deployed in different environments. The input data for the domain-specific computation comes from the sketching application, while the computation-heavy tasks are mostly performed in the software environment of the subproject. The resulting design calculation feedback is then visualized in the sketching application (except for the digital fabrication).

Most of the other subproject's computations and simulations rely on a structured geometry, suggesting the necessity of translation of sketches to proper geometric format through capturing the design intention. Thus, a shape inference algorithm aided by machine learning employing various stylus-and-geometric-related attributes has been conceptualized and coupled with the sketching tool, which derives a curve network from the artist's drawn polylines. In this setting, once the designer's sketch is finalized, it is converted into the desired 3D geometric format suitable for other downstream processes.

With most of the subprojects, the communication form is geometry or 3D polylines/curves. However, the model requirements vary for the different subproject simulations. Subprojects dealing with lighting simulations and haptic feedback in VR mainly deal with triangular meshes. Triangular meshes are also required by the digital fabrication tools. On the other hand, there are some projects that require other geometric formats for communication: For "Computational Immediacy", point clouds are required. Dealing with automated high-order paneling of freeform surfaces, depends on a curve network comprising of the boundary and paneling layout curves. Dealing with structural analysis and mechanics, volumetric tetrahedral meshes computed from triangular meshes must be considered. To generate and deform flexible foldable quad-meshes, three planar polylines must be drawn as input in the sketching application – the profile, the trajectory and the prism curve. The geometrical mesh is then computed in the computational software.

At the current state of the research, the assignment of material properties and structural system requirements is manually conducted in the design workflow, thus resulting in a semi-automated approach. Since most of the computational methods and results of the different researches are highly dependent on the construction and material types of designed sketches, a geometry- and computation-based material ontology needs to be developed and integrated in the platform in future research to automate the process and provide informed feedback.

5 Proof of Concept

Using a basic element of architecture – a wall – a proof of concept for the proposed framework was conducted. In this particular use case, a wall of a theater stage design setting was used due for several reasons: the small scale of space and short temporal duration offer the opportunity of testing the design in full scale utilizing the created mixed-reality sketching tool; the absence of usual building regulations and procurement procedures allows a greater design freedom and the exploration of new ways of form finding.

A freeform wall was sketched in the mixed-reality sketching application and then transferred to the specific subproject simulations for computation, simulation or fabrication. Figure 3 describes the integration status achieved and the visualization results of the individual subprojects for the wall use case.

The proof of concept demonstrated that data exchange to the different research areas is possible starting from our sketching and integration platform. However, manual intermediate steps are still required for post-processing or data exchange. At the current state of the research, providing feedback in real time from the computational environment of every subproject is not possible. However, in the future, feedback from the subprojects should be provided via a real-time data exchange over the network. By answering the research questions in the following, the current achievements and challenges for providing immediate feedback and automation of calculations and simulations directly into the platform with steps for future research are discussed.

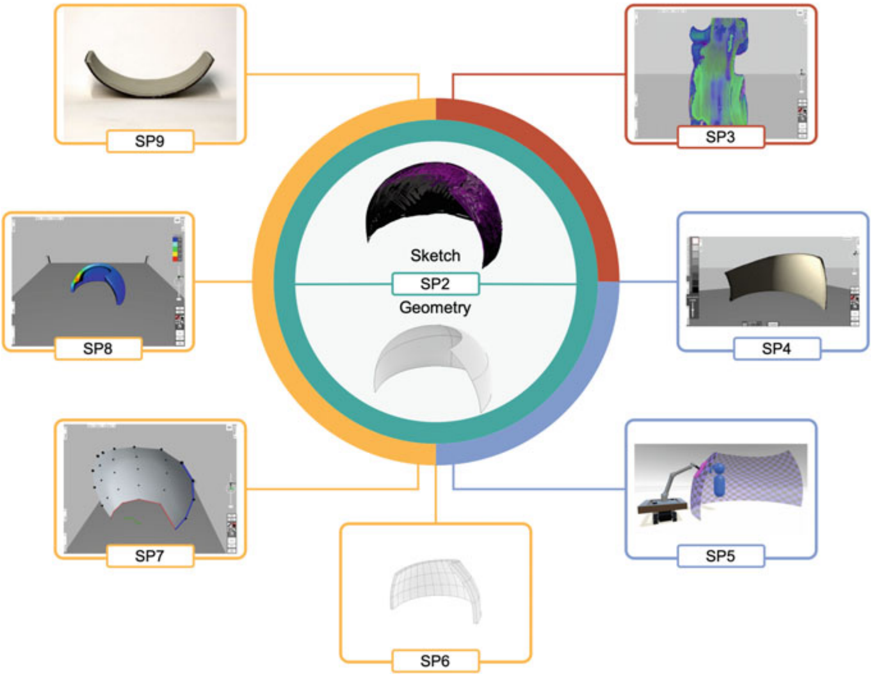

Fig. 3. Results of the proof of concept. At the center, a sketched wall in the sketching tool and its corresponding geometry inferred is shown, while other images in the figure depict latest integration status with each sub-project's specific simulations and computations

The **RQ1** could be answered by integrating simulation feedback of two different geometrical form-finding methods into the integration platform. The first method is a plug-in for transformable flexible quad-surface generation programmed in Rhino/Grasshopper (SP7) which was integrated into the sketching application in Unity to use the functionalities and feedback for transformable designs directly in the platform. The proof-of concept demonstrates that the drawing of three polylines automatically generates a transformable surface which can be manipulated directly in the sketching application. The transformable surfaces can be used for generation of various canvases to further sketching on. One interesting area to be investigated in future is how different designed surfaces can be approximated by V- or T-surfaces, which would be interesting for kinetic walls. The second simulation method finds smooth and discrete surfaces with interesting panel shapes to sketched designs (SP6). The proof of concept demonstrates that the enabled geometry exchange between the integration platform and the respective simulation software of SP6 works, however, automated immediate visualization feedback to the sketching application is not implemented and manual geometry exchange is still necessary. In future research, direct integration possibilities of the paneling simulation software and the generation of different types of paneling layouts will be explored. In addition, the constructability of the generated transformable surfaces and discrete paneled surfaces in combination with the structural analysis is of importance in ongoing research.

To answer **RQ2**, a simulation method for optimization of lighting scenes in the sketching application and a method for haptic feedback in VR to sketched designs were integrated in the platform. A workflow has been created that allows automatic lighting generation and optimization by SP4's software system after sketching lighting scenarios in the application by drawing lighter and darker strokes during sketching. Thus, a way to get direct lighting feedback on sketched designs has been achieved. To enable more accurate simulations in future, additional lighting parameters and user input (e.g., light source position) need to be considered in the sketching application for more accurate optimization. In addition, the integration of material information to account for surface properties (e.g., reflectance) will be critical for illumination simulation. The exchange with haptic feedback, SP5, is currently in progress. The haptic subproject consists of two parts: a VR subsystem based on Unity 3D game engine and a robotic standalone platform based on Robot Operation System (ROS). The Unity application handles the visualization for the user and communicates user's actions to the autonomous mobile collaborative robot (Cobot). The focus of the subproject is on the development of the safe and versatile robotic platform. Based on the user's actions, the Cobot adapts its behavior and when needed provides the necessary haptic feedback. The role of the Unity application is to define the parameters of interaction and communication with the robotic platform for haptics that will be migrated to the sketching tool later on. Since both applications are developed in Unity, the integration should not be problematic. Currently, the Unity subproject is used for testing and fine-tuning of the robotic platform in various scenarios. The integration of the sketches and their structural deformation for haptic feedback requires the following pipeline. The geometry of sketches is forwarded to the structural analysis method for computation of all the possible deformations, and sent to SP5. One of the important challenges is to maintain the simulation in real-time yet still get realistic results.

The **RQ3** was answered by developing a workflow to receive structural feedback to designed sketches. The users sketches a design, and receives visual structural feedback. The structural analysis, however, is currently performed in an external FEM software and not directly integrated, thus intermediate manual steps are necessary. More parameter input possibilities such as definition of load application and boundary condition will be necessary to integrate directly into the sketching application for immediate structural analysis feedback. Two approaches can be distinguished in relation to the incorporation of information about the mechanical performance of materials into the design process. First, analytical models based on methods of continuum micromechanics, e.g. [64, 65]. With such models, mechanical properties of different materials can be determined very efficiently and real-time feedback on the design process is possible. Second, numerical models, describing geometrically more complex structures and non-linear mechanical processes [69, 70], can only interact in real time if these simulations are restricted to a small number of degrees of freedom and simple material behavior. An alternative is the pre-calculation of the mechanical behavior and the generation of meta-models for certain design tasks. This means that even more complex mechanical behavior can be integrated into the early-stage design process in real time.

The **RQ4** was answered by creating a workflow that sketched designs can be directly printed by digital prototyping methods through geometry export out of the platform. By integrating a novel material ontology in future research it will be possible to also simulate and analyze some novel materials as composite clay-mycelium within the platform. The hybrid workflow for physical/digital modeling of architectural concept models based on 3D point clouds and machine learning does not happen over the network, but as a functionality that is implemented and integrated directly into the sketching application. The transfer of design features from learned point clouds via 2D representations onto newly created models in creative design processes will be explored in future research.

A limitation of the presented research is that currently the integration and simulation feedback of every sub-project was investigated in a separate manner. The presented workflow neglects the simultaneous presentation of simulations of several subprojects, e.g. panelization of a surface with simultaneous structural analysis, generation of foldable surfaces including illumination analysis, effects of haptics on illumination optimization, haptic feedback from point clouds in VR, etc. A workflow suitable for this purpose will be explored in the future.

6 Conclusion

This paper portrays the development of an innovative, digitally supported integrated design framework, which allows capturing AEC-domain specific multidisciplinary design requirements via a digital semantic sketchbook. An integrative mixed-reality sketching application transforms geometry inferred from sketches and obtained through a machine learning-based algorithm to computable 3D geometry to enable subdomain specific simulation, computation and fabrication. The provided framework offers a multidisciplinary integration platform for design automation and simulation tools, thus enabling interactive design feedback at an early design stage. The main goal is to generate a platform in a way that promotes joint conversations that designers need to have in the AEC industry, rather than providing a customized solution.

The findings of the presented study show that different simulation aims need different types of geometry and data inputs. This paper focused on geometry exchange and the integration possibility of research in the field of geometrical form-finding, structural and material analysis, lighting optimization, haptic feedback in VR and digital fabrication. Discrete material information was neglected at this stage. In the current state of the research, the integration of material information had to be added manually in the design process and the respective computational tools. The development and integration of a geometry and computation-related material ontology in future research will enable the advancement of geometrical strategies for the definition of freeform surfaces based on their material and functional properties and the automated enrichment of the computational geometrical models with material and structural information, shortening the design process and fastening the feedback.

The proof-of-concept demonstrates that the developed design and integration platform has the potential to shift early design workflows from a linear process (concept – modeling – materialization) to a process of immediate feedback. Results reveal that for some sub-domains, data exchange and simulation or computation currently work semi-automatically. The presented haptic feedback VR simulation platform could not be integrated and tested yet. Further research will focus on the improvement of the data exchange, automation of the design process to provide immediate feedback and the integration of the aforementioned material ontology. The multidisciplinary design and simulation methodology will then be tested within a user study, testing within an interdisciplinary student design studio to evaluate the developed workflows and tools as well as the generated designs from a user perspective.

In future research, the methodology will be extended to the application to real architectural buildings and models. In particular, it is aimed that the sketched objects with their semantic attributes will be converted accordingly so that the multidisciplinary integration platform can be connected to current BIM environments.

In conclusion, the overall field of computational design addressed in the research project SFB – ACD is vast, and the proposed subprojects represent only specific challenges in this field. However, the developed platform paves the way for a new direction of multidisciplinary integration and computational design tools, with a deep impact on this research field. The proposed framework promotes joint conversations that designers need to have in the AEC industry and can be applied to various tools and customized solutions relevant for researchers in the fields of design visualization, geometrical form-finding, structural and material analysis, lighting optimization, haptic feedback and fabrication.

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Comparative Application of Digital Image Processing and Kuz-Ram Model in Blast Fragmentation Analysis: Case of Shayona Cement Quarry

Jabulani Matsimbe, Martin Shaba, Innocent Musonda, and Megersa Dinka

Abstract Blasting operation affects all downstream processes in the mining and construction cycle hence the need to carry out an effective blast to give the desired fragmentation. The present study compares the application of digital image processing and the Kuz-Ram model in particle size distribution analysis at a limestone quarry. Performance assessment utilized the root mean square error, correlation, and regression analysis. Digital image processing utilized WipFrag V3.3 software to analyze the images and benchmark improvements. One blast session was carried out for each mine site. Particle size less than 10 mm, and greater than 300 mm were treated as fines and oversize respectively. Results showed that the model predicted 2% fines and 2% oversize material while the observations on measured fragmentation showed 16.5% fines and 0% oversize for the Chikoa blast. For the Livwezi blast, the model predicted 3% fines and 1% oversize while the observations on measured fragmentation showed 0.27% fines and 42% oversize. The blast from Chikoa performed optimally better than that from the Livwezi mine site. The Kuz-Ram model performed well at predicting fragmentation for the Livwezi site with a 90.42% correlation while for Chikoa it was an 85.39% correlation. The model performed with high correlation values implying that it can be used on both sites to predict fragmentation during preliminary blast design.

Keywords blasting · construction · computing · fragmentation · mining · photogrammetry · wipfrag

J. Matsimbe (✉) · I. Musonda
Centre for Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2092, South Africa
e-mail: jmatsimbe@poly.ac.mw

J. Matsimbe · M. Dinka
Department of Civil Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg 2006, South Africa

J. Matsimbe · M. Shaba
Department of Mining Engineering, Malawi University of Business and Applied Sciences, P/Bag 303, Chichiri, , Blantyre 3, Malawi

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1 Introduction

A carefully engineered blasting operation is important for the success of surface excavations. As open pits become deeper, quality separation to avoid dilution/ore losses and energy cost concerns should be given greater attention to optimizing the entire mine-mill fragmentation system [1]. Blasting in civil and mining operations is characterized by a sudden release of energy and fragmentation of a rock mass initiated by explosives. The blasting process requires drilling, charging, and initiation [2]. Blasting is carried out to give the desired particle size distribution thereby optimizing the overall mine economics [3]. Properly fragmented rock removes hiccups in the downstream processes comprising loading, hauling, and crushing [4]. Therefore, it is necessary to optimize and predict the rock fragmentation distribution. Fragmentation models can be used to predict the probable particle size distribution dependent on a set of blasting parameters and selecting those that give the optimum fragmentation [5]. The response of rock mass to blasting energy is very complex due to its heterogeneous and anisotropic nature [6]. Therefore, it is difficult to obtain a mathematical relationship between the rock fragmentation and blast design parameters broadly categorized into controllable and uncontrollable [7]. Influential parameters on rock mass fragmentation consist of explosive properties, blast geometry, and rock mass properties [8]. The explosive properties and blast geometry are controllable parameters while rock mass is an uncontrollable parameter. Some of the quantitative methods for determining and predicting fragmentation size distribution include sieve analysis, direct observation, Swebrec function, digital image processing, artificial neural network, and empirical models such as the Kuz-Ram, modified Kuz-ram, Kuznetsov–Cunningham–Ouchterlony (KCO) and Julius Kruttschnitt Mineral Research Centre (JKMRC) Model. Ref. [5] assessed the performance of the Kuz-Ram model, Modified Kuz-Ram, and KCO models using the root mean square error and correlation and regression analysis to determine the most accurate model applicable to two mine sites in Ghana. The fragmentation analysis showed a high quantity of fines with an insignificant number of boulders from all the studied mines. All models had high correlation coefficients (R) above 95%, the modified Kuz-Ram model performed best at Mine A whilst the Kuz-Ram model performed best at Mine B. The Kuz-Ram model performed better in fines prediction than the KCO and Modified Kuz-Ram models.

Society's need for a sustainable supply of natural resources requires improved yield from blasting, crushing, and grinding, minimal transportation, and fewer amounts of non-hazardous waste. The first step towards a higher yield in the comminution process is blasting to specifications and producing fragmentation that requires less energy during the crushing and grinding stages [9]. Mining costs for unit operations such as loading, hauling, and crushing, can reduce with optimum rock fragmentation sizes [6]. In Malawi, there is a huge technology gap in blasting operations mostly in assessing the particle size distribution of blasted rock and making informed decisions on what/how to improve the blast design. There is a common usage of direct observation as the main method for analyzing rock fragmentation distribution in surface mines/civil works. This facilitates the use of a trial-and-error approach in blast design. This practice is costly, time-consuming, and tedious since a lot of resources are spent in the blast design stage to obtain optimal fragmentation. Therefore, it is imperative to start using methods such as digital image analysis and the Kuz-Ram model. Compared to other models, Ref. [10] attributed the preference of the Kuz-Ram model for fragmentation analysis due to its ease of parameterization and direct linkage between blast design and rock breakage. The empirical modeling methods provide much better results than qualitative techniques as they are repeatable and are not intrusive to production [9].

In hard rock mining, blasting is the most productive excavation technique applied to fragment in-situ rock to the required size for efficient loading and crushing [6]. Rock fragmentation is the breaking down of rocks into small particles for easy end-user handling. It is the ultimate measure of the efficiency of any production blasting operations [11]. As over/under fragmentation both tend to increase the cost of mining, the generation of fragment size in the desired range is necessary [12]. Quantification of rock fragmentation has attracted a lot of significance over the years. Different models have been used over the years to predict the size distribution resulting from blast design [10, 13, 14]. Ref. [10] further divided the models into two approaches consisting of empirical modeling which infers finer fragmentation from higher energy input, and mechanistic modeling which tracks the physics of detonation and the process of energy transfer in well-defined rock for specific blast layouts, deriving the whole range of blasting results. The mechanistic approach is difficult and time-consuming to use compared to empirical models hence it is rarely used. The Kuz-ram model was established in the 1980s and it has been used up to the present. It is used in estimating the mean fragment size resulting from a blast [5]. The Kuz-Ram model measures fragmentation by estimating the 50% passing block size of a muckpile [15]. According to [10], it has two adapted equations and one of them is the Kuznetsov equation which was developed by Kuznetsov in 1973 [16] and is used to calculate the mean particle size of a blast. It is given by Eq. 1:

$$X_m = AK^{-0.8}Q^{-\frac{1}{6}}.\left(\frac{115}{RWS}\right)^{\frac{19}{20}} \quad (1)$$

where: Xm = particle mean size of muckpile (cm), A = rock factor/blastability index (ranges from 0.8 to 22), K = powder factor (kg/m^3), Q = mass of explosive in a blast hole (kg), RWS = relative weight strength relative to ANFO. The blastability index (or rock factor) in Eq. 1 is given by Eq. 2 originally developed by Lilly in 1986 [10]. It is used to modify the average fragmentation based on the rock type and blast direction.

$$A = 0.06(RMD + RDI + HF) \quad (2)$$

where: RMD is the rock mass description, RDI is the rock density influence, and HF is the Hardness Factor. The Rosin–Rammler equation developed in 1933 by Rosin and Rammler [10] is very useful in coming up with a logarithmic cumulative size distribution. It is given by Eq. 3:

$$R_x = e^{\left[-0.693\left(\frac{X}{X_m}\right)^n\right]} \tag{3}$$

where: Rx = mass fraction retained on screen x, n = uniformity index (ranges from 0.7 to 2).

Figure 1 shows the bench blasting design parameters where D blasthole diameter (m), BH bench height (m), B burden (m), S blasthole spacing (m), SD blasthole subdrilling (m), SL blasthole stemming length (m), C explosive column height (m). Other parameters consist of the h_p length of the column charge (m), h_b length of the bottom charge (m), I_p concentration of the column charge (kg), I_b concentration of the bottom charge (kg/m), Q_p weight of column charge (kg), Q_b weight of bottom charge (kg), Q_e total weight of explosive used in a hole (kg), q powder factor (kg of explosives/m^3 of rock), g specific drilling (drilled meters/m^3 of rock), blasthole pattern, delay timing, and initiation sequence.

Figure 1 shows blast parameters used in the calculation of the uniformity index. The Uniformity Index characterizes the particle size distribution from a blast and is dependent on the blast geometry [10]. A high value of n signifies uniform fragmentation size while a low value indicates higher proportions of both fines and boulders [18]. It is given by Eq. 4:

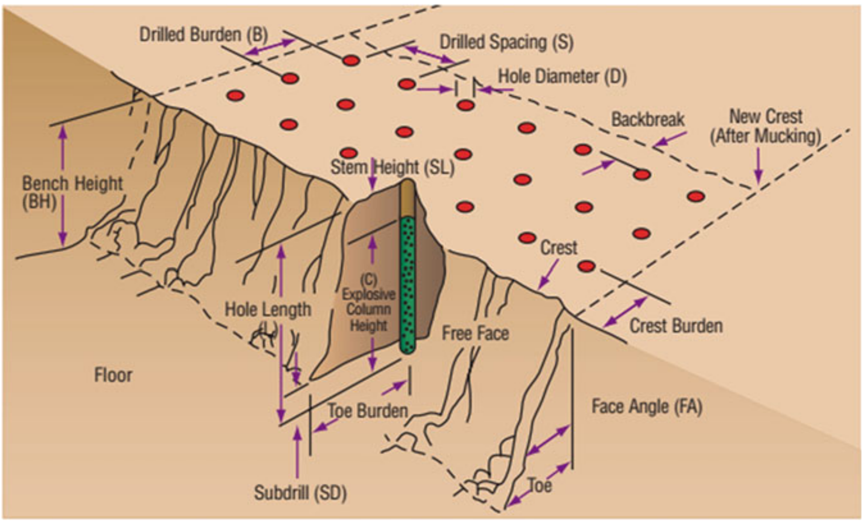

Fig. 1. Controllable parameters considered in blast design [17]

$$n = \left(2.2 - \frac{14B}{d}\right)\sqrt{\left(\frac{1+\frac{S}{B}}{2}\right)}\left(1 - \frac{W}{B}\right)\left(\left|\frac{BCL - CCL}{L}\right| + 0.1\right)^{0.1}\frac{L}{H} \quad (4)$$

where: B = Burden (m), S = Spacing (m), d = Hole diameter (mm), W = Standard deviation of drilling precision, L = Charge length (m), BCL = Bottom charge length (m), CCL = Column charge length (m), H = Bench height (m). Cunningham [19] observed that the uniformity coefficient n varies bwn 0.8 and 1.5.

The field of digital image processing refers to processing digital images using a digital computer [20]. One of the first applications of digital images was in the newspaper industry when pictures were first sent by submarine cable between London and New York around the 1920s [20]. The technique has been heavily applied in slope and rock fragment analysis in the mining industry. The subject of these images can be a muck pile, haul truck, leach pile, draw point, waste dump, stockpile, conveyor belt, or any other location where clear images of rock fragments can be obtained [11]. When the images have been acquired, they are input into software such as Split Desktop, WipFrag, FragScan, PowerSieve, etc.,[15] which use their set of algorithms to analyze the images and produce the Rosin–Rammler cumulative size distribution, the rock characterization factor (A), the mean fragment size, a histogram, and the blast geometry which can later be analyzed. The errors of the method can be reduced by capturing many high-quality images for analysis [15].

Drilling and blasting influence the economy of open pit excavations since the success of all downstream processes related to strata handling depend on the size of the blasted rock mass. Therefore, the evaluation of fragments obtained from blasting plays a very important role in monitoring compatibility with the handling and crushing machinery. Optimum fragmentation is necessary to ensure sustainable mining since both over/under fragmented rock tends to affect the cost of mining or excavation. A blasting operation is optimized when both the blasting and handling costs of fragmented rock are minimal [4]. Controllable parameters influencing the fragmentation in a rock blast consist of powder factor, stemming column, bench height, hole diameter, and burden. The analysis of fragmentation and blast design in reference to the controllable parameters can enhance the performance of a rock blast; therefore, the present study aims at conducting a digital image evaluation compared to the Kuz-Ram model in monitoring/predicting the mean fragment size and percentage of boulders. The adoption of the Kuz-Ram model and digital image processing in blasting design can help optimize excavation works and make them cost-effective leading to efficient downstream processes. This research is based on conventional small diameter blasting performed in a quarry to obtain the desired fragmentation with minimal cost.

2 Methodology

2.1 Study Area

The study area is in the Kasungu district found in the Central Region of the Republic of Malawi in Southern Africa. The Limestone mine sites namely Livwezi, and Chikoa at Shayona Cement are about 3 km apart. Figure 2 shows the Mine site with Livwezi located at 12°52′35.86″S latitude and 33°43′16.60″E longitude, and Chikoa located at 12°52 49.60 S and 33′44′33.75″E longitude. The study area was chosen because most of the data for blast geometry, rock mass properties, and explosive properties are known.

The mine is an open pit and practices conventional drilling, blasting, loading, and hauling. Malawi is comprised of mainly the Precambrian Basement Complex [21]. These rocks underlie most of the Central region of Malawi where Kasungu is located. Kasungu is mostly underlain by medium to high-grade metamorphic rocks of the Mozambique belt. The Livwezi deposit elongates along a Southwest-Northwest direction and is comprised of medium to coarse-grained marble within intercalations of calci-silicates, granulite, and amphibolite. It is folded into isoclinal folds whose foliations deep gently. The outcrop is associated with fractures without rock or mineral infillings. In the Southeast of the deposit, shear zones are recorded with a Northeast trend with infillings of very coarse crystals of calcite, quartz, and feldspar. The Chikoa deposit, however, has the same trend as the Livwezi deposit and its lithological sequence includes medium to very course-grained marble inter-banded with granitoid quartz-feldspathic rocks and biotite gneisses.

2.2 Data Collection

The resulting fragmentation from the Quarry blast operations was evaluated using WipFrag v3.3 digital image processing software and the Kuz-Ram empirical model. WipFrag is an auto-image generation granulometry software that utilizes digital images to evaluate fragment size distributions [15]. WipFrag uses automatic algorithms to identify definite blocks and develop a mesh outline or netting using state-of-the-art boundary or edge recognition techniques. It measures the 2D surface net of a block assemblage, transforms, and reconstructs a 3D block size distribution using geometric probability principles.

The Kuz-Ram model [10, 16] is an empirical relationship evaluating blast fragmentation through the incorporation of blast design parameters comprising blasting geometry, characteristics of explosives, explosive quantity, and rock properties. The Kuz-Ram model evaluates fragmentation through the estimation of the 50% passing

Table 1. Rock mass description value for various rock mass

Rock Description	RMD value
Friable	10
Massive	50
Vertically jointed	Use Jointed Rock Factor

Table 2. JCF interpretations from field observations

Observation	Interpreted value
Tight joints	1.0
Relaxed Joints	1.5
Gouge filled joints	2.0

block size of a muckpile. To compare the two techniques, statistical analyses were done.

i. **Rock Mass Description**

Table 1 shows the rock mass descriptor values used to describe its properties.

For the vertically jointed rock mass, the Jointed Rock Factor (JRF) is given by Eq. 5:

$$\text{JRF} = (\text{JCF} * \text{JPS}) + \text{JPA} \quad (5)$$

where: JCF = Joint Condition Factor, JPS = Joint Plane Spacing factor, JPA = Joint Plane Angle factor

ii. **Joint Condition Factor (JCF)**

From field observations, the joint condition factor will be interpreted and determined from Table 2.

iii. **Field tests**

Rock mass properties that were obtained on-site include Rock Mass Description (RMD) particularly Joint Plane Spacing and Joint Plane Angle factors, and Hardness Factor (HF) for use in the computation of the rock factor for use in the Kuz Ram model.

a. Joint plane spacing factor (JPS)

According to Cunningham [10], this factor is partly related to the absolute joint spacing, and partly to the ratio of spacing to drilling pattern, expressed as the reduced pattern P. Figure 3 shows the relationship between hole spacing and joint spacing on blasting fragmentation.

The reduced pattern, P, is given by Eq. 6:

$$P = \sqrt{B \times S} \quad (6)$$

Fig. 2. Location of mine site

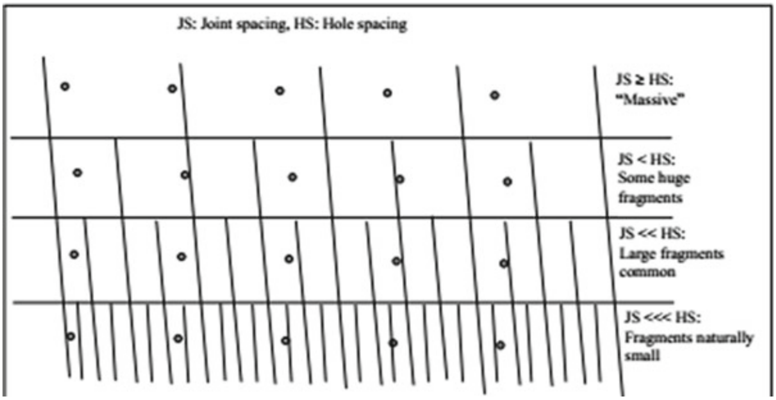

Fig. 3. Relationship between hole spacing and joint spacing on blasting fragmentation [10]

In order to determine the JPS factor, a field test to determine the joint spacing in the rock mass was carried out using a scan line of at least 3 m in length and calibrated in millimetres. The test procedure was adapted from ISRM 2007. The procedure is as described below:

- Whenever possible, the measuring tape should be held along the exposure such that the surface trace of the discontinuity set being measured is approximately perpendicular to the tape. If the tape is not perpendicular, the directional bias corrections are required to obtain true spacing
- All distances (d), between adjacent discontinuities are measured and recorded over a sampling length not less than 3 m (or the thickness of the rock unit being

observed if this is less than 3 m). The sampling length should preferably be greater than ten times the estimated spacing. The distances (d) should be measured to within 5% of their absolute values.

- The smallest angle, (α) between the measuring tape and the observed joint set is measured with a compass to the nearest 5°.
- The most common (modal) spacing is calculated from Eq. 7:

$$S = d_m \sin\alpha \tag{7}$$

where d_m is the most common (modal) distance measured. It is helpful to present the variation spacing using the histogram. When the joint spacing is determined, the mean value found was referred to in Table 3 together with the reduced pattern parameter to determine the joint plane spacing factor.

b. Joint Plane Angle

Data for joint plane angle was collected using a clinometer to determine the joint plane angle. The procedures for data collection followed ISRM standards 2007. The procedure includes:

a. The maximum declination (dip) of the mean plane of the discontinuity is measured with the clinometer and should be expressed in degrees as a two-digit number e.g., 05° from 0–90°.
b. The azimuth of the dip (dip direction) is measured in degrees counted clockwise from true north and expressed as a three-digit number for example 010° from 000°–360°.
c. The dip and dip direction should be recorded in that order, with the three-digit and two digits number separated by a line

The collected data as shown in Table 4 was then used to determine the Joint Plane Angle factor.

Table 3. Interpreted value of JPS from JS and P

Joint Spacing	JPS	Remark
<0.1 m	10	fine fragmentation will result from close joint
0.1–0.3 m	20	unholed blocks are becoming plentiful and large
0.3 to 95% of P	80	some very large blocks are likely to be left
>P	50	all blocks will be intersected

Table 4. Determining Joint Plane Angle

Dip out of face	40
Strike out of face	30
Dip into face	20

iv. **Hardness factor**

For the hardness factor, data for the uniaxial compressive strength was estimated by conducting a type L Schmidt rebound hammer test following ASTM C805. Later, a specific gravity test using ASTM D792 was done to determine the unit weight of the rock.

v. **Blast sessions**

One blast session was conducted for each mine site with a total of 6 images being analyzed for each blast. Digital images which were taken for image analysis were randomly sampled. To minimize errors, the camera lens was placed perpendicular and very close to the surface of the blasted muckpile. However, there is a possibility of deviation from this norm in actual practice. Therefore, the images were captured from the viewpoint exactly in front of the muckpile with the horizontal axis of the camera at some angle order than 90° to the face of the muck pile. Double scaling objects of known dimensions were placed on the surface of the muck pile when taking the images to provide scale and compensate for the slope of the muckpile [9].

3 Results and Discussion

Performance assessment of the Kuz Ram model using root mean square error was done in Microsoft Excel 2013. Correlation and regression analysis for assessing model performance was done using Minitab 20 statistical software. Digital image processing utilized WipFrag V3.3 software to analyze the images.

3.1 Particle Size Distribution

Figures 4, 5, 6 and 7 show the analysis from the time the image is taken from a muckpile containing two bamboo sticks 1.7 m in length used for scaling the image and compensation for the slope of the muckpile until its particle size distribution is plotted by the software.

3.2 Specific Density Test Results

The results of the specific density test for the rock samples from Chikoa and Livwezi are presented in Table 5.

Fig. 4. Freshly shot image from the muck pile

Fig. 5. Auto delineated image

3.3 Uniaxial Compressive Strength

For the Schmidt hammer rebound test conducted on the field, the uniaxial compressive strength (UCS) of the rock mass determined is shown in Table 6.

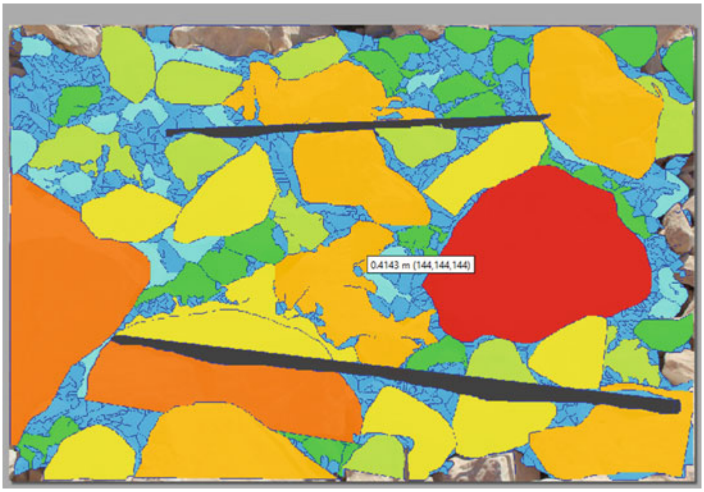

Fig. 6. Image after auto and manual delineations

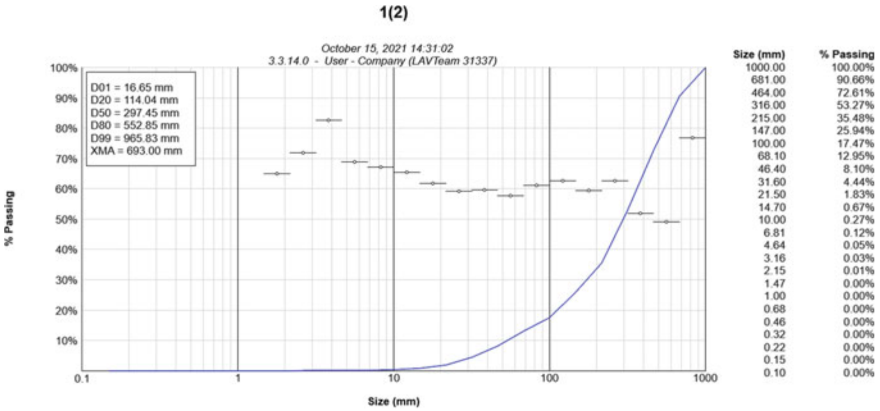

Fig. 7. Final processed image showing the particle size distribution

3.4 *Kuz-Ram Fragmentation Prediction*

The utilized explosive was Ammonium Nitrate Fuel Oil (ANFO) with a density of 0.8, bottom charge Explogel V8 32 × 270 mm (Watergel), and relative weight strength. The rock mass and blast design parameters are shown in Tables 7 and 8, respectively.

The predicted values by the model from the adapted Kuznetsov and Rossin-Rammler equations are presented in Table 9 (Table 10).

Figures 8 and 9 shows the particle size distribution for the Chikoa and Livwezi blasts predicted by the model.

Table 5. Results for specific density test

Description			Livwezi			Chikoa		
Mass of bottle + rock + water	m_3	g	1546.59	1480.35	1476.95	1452.92	1439.4	1489.99
Mass of bottle + rock	m_2	g	592.3	515	511.23	461.96	447.76	509.91
Mass of bottles full of water	m_4	g	1337.14	1318.66	1318.71	1318.22	1318.33	1317.84
Mass of bottle	m_1	g	258.39	258.36	259.07	258.62	260.05	258.91
Mass of rock	m_2-m_1	g	333.91	256.64	252.16	203.34	187.71	251
Mass of water in a full bottle	m_4-m_1	g	1078.75	1060.3	1059.64	1059.6	1058.28	1058.93
Mass of water used	m_3-m_2	g	954.29	965.35	965.72	990.96	991.64	980.08
Volume of rock	$(m_4-m_1)-(m_3-m_2)$	mL	124.46	94.95	93.92	68.64	66.64	78.85
Rock density	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$		2.68287	2.702896	2.684838	2.962413	2.816777	3.183259
Average density				2.690201			2.987483	

Table 6. Uniaxial Compressive Strength (UCS) of rock values

Place	UCS (MPa)
Chikoa	89
Livwezi	54

Table 7. Rock mass parameters

Parameter	Chikoa Blast	Livwezi Blast
Uniaxial compressive stress (MPa)	89	53.5
Specific density (t/m^3)	0.299	0.268
Unit weight (KN/m^3)	29.9	26.8
Rock Mass Description (RMD)	50	50

Table 8. Blast Parameters for both sites

Parameter	Chikoa Blast	Livwezi Blast
Bench Height, H (m)	12	7.5
Hole diameter (mm)	100	100
Stemming height (m)	1.5	1.5
Sub drill (m)	0.5	0.5
Burden, B (m)	2.5	2.3
Spacing, S (m)	2.5	2.5
ANFO per hole (kg)	65.97	37.70
Number of holes	41	52
Total mass of ANFO required (kg)	2704.91	1960.35
Blast volume (m^3)	3075	2242.5
Powder Factor (kg/m^3)	0.88	0.87
Drill Accuracy	95	96
Hole Deviation	0.125	0.1
Bottom Charge Length (m)	0.27	0.27
Column Charge Length (m)	10.23	5.73
Hardness Factor	10.6	15.4

Table 9. Predicted values from the Kuz-Ram model

Parameter	Predicted Value	
	Chikoa Blast	Livwezi Blast
Uniformity Index	1.59	1.44
Rock Factor	4.25	3.81
Mean Particle Size (cm)	10.34	8.49

Table 10. Predicted Results by the Rosin–Rammler size distribution

Size	Chikoa Predicted result		Livwezi Predicted result	
X(cm)	Retained Rx	% passing	Retained Rx	% passing
100	6.85276E-12	100	3.06502E-11	100
68.1	8.79464E-07	99.99991205	9.01428E-07	99.99990986
46.4	0.000515769	99.94842306	0.000332382	99.96676175
31.6	0.016465978	98.35340223	0.009997071	99.00029295
21.5	0.108149064	89.18509362	0.071036159	92.89638408
14.7	0.296951846	70.30481545	0.216681555	78.33184452
10	0.518149079	48.18509206	0.415623513	58.43764868
6.81	0.700021146	29.99788538	0.603616319	39.63836808
4.64	0.823975723	17.60242767	0.747909078	25.20909219
3.16	0.900296634	9.970336592	0.84617571	15.38242901
2.15	0.944698406	5.530159395	0.908544344	9.145565628
1.47	0.969422021	3.057797864	0.9460454	5.395459961
1	0.983323919	1.667608081	0.968659715	3.134028505
0.681	0.990919569	0.908043053	0.98185819	1.814180984
0.464	0.995060167	0.493983292	0.98952056	1.047944021
0.316	0.997317226	0.268277412	0.993960628	0.603937201
0.215	0.998545993	0.145400695	0.996527578	0.347242235
0.147	0.999206015	0.079398505	0.99799046	0.200954017
0.01	0.999988999	0.001100115	0.999958118	0.004188158
0.0068	0.999994047	0.000595344	0.99997597	0.002403028
0.0046	0.999996805	0.000319521	0.999986315	0.001368477
0.0032	0.999998207	0.000179293	0.999991887	0.000811348
0.0022	0.999999013	9.87367E-05	0.999995271	0.000472936
0.0015	0.999999463	5.36604E-05	0.999997276	0.000272399
0.001	0.999999719	2.81378E-05	0.999998481	0.000151897

3.5 Digital Image Processing Results

The particle size distribution analyses of the muckpile obtained from the three different blasts using WipFrag program are shown in Figs. 10 and 11. The allowable fragment maximum handled by the primary crusher is 1000 mm.

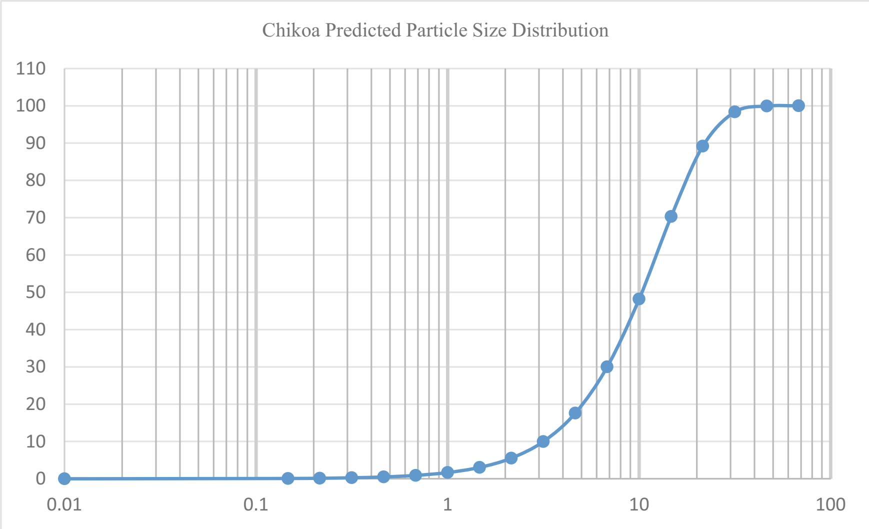

Fig. 8. Chikoa mine blast particle size distribution

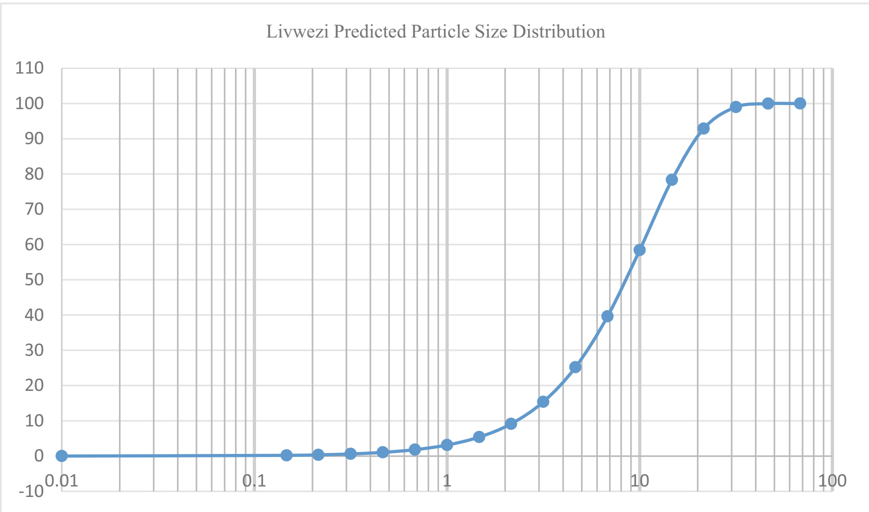

Fig. 9. Predicted size distribution for the Livwezi blast

3.6 Chikoa Blast

Figures 12 and 14 show the particle size distribution curve of the blast design determined from the Kuz-Ram model while Figs. 13 and 15 compares the Kuz-Ram curve with the two results obtained from WipFrag. The particle size distribution from the

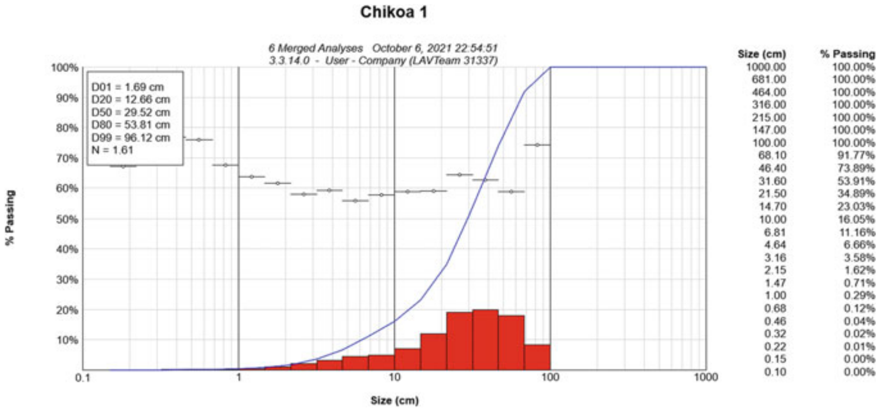

Fig. 10. WipFrag image analysis for Chikoa blast

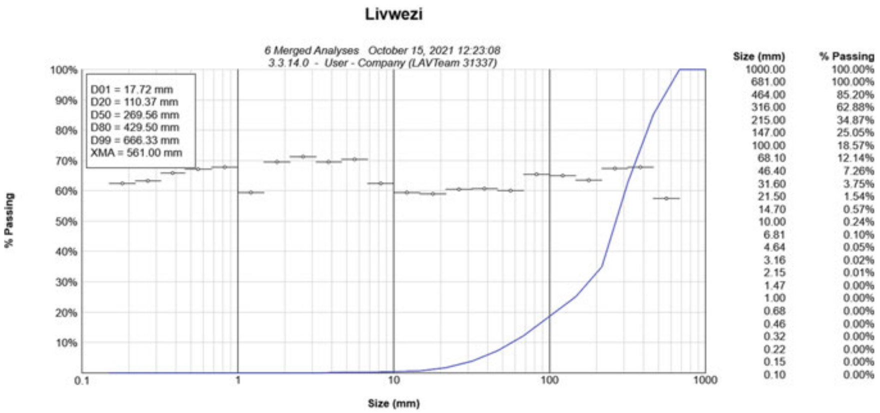

Fig. 11. WipFrag image analysis for Livwezi blast

Kuz-Ram model deviates from that of the WipFrag program despite showing similar trend. The model shows that all fragments are less than the 1000 mm benchmark indicating a tolerable range of boulders. The differences in size distribution can be attributed to the heterogeneous nature of the rock mass structural properties and human error [15]. The mean particle size predicted by the model was 10.23 cm while the actual particle mean size was 3 cm. The mean particle size gives a measure of the average fragmentation of the muck pile. This in turn shows that the model overpredicted the mean particle size for the muck pile.

From Fig. 13, the model predicted 2% fines (less than 10 mm) and 2% oversize material (over 300 mm). The measured results show 16.5% fines and 0% oversize material. This shows fines underprediction percentage error of 87% by the model while the oversize material was overpredicted with an error of 50%. This finding

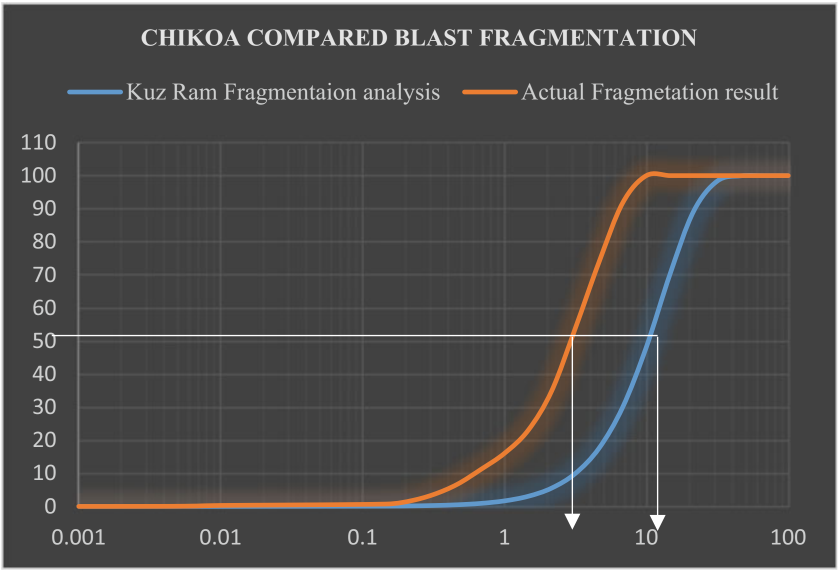

Fig. 12. Comparison between the predicted and actual results

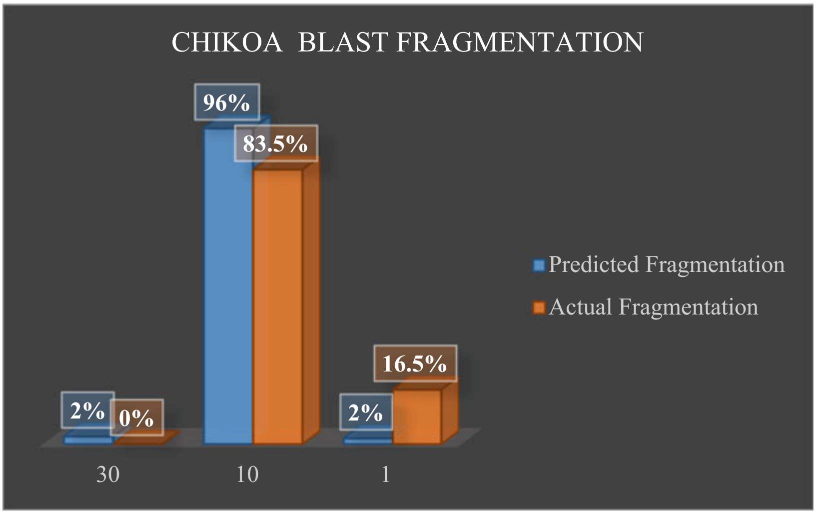

Fig. 13. Percentage fines, range, and oversize for predicted and actual results

agrees with studies by [13–15] who found that the Kuz-Ram model underestimates the number of fines in a mine blast. The percentage range from 10 mm mesh size to 300 mm was predicted at 96% while the measured percentage range was 83.5%.

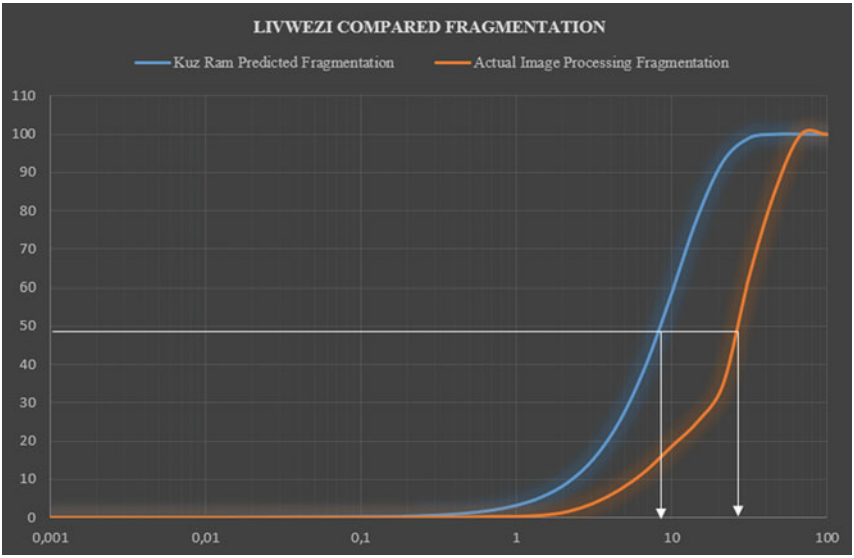

Fig. 14. Comparative particle size distribution

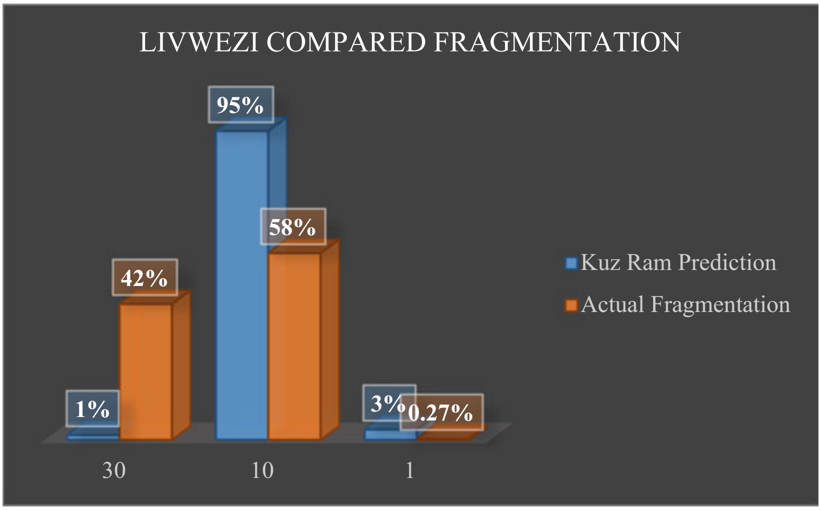

Fig. 15. Comparison of fines and oversize for predicted and measured fragmentation

3.7 Livwezi Blast

The Livwezi blast produced a measured fragmentation mean particle size of 20.8 cm while the model predicted a mean particle size of 8.49 cm. Figure 14 shows a comparison of the particle size distribution predicted by the model against the measured one with the line drawn perpendicular to the Y-axis at 50% crossing the two graphs at their respective mean particle size values. The graphs also show that the model underpredicted the overall particle size distribution as observed that its graph is to the left of the measured distribution.

From Fig. 15, the model predicted 3% fines (less than 10 mm), a percent in the size range of 95%, and an oversize (greater than 300 mm) of 1%. Measured results show 0.27% fines, a percent in the size range of 58%, and an oversize retained percentage of 42%. Similar findings on overprediction of fines were found by Ref. [5] in contrast to underprediction of fines found by Ref. [14]. From the fine's prediction, the model gave a prediction error of 91% which is a very high error in fines prediction. Furthermore, the model underpredicted the boulder size similar to findings by Ref. [5] at Mine B.

3.8 Model Performance

As shown in Table 11, the root mean square error (RMSE) calculated in Microsoft Excel gave an error of 3.33 (Livwezi) and 23.85 (Chikoa). Linear regression (R^2) between the model and the measured data shows 81.76% (Livwezi) and 79.92% (Chikoa) blasts. Correlation coefficients (r) of 85.39% (for Chikoa) and 90.42% (for Livwezi) were calculated. Livwezi blast had the least root mean square error and high regression and correlation coefficient values which shows that the model performed well on the Livwezi blast than on the Chikoa blast. This also shows that the model performs well on certain sites than on others. The model had a weak performance in predicting fines at Chikoa (2% vs 16.5%), and boulders at Livwezi (1% vs 42%) but a slightly better performance in predicting fines at Livwezi (3% vs 0.27%) and boulders (2% vs 0%) at Chikoa.

Table 11. RMSE, Regression, and correlation values

Mining Location	Root Mean Square Error (RMSE)	Regression (R^2)	Correlation coefficient (r)
Chikoa blast	23.85	79.92%	85.39%
Livwezi blast	3.33	81.76%	90.42%

4 Conclusion

The research focused on reducing the technological gap in the mining industry in Malawi by applying the Kuz-Ram model and digital image processing techniques to analyze rock mass fragmentation. This can help in making better blast design decisions to optimize mining processes and costs. Field tests, observations, and laboratory tests were conducted to meet the objectives of the research. It was found that the Kuz-Ram model predicted 2% fines (less than 10 mm) and 2% oversize material (greater than 300 mm) for the Chikoa blast; and 3% fines (less than 10 mm) and 1% oversize (greater than 300 mm) for the Livwezi blast. The measured fragmentation showed 16.5% fines and 0% oversize material for the Chikoa blast; and 0.27% fines and 42% oversize for the Livwezi blast. The model performed well in predicting fragmentation at the Livwezi mine site with a correlation of 90.42% while the correlation for the Chikoa mine was 85.39%. Since the two blasts used a similar blast design and explosives, the differences can be attributed to variations in rock mass structural properties e.g., Compressive strength, groundwater, joint fillings, and aperture. Due to high correlation and regression values, the model can be used on both mining sites for preliminary blast design with sufficient prior knowledge of the rock mass properties as an alternative to the trial-and-error approach. Ref. [15] observed that the fragment size distribution obtained from Kuz-Ram vary from that of WipFrag but followed a similar trend. Future research work should consider using other models such as JKRMC, KCO, and Modified Kuz-Ram model on both mining sites to ascertain the accuracy of the Kuz-Ram model considering that the model seems to work best on certain sites and not on others.

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Technology-Enriched Engineering Pedagogy

Proposal of a Collaborative Teaching Method for AEC Supported by Additive Manufacturing Use

Márcio Henrique de Sousa Carboni, Sérgio Scheer, and Armando Luis Yoshio Ito

Abstract The Brazilian construction industry presents low productivity and limited international competitiveness. In this scenario, two relevant aspects are identified: academic education and technology adoption. In view of this context, two movements stand out. The first is the reformulation of the Brazilian National Curriculum Guidelines (DCNs) for Civil Engineering and Architecture undergraduate courses, which seeks to improve professional qualification, with a greater focus on the expectations of the industry of the 4th Industrial Revolution. The second is the emergence of new professionals, capable of engaging in the AEC (Architecture, Engineering and Construction) ecosystem to assist in the adoption of new technologies, linked to Industry 4.0. Among various innovative technologies, this research focus on Additive Manufacturing (AM), as it presents a great disruptive potential for civil construction industry, especially in education. Among the new workers who are joining the AEC industry, Graphic Expression professionals, graduated from Federal University of Paraná (Brazil), are inducing agents for the adoption of new technologies. For the effective incorporation of these elements in the AEC ecosystem, teaching programs are required to provide the fundamentals of technology, allowing future professionals to discover their capabilities. This paper presents a proposal of a collaborative teaching method for AEC, supported by AM use. This method, grounded on constructivist pedagogy for teaching and learning, is the result of a Design Science Research (DSR) approach. It puts together students from Civil Engineering, Architecture and Graphic Expression undergraduate courses, who then work on an interdisciplinary setting, studying a common theme. Our method uses Additive Manufacturing, Project-based Learning (PBL) and Collaborative Learning as teaching tools, with an emphasis in motivation, always considering the best conditions for students. In this paper, we establish important contents to be worked on in a hybrid teaching model, which uses distance learning to teach theoretical concepts and practical laboratory experience to solve problems collaboratively, ensuring the development of

M. H. de Sousa Carboni (✉) · S. Scheer
Federal University of Paraná, Curitiba PR, Brazil
e-mail: mhcarboni@ufpr.br

A. L. Y. Ito
Federal University of Technology – Parana, Curitiba PR, Brazil

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skills and competences. Finally, the present paper indicates seven important steps for the development of the proposed educational activities.

Keywords Additive Manufacturing · Project-based Learning · Collaborative Learning · Graphic Expression · Teaching Method

1 Introduction

The Brazilian industry is in a position of low competitiveness and innovation in the international market. According to the Global Innovation Index, Brazil lost 22 positions between 2011 and 2016, ranking 69th out of the 123 countries evaluated. This low performance was mainly due to the score obtained in human resources and research, especially in the area of engineering [1].

Compared to developed countries, Brazil presents a considerably retrograde reality, since a large part of its national industry is not even in the Third Industrial Revolution [2]. Several authors point out that, in the construction industry, this scenario is even worse, since there are delays in the adoption of technologies and a decline in the level of productivity in comparison to other industries [3–6].

Part of this situation is a result of the precarious training of professionals in the area. According to [1], between 2015 and 2017, Brazil presented an occupancy rate in Engineering undergraduate courses of less than 30%. The author also states that there is evidence of a lack of interest in Engineering courses, beyond high dropout rate among students – more than 50%, according to the National Council of Education study CNE/CES n. 1/2019 [7].

Among other reasons, it stands out the unpreparedness of students, as a result of weak basic education, as well as the unattractive organization of curricula, and other disincentives that keep student away from professional practice [1, 8].

However, there are undeniable attempts to evolve, such as the recurring themes of BIM, lean construction, modular construction, and digital manufacturing. In the latter case, we can include Rapid Prototyping (RP) and Digital Fabrication (DF) technologies, which make it possible to build physical elements from 3D models, created with the support of CAD/BIM tools. In this scenario, we emphasize the use of the additive processes known as Additive Manufacturing (AM), or 3D printing. AM is the process of manufacturing physical models, using data from a virtual CAD/BIM model, through the deposition of layers that will be manufactured successively, with the goal of obtaining the complete geometry of the part [9–11].

Such technologies can be partly or fully inserted into the design-construction process of architecture, since they can be applied in its different stages, from conceptual architectural design to the molds of construction elements. They are also applicable in the manufacturing of final elements, which will then be ready for installation in the building. However, in Brazil, the use of DF as a constructive technique is insipient, given the country's small industrialization in AEC. For this reason, such technologies are mainly addressed in higher education centers, in order to guarantee the experimentation and training of professionals who are able to work with them [12].

In the teaching–learning process, the support and benefits of 3D printing in the most different areas is already a reality [13–17]. Such areas include arts, mathematics, engineering, design, archeology and historical heritage, astronomy, architecture and urbanism, medicine and anatomy.

Physical models can assist students in the spatial understanding of varied phenomena. Consequently, they increase students' involvement in classes. They allow an appropriate language for learning, which facilitates and rationalizes the process of learner's thinking, in order to replace a naive view of reality with a more critical and comprehensive posture [18]. In areas that demand creativity and notions of design, they facilitate the understanding of design processes, allowing students to transfer their ideas to reality and to learn about the weaknesses and virtues of their projects. Thus, students are ablet experience the interactive cycle of design processes [16, 19].

The evolution of digital technologies, especially since the end of the twentieth century, has subjected society to profound changes in the processes of conceiving, producing, disseminating, learning and applying knowledge, with social, cultural, technical and educational implications [20]. In this context of rapid changes and technological evolution, the role of the different professionals involved in the AEC (Architecture, Engineering and Construction) industry is changing dramatically. New operating niches are emerging specifically for the use of new technologies [12, 21].

In this context, two movements stand out. The first involves discussions about the Civil Engineering (CE) and the Architecture and Urbanism (AU) curricula of Brazilian universities, which culminated in the reformulation of the Brazilian National Curriculum Guidelines (DCNs) for Engineering in 2019, and in the elaboration of a proposal to change DCNs for Architecture and Urbanism (not yet approved by the Ministry of Education). The second is related to the creation, in 2012, of the first bachelor's degree in Graphic Expression (CEGRAF), at Federal University of Paraná (UFPR), which stems precisely from the perception of the great demand for generalist professionals with focus on new digital technologies.

For the effective incorporation of such elements in the AEC ecosystem, educational programs are required to provide key technology fundamentals, allowing future professionals to discover their capabilities, which must be aligned with the needs of an education for the twenty-first century society.

This paper presents a proposal of a collaborative teaching method for AEC supported by AM use, which puts together students from Civil Engineering, Architecture and Graphic Expression (GE) undergraduate courses, to assure interdisciplinary learning and studies on a common theme. Additive Manufacturing, Project-based Learning (PBL) and Collaborative Learning are used as teaching tools. We also consider motivation and appropriate conditions for all students, based on the MUSIC academic motivation model, which presents 5 components for the design of a course: eMpowerment, Usefulness, Success, Interest and Caring. We also establish important contents to be included in a hybrid teaching model, with the distance learning of theoretical concepts, combined with practical laboratory experience, so that students learn to solve problems collaboratively, ensuring the development of news skills and competences. Finally, we indicate seven important steps for the development of the proposed educational activities.

1.1 Brazilian National Curriculum Guidelines (DCNs) for Civil Engineering and Architecture Undergraduate Courses

In Brazil, the academic education of engineers does not focus enough on the work environment. It is also disconnected from the expectations of the 4th Industrial Revolution industry. Given this scenario, in 2008 a movement of large companies, called Entrepreneurial Mobilization for Innovation (MEI), coordinated by the Brazilian National Confederation of Industry (CNI), started to work for the improvement of engineering education in Brazil, in line with the agenda of international trends.

In 2019, the work of MEI, together with ABENGE (Brazilian Association of Education in Engineering), culminated in the reformulation of the 2002 Engineering DCNs [22]. The new DCNs propose a new institutional organization for curriculum, stimulating a diversity of learning forms. The idea is to extrapolate the traditional classroom, in order to guarantee the interaction of teaching with research and extension activities, as forms of learning, and to promote active teaching methodologies [1].

These guidelines seek to create an environment, in undergraduate courses, that allows students to exercise entrepreneurship inside or outside companies, with a greater potential to develop their talents, skills and abilities [2]. With this aim, some suggested strategies are: to create flexible and student-centered curricula; to emphasize the development of competences expected from graduates; to encourage the adoption of active learning methodologies (applied knowledge); to ensure collaboration between universities and companies, with the idea of bringing courses closer to the market; to develop multidisciplinary programs; and to combine classroom and distance activities [22].

The path in Architecture and Urbanism was similar. In 2013, meetings organized by the Brazilian Association of Architecture and Urbanism Teaching (ABEA) promotes discussions on the rebuilding of the DCNs created in 2006 [23] and amended in 2010 [24]. Later, after 2018, discussions continued in the Education and Training Committees of the Brazilian Council of Architecture and Urbanism (CAU/BR). In 2019, a new proposal for DCNs of AU undergraduate courses was put forth.

As for Engineering, some of the main changes proposed for Architecture and Urbanism seek to draw attention to the following aspects: the use of active teaching methodologies, ensuring students' active participation in the knowledge construction process; diversification of teaching and learning environments, so that students have professional experience in the labor market and collaborative inter-professional practices; and the possibility of curricular flexibility, which allows the search for innovation inherent in the AEC area [25].

It should be noted that the concept of Industry 4.0 is understood as the current approach to changes in production processes and business models that employ a high degree of technology in the production chain. The goal is to guarantee increased productivity and competitiveness, generating new values and services for both clients and organizations [26]. In this context, technologies such as Internet of Things (IoT), artificial intelligence, digital manufacturing, additive manufacturing, big data and cloud computing are fundamental.

In the proposal of the new DCNs for architecture, for the first time, the "Digital and Physical Modeling Processes and Tools" are mentioned as mandatory curricular content. Therefore, the DCNs introduces the obligation of at least one digital modeling and fabrication laboratory in undergraduate courses, emphasizing the importance of new technologies, disseminated as fundamental concepts for Industry 4.0 and for all Architecture and Urbanism activity. This is reflected in the skills and abilities that students are supposed to develop in AU undergraduate courses [25].

As for Engineering, training in Architecture and Urbanism should also be reformulated, with a focus on professional practice, collaboration, active teaching methodologies, beyond technological education.

1.2 Graphic Expression Professional

In 2012, a bachelor's degree in Graphic Expression (CEGRAF) was created at Federal University of Paraná (UFPR). Its creation was motivated by the identification, in the industry, of a lack of communication and understanding among professionals involved in the process of design and manufacturing. Lack of technical knowledge, combined with the poor exchange of information between different professionals, caused delays, with consequent financial losses to the business [27].

There are no specific DCNs for Graphic Expression, considering that the course is currently unique in the country, as a bachelor's degree in its specific approach. Its objective is "to train professionals who work in the development of digital graphic projects, in the range of existing functions between creation and production, who participate in multidisciplinary teams" [28], in the areas of architecture, engineering and industrial products, based on the concepts of digital design and prototyping. A broad education is a requirement for such professionals, so that they can understand important elements from several areas, to communicate with different professionals, collaborating in project development processes.

Graphic Expression students were well received by the market, inside internships in modeling and digital models, project compatibility through digital technologies, and product production through digital manufacturing processes. In 2018, the evolution of labor market trends with new technologies reinforced the need to include new content in the curriculum, in line with the principles of Creative Economy and Maker Movement [29].

Therefore, the Graphic Expression undergraduate course was restructured, to ensure a greater focus on knowledge in digital technologies (such as digital modeling, BIM, three-dimensional capture and digitization, digital fabrication and prototyping, and virtual and augmented reality), beyond theoretical grounding in geometry concepts, architecture, design, and engineering. These new professionals present themselves to the market with the potential to be a part of collaborative projects with other professionals, in the fields of architecture, engineering, arts and mathematics. Specifically, considering the focus on the expertise acquired on digital modeling and prototyping technologies, we can conclude that there is great potential for complementarity with Architecture and Engineering courses, which still have difficulties in integrating such topics into their curricula.

2 Method

The proposal for a teaching method presented in this work is the result of a Design Science Research (DSR) approach. The product of a DSR is an "artifact", which is something artificial, conceived by man, carried out with the aim of fulfilling a purpose in a given environment [30]. According to [31] classification (constructs, models, methods, instantiations), the artifact developed in this work is essentially a method with a conceptual structure for using Additive Manufacturing as an integration tool for students of AEC courses.

Other research methods were used to support problem awareness, data collection, and artifact formulation. Among them, we used systematic literature review [32], action-research, beyond a survey carried out by students in 2019. This artifact is part of a doctoral thesis and will still be tested and evaluated.

3 Results and Discussion

In this section, we present and discuss the collaborative teaching method for AEC, supported by the Additive Manufacturing use, considering its elements.

3.1 Interdisciplinary Learning for AEC

The collaborative teaching method for AEC, supported by AM use (Fig. 1), is grounded on constructivist pedagogy for teaching and learning. It is also aligned with the development of competencies and skills expected of AEC professionals in the twenty-first century.

This method aims at ensuring the interdisciplinary learning of students of Architecture and Urbanism, Civil Engineering and Graphic Expression, in the light of the

Fig. 1. Collaborative teaching method for AEC supported by AM use

interdisciplinarity concept considered by Gatto [33], characterized by the following aspects: (1) to have an object in common; (2) to be searched at the same time (simultaneity); (3) by specialists from different disciplines or areas; (4) in close cooperation (collaborative work); (5) with constant exchange of information; (6) sharing the same goals to achieve an integrated analysis of the common object or problem.

Initially, the topic of study, which will be approached through PBL activities, must be defined. Such topic must be explored by the different undergraduate courses (Architecture and Urbanism, Civil Engineering and Graphic Expression), using Additive Manufacturing as a teaching tool and as an integration and stimulus factor, so that students develop their skills in communication, collaboration, problem solving, technological literacy, and autonomy, in addition to the technical knowledge necessary for their professions.

Several topics can be addressed, from which we cite a few.

One possibility is Building Information Modeling (BIM). BIM is strategic for the development of the AEC industry, considering the efforts of the Brazilian Federal Government, which launched the National Strategy for the Dissemination of Building Information Modeling in Brazil in 2019 [34]. The program seeks to promote a suitable environment for the investment in BIM, ensuring its diffusion in the country. In addition, it has great adherence to the innovative technologies of Industry 4.0 (such as Additive Manufacturing), in search of modernizing the civil construction industry. However, Brazilian undergraduate curricula still require rebuilding for the effective implementation of BIM. At UFPR, for example, the only undergraduate course with a specific mandatory discipline about BIM is Graphic Expression.

Another possibility is “structural systems”. According to [35], the importance of teaching the theory of the subject in Civil Engineering courses is settled, but the focus is quite technicist, based on activities of calculation and on the analysis of structural dimensioning. Engineering students end up having difficulties in the previous stage, which encompass the structural conception and establishment of structural arrangements, an activity that requires intuitive and creative skills.

On the other hand, the authors state that “the teaching of structures seems to remain deficient in Architecture courses” [35] (p. 184), even though it is the subject of recurrent research, publications, and even specific events, such as the National Meeting on Teaching Structures in Architecture Schools (ENEEEA). In any case, it is undeniable that the structural design is a fundamental stage for architectural design. Therefore, architecture students need to master the use and functions of structural systems. Although this is not a specific topic addressed in the Graphic Expression undergraduate course, it leads to several approaches that involve knowledge in the area, considering both the representation and the technical point of view of calculation.

The physical experimental model is the most discussed and recommended resource in seminars, meetings, lectures and published papers on the teaching of disciplines in the area of structures [35]. It allows a real visualization of the phenomena, demonstrating concepts in an intuitive, reliable, and tangible way. This scenario assures us that uniting such concepts with Additive Manufacturing is an appropriate strategy to expand collaboration between the different courses we have exposed.

To make the application of the proposed method tangible, we sought a theme that would work on the importance of understanding “construction systems”, so that students could explore the concept of BIM in the future. We believe that it is essential to understand how a building is built, so that it is possible to work well with BIM.

In conclusion, we chose “architectural details” as the central topic of learning. It is a small piece of the whole, but it characterizes and defines the entire building. "Indeed, detail is architecture at its smallest size” [36].

The connection of different materials leads to several problems that must be solved by the designer. It is common in academia to approach such topic only with 2D drawings, an abstract representation, but students need, first, to understand the function of 3D elements in their context. By working with 3D printed models, students can simulate how to build, understand the relationship of elements, and visualize them spatially.

3.2 Conditions and Academic Motivation

To develop a successful method, firstly we need right conditions. It is necessary to have an environment focused on students, in which they will have an active role in their learning and will be able to act, discuss, problematize, and analyze their actions. According to Elmôr Filho [37], an active learning environment should be a common place where students and teachers are cognitively active, in order to actively participate in reflective, interactive, collaborative and cooperative activities. It requires the commitment of all students, but also of the teachers, to conduct the activities in a way that all students feel valued and welcomed by the group.

Also, it is important to consider that getting students from different areas to solve a problem within time constraints can be a stressful experience [38]. Thus, it is important to ensure students' motivation. Academic motivation is a process that is perceived both by actions (e.g., attention, effort, persistence) and verbalizations (e.g., "I like biology"), through which goal-directed physical or mental activities are instigated and maintained [39].

All things considered, we used the MUSIC Model of Academic Motivation, developed by Jones [39], to support our method. This model is grounded on a social-cognitive theoretical framework and seeks to increase students' motivation, to allow greater student learning. It consists of five components that ought to be considered when designing a course: (1) empowerment, (2) usefulness, (3) success, (4) interest, and (5) caring.

Empowerment. It considers the amount of perceived control that learners have over their learning. It relates to students' autonomy and the perception of both a high level of freedom and a sense of choice over their actions during an activity. It varies from student to student, since it depends on several variables, including content difficulty, student's skills, beyond the student's previous experiences with the content. But the essential factor is "that students must believe they have *some* control over *some* aspect of their learning" [39].

Usefulness. Students must understand why the activities are useful for their education and how they will use them in their professions and lives. Studies show that students are more motivated when they have long-term goals in mind, compared to students that have only short-term goals [39].

Success. Students must believe that their efforts will be valuable for their future. This aspect is related to their self-perception of competence, that is, that their knowledge and skills are sufficient to complete given tasks. If they believe they will succeed, they will try harder and persist longer in the activity. They will also be more resilient in the face of difficulties. It is important to make all course objectives clear, providing clear and understandable assessment criteria, beyond accurate and honest feedback [39].

Interest. Topics and activities should be interesting to students. The idea of interest consists of two components: an affective component of positive emotion (the liking) and a cognitive component of concentration (the engagement). This relates to attention, memory, comprehension, and deeper cognitive engagement. Hands-on activities and contents that relate to students' background knowledge are useful strategies. It is also important to incorporate other components of the MUSIC model, which can promote individual interest [39].

Caring. This concept is related to the students' perception that the instructors care about their learning and that they desire to impact their lives positively. There are several terms to refer to the concept of caring, such as sense of community, bonding, attachment, involvement, and commitment. In this context, the instructor behavior is determinant. It is important to listen to students' opinions and ideas, devote time to help students, and show concern and interest in students' personal/professional lives.

3.3 Teaching Tools for Active Learning

Teaching tools include everything that helps in the teaching–learning process. Especially active learning approaches demand a variety of tools in order to ensure success. It is important to evaluate the goals of a given teaching activity and the type of learners when choosing the most appropriate tool to meet specific learning goals [40].

Our method is based on the use of three teaching tools: Project-based Learning (PBL), Collaborative Learning (CL), and Additive Manufacturing.

The PBL (Project-based learning) approach is a student-centered pedagogy that involves interdisciplinary teaching–learning activities in an active-collaborative learning environment. Students are tutored by qualified teachers, developing in-depth knowledge by answering to real-world questions, problems, and challenges. The classroom becomes an open space for ideas, knowledge, languages, and realities, stimulating conversations and generating bonds. The problem approach allows students to grow individually and collectively in their learning experience, through the construction of meanings that generate reflections, giving new significance to their experiences. Through this method, students become managers of their learning process [11, 41].

Teaching AM through the PBL approach is common practice. Authors [32] identify numerous works that use AM in higher education, by putting together students from different undergraduate courses with the support of a PBL approach, with the aim of promoting students' engagement with their learning. In addition, the method helps to bring teaching closer to students' reality, culminating in more meaningful learning.

Collaborative learning refers to an instruction/learning method in which students work together, in small groups, towards a common goal [42]. It complements the PBL approach, given the complementarity of latent knowledge of students from three different courses (AU, CE, and GE). Students can teach concepts to each other efficiently, while they work together to solve problems. In this context, Graphic Expression students in an AEC group are important, because they have more in-depth knowledge of digital technologies, such as Additive Manufacturing.

Additive Manufacturing, as we have already pointed out, has a special use in education. It offers gains for the teaching–learning process, by combining PBL and

AM, such as greater student interest, aptitude to understand abstract concepts, stimulus for the construction of student-centered and collaborative knowledge, and the possibility of interdisciplinary integration [32].

Based on such foundations, the proposed method was organized so that students build their own learning. In this context, Additive Manufacturing is a tool that keeps them motivated to solve challenges.

3.4 Passive/Active Learning of AM

AM learning was used in both passive and active ways [43], according to the undergraduate program characteristics and objectives.

Incorporating AM passively into courses means using AM as a support tool for teaching. It makes sense to use this type of approach for AEC, since the main objective of training these professionals is not the operation of digital fabrication equipment, but the training of professionals who understand the technology, who know how to take advantage of it to solve problems, and who are able to work in multidisciplinary teams [32].

However, one of the barriers to AM adoption in teaching is the lack of familiarity with the technology [33], both by students e teachers. This reinforces the idea of including a more experienced and focused AM future professional in an interdisciplinary AEC group, such as the Graphic Expression one. The proposed method provides an active AM teaching way, in which the activities that are developed present an explicit focus on concepts related to 3D printing. Some important didactic objectives for AM are:

- Learning and applying design principles to Additive Manufacturing
- Learning AM fundamentals and basic operating principles
- Stimulating creative competence using 3D printing
- Gaining experience in the operation of AM machines
- Identifying advantages and/or limitations of AM technologies

3.5 Hybrid Education

Although the specific study of AM is important, the main objective of the presented method is the interdisciplinary integration of AEC students. In order to fulfil this goal, hybrid education should be explored. In this context, theoretical and more introductory contents could be addressed with extra-class activities at distance, using video classes, beyond materials that support students in hands-on activities. This allows Architecture and Civil Engineering students to delve deeper into AM, in case they are interested. Most of class (or laboratory) time can be used to explore the development of skills and knowledge through practical experiences in groups [32].

In Table 1, we present AM contents explored at distance and in laboratory.

Table 1. Hybrid education of AM contents

Approach	AM Contents
Distance learning	AM Fundamentals
	Fundamentals in 3D printer operation
	Design for manufacturing (DFM)
Laboratory	Study common objects using AM as a tool
	Stimulate creative competence
	Gain experience in AM operation
	Identify AM advantages/limitations

3.6 7-Step Pedagogical Model

To ensure the best development of the activities proposed in the collaborative teaching method for AEC students, we recommend 7 steps (Fig. 2), based on the "Pedagogical Model for Introducing 3D Printing Technologies" [44]. This pedagogical model is grounded on a classic instructional design theory, the "Conditions of Learning" [45]. According to Gagne, there are nine instructional events that must be followed when designing a course. Each instructional event is related to a specific cognitive process.

Also, we relate to the instructional events in which categories of academic motivation [39] should be explored, considering the kind of hybrid education strategy that can be adopted and the staff that should be involved in each step.

In this model, the subject of "constructive architectural details" was considered a common object of study. However, it can be applied to any chosen topic, as previously mentioned (e.g., BIM, structural systems, didactic models). As an example of an activity, students should build 3D printed physical models that represent constructive architectural details of iconic buildings.

Before analyzing the 7 steps, it is important to note that interdisciplinary groups must be balanced in terms of number of members and technical background. It is assumed that most architecture and civil engineering students have no knowledge in 3D printing. Thus, graphic expression students should at least have knowledge of the basic principles of additive manufacturing.

Another decisive factor is the need for knowledge in 3D CAD/BIM modeling to work with AM. Therefore, it is recommended that instructors carry out an initial questionnaire to assess students' abilities, so that they create groups in which at least one member has more experience or more advanced skills. These "advanced" students will be able to share their knowledge with the groups (collaborative learning).

The first step is to get the attention of all participants. In order to fulfil this objective, the instructor can present the course, with samples of what was developed in previous editions. To present the importance and usefulness of the topic, a professional can be invited to lecture on the common object chosen to be studied.

Next (step 2), the instructor must define the objectives and expectations of all activities. This is important for students to realize they will be able to complete tasks with the skills they already have and/or will develop in the process. To guarantee

Step	Pedagogical Model for Collaborative Education Method for AEC Supported by the AM Use	Nine Instructional Events [Cognitive process] (GAGNE, 1985)	Music Model of Academic Motivation (JONES, 2009)	Hybrid Education	Staff Involved	Remark
1 GAIN ATTENTION	Instructor presents the course and exposes similar works already done. Instructor or professional guest lectures on constructive details (object of study). Groups of 3 to 6 students, if possible, at least one from each AEC undergraduate course	1. Gaining attention [reception]	Usefulness, Interest, Caring	In-person classes / Online meetings	Instructor, Invited professio-nals	Instructor divides groups based on each student's skills and knowledge. Seeking to mix beginners and advanced students. Activate motivation by presenting the importance of activities applied in professional life.
2 EXPLAIN GOALS	Instructor explains goals. Lectures on constructive details (object of study), AM fundamentals, basic settings for 3D printing and Design for Manufacturing (DFM). Students choose constructive details they will represent (object of study).	2. Informing learner of the objective [expectancy]	eMpower-ment, Success, Interest	Online meetings, Recorded video classes	Instructor	Activate motivation by making it clear what the expectation of the activity is, the importance of the content for their professional life and giving students autonomy to choose situations they want to deal with or solve.
3 HELP WITH SOLUTIONS	Instructor/tutors assist teams in developing solutions, acting as a consultant, without saying if there is "right" or "wrong".	3. Stimulating recall of prior knowledge [retrieval] 4. Presenting the stimulus material [selective perception] 5. Providing learning guidance [semantic encoding]	eMpower-ment, Caring.	Laboratory	Instructor, Tutors	Instructor should encourage the generation of options so the students themselves can assess the best solution to the problem.
4 REVIEW SOLUTIONS	Students create/review the 3D modeling of their solutions with a focus on Design for Manufacturing (DFM). If necessary, with the help of advanced students or course monitors.	[semantic encoding]	eMpower-ment, Interest	Laboratory / at home	Monitors, Advanced Students	Self-learning and Collaborative learning approach to provide flexibility to suit individual student's learning style and need. "Advanced" students can assist with orientation.
5 ADVISE WITH DIFICULTIES	When students encounter technical difficulties, they can seek assistance from the instructor, tutors or monitors who do a conference on the DFM rules.	5. Providing learning guidance [semantic encoding] 6. Eliciting performance [responding] 7. Providing feedback [reinforcement]	Success, Caring	Laboratory	Instructor, Tutors, Monitors	Students with weak technical skills can receive extra help. **Repeat step 4 if need**
6 EVALUATE CONSTRUC-TABILITY	Students present their design proposal and 3D printing planning of the model to instructor or lab manager/monitors who evaluate constructability and printability.	8. Assessing performance [retrieval]	Success, Caring	Laboratory	Laboratory Manager, Instructor, Monitors	It is very important that the laboratory maintenance is up to date and the support of monitors/lab manager to monitor the prints.
7 PROTOTY-PING AND DISCUSSING RESULTS	Responsible for the 3D printers generate the teams' printing planning in order to group several pieces. Students receive their 3D objects and perform the final assembly and present it to everyone. Instructor evaluates the result together with all students, mediating the discussion.	9. Enhancing retention and transfer [generalization]	Success, Interest, Caring	Laboratory	Laboratory Manager, Monitors, Instructor	Batch printing reduces time-consuming printing. Share different experiences to solve the same problem. Hear the students' opinion about what were the biggest difficulties, what they would do differently, what were the lessons learned.

Fig. 2. 7-step pedagogical model for collaborative teaching method for AEC supported by AM use

the necessary theoretical knowledge, at this stage, recorded classes can be produced for students to watch outside class hours. Students can absorb the content according to their need and availability. When dealing with AM, we suggest that at least three themes be explored: AM fundamentals, basic settings for 3D printing, and Design for Manufacturing (DFM).

After completing this theoretical conceptualization phase, teams choose what they will represent. Each team chooses at least three references. The instructor should guide which ones could create more difficulty during the process and/or improve results. Nonetheless, students must have some control over the tasks.

In step 3, it is time for a considerable amount of teamwork. Students must develop 3D models that represent their architectural details. They will need to: use their knowledge to understand the functions and relationships of each constructive element; conceive a three-dimensional visualization from, usually, two-dimensional drawings; and plan their model considering DFM rules – that is, observing the needs, facilities and difficulties of 3D printing and assembly.

Instructors, or guest professionals who can act as tutors for the teams, must accompany the development of solutions, but never state whether something is right or wrong. They should point out problems or difficulties that students may face, encouraging the rapid process of prototyping solutions and exploring the benefits brought by the use of 3D printing.

In the next step (step 4), students are given a moment to review their proposals and exercise collaborative learning and autonomy. They must review their solutions and analyze the 3D models with a focus on Design for Manufacturing (DFM) rules, retrieving the concepts presented in theoretical and distance classes. Especially, they should prioritize a large base for better adhesion to the printing bed and avoid thin cross-sections in the lower section, as the fast movement of the 3D printer can generate vibrations in the piece and its eventual break during the process. The projecting of elements that are not supported by a previous layer should be designed with a maximum angle of 45º to the vertical plane [46]. Advanced students can help teams with a critical look.

When students encounter technical difficulties, they can seek assistance from instructors, tutors, or monitors (step 5). Now, the instructor can guide the students, indicating the best practices for the process of manufacturing, considering that, in this phase, experience with 3D printing is highly important. Attention should be paid to individual difficulties. The instructor ought to dedicate more time to the ones that present greater difficulties. If instructors deem it necessary, they can invite students to repeat step 4.

In step 6, students present their design proposal and their 3D printing planning to instructors or laboratory manager/monitors, who evaluate their work in terms of constructability and printability. Authors [47] refer to the "manufacturability analysis" (or "constructability analysis") for AM as the need to evaluate specific factors, such as: build volume, minimum feature size, amount of support material, printing time, estimation of surface roughness, and build orientation.

Finally (step 7), the responsible for the 3D printers in the laboratory receive the models and generate the print planning for the teams, with the aim of grouping several parts in a single print, in order to reduce printing time. Students should follow the process in accordance with instructions given by monitors or lab managers. Later, they must finish the assemblance of their physical models and present them to the class.

The instructor conducts an evaluation of the results, together with the class, mediating a discussion. This learning community should share different ways to solve the same problem, listening to students' opinions on the main difficulties faced throughout the process, considering what they would do differently and what lessons were learned. Also, it is important to share students' feedbacks with everyone, due to the importance of integrating students from different AEC undergraduate courses.

4 Conclusion and Future Work

We presented a proposal of a collaborative teaching method for AEC, supported by Additive Manufacturing, that should be used by educators to integrate different students, in order to stimulate educational experiences, as close as possible to the professional practice.

Additive Manufacturing allows the approach of different contents in a practical and tangible way. In addition to being an important technology to be included in the civil construction area, with the precepts of industry 4.0, AM enables several gains, allowing greater student engagement with their education.

In summary, our method is based on three major components: interdisciplinarity, technology, and people. An important part of success relies on the fact that people must be motivated to learn, to collaborate and to be active actors of their own education. Given this context, we present ways to ensure that possibility, by working with the seven steps of our method, with the MUSIC model of academic motivation.

Furthermore, we expect that collaborative educational experiences bring together other professionals who are not used to being part of the AEC area, but who have great potential to optimize processes, by including new technologies, such as Graphic Expression professionals.

This work is part of a doctoral research. The next steps are the application of the method in interdisciplinary courses, followed by its validation.

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Development of a Safe and Anthropomorphic Drone in an Interdisciplinary Research-Oriented Construction Management Course

Gilles Albeaino, Sebastian Paulis, Masoud Gheisari, and Raja R. A. Issa

Abstract This paper discusses a recent educational effort to develop interdisciplinary educational projects within the construction curriculum through a research-oriented undergraduate honors course. Second semester freshman honors students from different fields (e.g., construction, architecture, engineering, computer science) developed a social drone featuring anthropomorphic characteristics and safety features that could enable safer, user-friendlier, and improved onsite human-drone collaboration and interaction in the future. First, a group of interdisciplinary undergraduate students were asked to perform an exhaustive literature review to identify: (1) drone applications in construction equipped with onboard sensors to perform data collection; (2) safety-related challenges that drones could encounter on jobsites; and (3) anthropomorphic characteristics (e.g., facial expressions) and features that have been used in the fields of human-drone interaction (HDI) and human-robot interaction (HRI). Based on the retrieved information, students were then asked to develop a social drone design concept considering safety (overcoming typical safety challenges found with regular drones used in construction), anthropomorphism (making the design more user-friendly), and capability to accomplish the same construction tasks as its previous non-social models. Upon model conceptualization, students had to rely on 3D modeling software packages and Virtual Reality (VR)-compatible game engines to program and bring their designed social drone model to life within a VR

G. Albeaino
Department of Construction Science, Texas A&M University, 3137 TAMU, College Station, TX 77843, USA
e-mail: gilles.albeaino@tamu.edu

M. Gheisari · R. R. A. Issa (✉)
Rinker School of Construction Management, 573 Newell Dr, Gainesville, FL 32603, USA
e-mail: raymond-issa@ufl.edu

S. Paulis
Herbert Wertheim College of Engineering, University of Florida, 1949 Stadium Road, Gainesville, FL 32611, USA

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environment. Through critical thinking, students were provided with an opportunity to actively collaborate with peers from different STEM fields to evaluate information gathered from the construction, HDI, and HRI literature, and apply the acquired theoretical knowledge to design, develop and program a safe and anthropomorphic social drone.

Keywords Drones · Safety · Construction education · Robot anthropomorphism · Interdisciplinary and collaborative work · Undergraduate research

1 Introduction

Interdisciplinary work takes into consideration diverse skills, topics, and tasks to account for specific academic subjects while collecting related information across different fields. Whether through structured classroom activities, capstone projects, or competitions, educators have long realized the importance of interdisciplinary and collaborative type of work and have been promoting to a certain extent, collaboration, and group work in their day-to-day courses [5]. This allows students, particularly those seeking Science, Technology, Engineering, and Mathematics (STEM) degrees, to simulate what they are most likely to encounter or deal with upon graduation, emphasizing the importance of knowledge retention, engagement, and scalability towards the real world. Not only does interdisciplinary group work incentivize growth in academic fields but it also increases awareness for new technologies that are rapidly being integrated in the workplace [7]. Indeed, STEM graduates need to work together to achieve one common goal: finding innovative solutions to complex real-world problems.

Construction Management (CM), which involves stakeholders and professionals from overlapping fields (e.g., construction, management, architecture, engineering) and backgrounds, with commonalities and differences in their skills (e.g., communication, leadership, creativity, independence, trust), is one of those fields that benefits from interdisciplinary academic efforts. For example, through an interdisciplinary approach integrating Building Information Modeling (BIM) in the Construction Management and Engineering (CME) curriculum, Demirdoven (2015) demonstrated how the implementation of collaborative BIM education is associated with improved overall student satisfaction and preparation for leadership roles in construction [1]. Another study combining BIM and interdisciplinary projects to achieve higher levels of depth in academic trainings yielded positive results when observing how sustainable design options were analyzed earlier through student collaboration [4]. In the engineering domain, Molina et al. (2014) have implemented Unmanned Aerial Vehicle (also referred to as drone) projects with quadrotor limitations in curriculums, providing students with hands-on experience and demonstrating the effectiveness of collaboration in the classroom [6]. A very recent study [2] also implemented interdisciplinary efforts with modern technologies and projects, focusing on the student's engagement to reach greater levels of understanding and ability with "soft skills" for a variety of fields. By prioritizing the professional experience in collaborative efforts with many backgrounds, students were capable of translating their abilities into a more real world simulated situation. This highlights the importance of combining interdisciplinary work with academic teachings towards STEM fields in general, and construction in particular.

The purpose behind this study is to reflect on the outcomes of a case study conducted in a research-oriented undergraduate honors course with the aim of promoting interdisciplinary and collaborative type of work among students of different STEM disciplines. Many studies have explored collaboration and interdisciplinary work in construction education [1, 5], this project challenged a set of diverse students to rely on their knowledge acquired from the tools and concepts covered throughout the course, the findings of their own research, and their wide-ranging yet overlapping backgrounds (e.g., construction, architecture, engineering, computer science), and apply this knowledge to solve real-world problems while meeting internal and external deadlines. This ultimately challenged their decision-making and critical thinking capabilities and, through interdisciplinary information- and knowledge-sharing, exposed them to a wide variety of new theoretical and practical tools and technologies, some of which have not been previously explored in construction and could otherwise be too difficult to acquire in discipline-specific courses. More specifically, the project involved developing a social drone with anthropomorphic and safety characteristics that would enable safe human-drone collaboration and interaction on construction jobsites. This required students to: (1) perform literature search to identify current drone design limitations and understand different configurations being used in construction; (2) conceptualize and design drone models while taking into consideration the findings of the literature search and the goal of the project; (3) develop the finalized platform design (including all the components and features) using 3D modeling software; and (4) integrate the 3D drone model into VR-compatible game engine and program it to simulate real-world platform movement in the built environment, ultimately allowing them to further develop their skills and accomplish their shared goals.

2 Methods

2.1 Course Description and Project Integration

The interdisciplinary project was integrated in BCN4905: Special Studies in Construction, a dynamic and research-oriented undergraduate honors course that provides second semester freshman honors students from different disciplines (e.g., architecture, engineering, construction, computer science) with the opportunity to collaboratively find solutions to different problems. The course focuses on enhancing students' understanding of how advanced construction technologies can be used in CM to improve the performance and productivity of construction processes. It also introduces students to modern automation techniques and applications within the construction industry. The course is divided into two main parts. The first part, which accounts for approximately 70% of the semester, was dedicated towards direct exposure to topics and technologies used in construction. The covered topics mainly include: (1) Building Information Modeling (architectural modeling); (2) Simulation and Reality Capture (creating animations and 4D simulations, as well as generating point clouds and conducting comparative analyses using laser scanning and drone-mediated photogrammetry); (3) Virtual/Augmented/Mixed Reality—VR/AR/MR (exposing students to a variety of applications); (4) computational design (introducing generative and parametric design); as well as (5) robotics, automation, and 3D printing. Through these diversified technologies, the students received introductory experiences with modern practices while learning about processes and critical criteria when discussing the techniques and solutions used in construction. This ultimately provided them with opportunities to explore their own connections with respect to each technology/subject, promoting higher levels of growth in interdisciplinary skills. The other part of the course requires students to allocate a large portion of their time towards a technical interdisciplinary project revolving around and applying in-class topics and their diversified perspectives to solve a particular problem within the construction industry.

The aim of the Spring 2022 student project was to explore drone anthropomorphism and safety in construction. More specifically, students were asked to develop a social drone, featuring anthropomorphic characteristics and safety features that would enable safe human-drone collaboration and interaction on construction jobsites. The increased adoption of drones in the Architecture, Engineering, Construction, and Operations (AECO) domain, this technology has been associated with several increased safety risks (i.e., physical risks, attentional costs, negative psychophysiological effects) that could jeopardize its usage on jobsites [3]. The goal was to develop virtual drones with anthropomorphic characteristics and safety features to improve construction professionals' perception of these aerial platforms and potentially reduce the risks associated with their presence on jobsites. Students were asked at first to collaboratively perform an exhaustive literature review to: (1) identify all drone applications in construction together with the sensors used to perform data collection; (2) identify all the safety-related challenges that drones could encounter on jobsites (which potentially cause hazardous situations); and (3) identify the anthropomorphic features/characteristics used to design drones from the human-robot interaction (HRI) and Human-Drone interaction (HDI) literature. Based on the identified information from the literature, students were then asked to develop a drone design prototype that: (1) is capable of being fitted with any of the data collection sensors typically used in construction (to accomplish same construction tasks as its previous non-social models); (2) is considered safe (overcoming typical safety challenges found with regular drones used in construction); and (3) has anthropomorphic characteristics (to make it social and more user-friendly). The project criteria were broken down to several requirements, encouraging students to implement different approaches, processes, and technologies to collaboratively achieve the final product. The project steps included: Literature Review, Conceptual Design, 3D Model Development, Virtual Reality Implementation, and Project Presentation. Through these five major steps in the timeline of the project, students were given the opportunity to work in different environments, promoting the use of different skills, including: discovery, comprehension, creativity, communication, computer programming, 3D computer-aided design, art, and scientific writing. By breaking down the structure of the project in this manner, students would not only learn about the current status and requirements for drones in construction but would also develop knowledge and strengths in more fields besides construction (e.g., in critical thinking, innovation, physics, human-robot interaction, psychology, culture, safety, feasibility versus theory, and perception).

3 Results

3.1 Literature Review

The literature review involved a variety of topics for the students to consider, e.g., drone applications in construction, data collection sensors mounted on drones, challenges associated with drone usage in construction, drone physics and configurations (including software and hardware components and materials). The first step of the literature review was to identify the different drone applications (i.e., progress monitoring, site planning, site mapping and surveying, earthmoving, building inspection, safety management, building maintenance, post-disaster reconnaissance, aerial construction, security surveillance, material handling, and site communication), and sensors (i.e., Red-Green-Blue and Thermal cameras, Light detection and ranging devices and Laser scanners) used to collect information (i.e., images, videos) on construction jobsites. The safety challenges affecting drone usage in construction were then identified, and all these factors (i.e., drone applications, drone sensors and design, safety challenges, anthropomorphism) were taken into consideration, under different drone tasks and scenarios, in the next steps of the drone design. For example, in the case of drone collision, the aerial platform may descend rapidly on a civilian or worker, requiring safety measures to reduce vertical collision forces; the drone may collide horizontally with a civilian in the event of a malfunction, requiring safety measures to reduce horizontal collision forces. In addition, the drone needs to have the capability to interact with civilians and workers in some fashion to execute safe maneuvers and promote healthy interactions and safety, keeping workers from feeling threatened or in danger and ensuring safe human-drone interaction on jobsites.

This method of placing a high value behind the interaction between students of different backgrounds and disciplines allowed them to develop a body of knowledge that would support their future endeavors. The students read, interpreted, cited, summarized, and sectionalized the literature review for each topic, encapsulating the unique aspects of the topics while considering the overlap between them. The literature review covered high level interactions between topics and their specific relevance to each other. By performing the literature review, students were able to strengthen their ability to analyze and synthesize large amounts of data in a short period of time and coordinate actions for knowledge discovery amongst their group. These skills not only benefited the literature review but were also used in other collaborative tasks, like designing, modeling, virtual implementation, and presentation.

3.2 Conceptual Design

After performing the literature review and collecting background information, the students listed their requirements and objectives for the drone and proceeded to iteratively sketch new designs with their criteria. Each set of sketches involved labels to symbolize the function or purpose of the interconnected components and were visualized from multiple perspectives. After every iteration, the students would discuss amongst one another how different aspects of the current design could be enhanced to better suit the problems. After internal discussion, they would present their most recent version of their sketches to the instructors. By doing so, new perspectives and points of clarity were brought up as part of the student-student and students-instructor conversations. With each discussion, new changes were listed, and the students would create new designs to fulfill their change logs. By performing this design and review process, students were able to consider a wide variety of perspectives from peers and literature context, as well as acquiring "soft skills" involving receptiveness and willingness to change and adapt to new information and ideas. These soft skills impacted the effectiveness of collaboration when progressing through future stages of the project. This iterative process led to the final selection of the drone's capabilities and conceptual design, incorporating several safety and anthropomorphic features, which are summarized in Table 1. The final conceptual design of the drone is shown in Fig. 1. The overall design included, in addition to typical drone components, modular ligaments, parachutes, airbags, rotor guards, obstacle avoidance systems, modular sensor mount, animalistic shell, as well as built-in input/output sensors for human interaction. The required sensors had contextual support from computer science requirements, safety requirements, and anthropomorphic characteristics selected through the interdisciplinary efforts.

3.3 3D Model Development

With thorough sketches, the students implemented the 2D representation of the drone into a 3D environment using Autodesk® Fusion 360 as their selected software. Through the support and context of both, the literature review as well as the conceptual design sketches, the students had all high-level resources to frame the general

Table 1 Anthropomorphic and safety features incorporated in the final drone design

Features	Description
OLED Screen	Convey Emotions and establish emotional connection
Speaker	Increase understandable intention between drones and humans and improve the communication between drones and humans
Bee-like Shell	Ensure more natural interaction while relying on animal-like design
Camera	Read gestures and reactions and react accordingly
Proximity Sensors	Establish obstacle avoidance system to improve safety during operation
Rotor Guards	Increase safety and resilience of drone, pilot, and individuals nearby
Airbag Module	Decrease probability of fatality from a drone falling and reduce damaged objects in possible crashes
Parachute Recovery System	Decrease probability of fatality from a drone falling and reduce damaged objects in possible crashes
Nano-tech Batteries	Wide operating thermal range, allowing for universal use in different climates while not catching fire
Microphone/ Speaker Unit	Allows for remote communication between operator and people near the drone
LED Screen	Allows for workers to see visual representations of facial patterns and voice oscillations

parameters surrounding the model. To fulfill all environmental variables associated with the model, the students had to set low-level requirements that would progress the model to its final state. Therefore, they defined what commercial parts would serve to fulfill the drone's capabilities; each commercial part was either modeled in 3D space or obtained from a model provided by the manufacturer. With all preliminary parts modeled, the students imported all parts into a singular assembly to validate the layout of all systems relative to the sketches. At this point, the main chassis could be defined with all specific information like mounting holes, attachment mechanisms, fittings, and tolerances. Finally, the animalistic shell was modeled to mimic the defined sketches while encapsulating all components as necessary (Fig. 2). With all parts and systems created and assembled, the drone was ready for virtual integration in a game engine. By performing this 3D modeling work, students were able to better understand the steps required to prepare a project for a next phase and learned better practices for project management when dealing with new environments. Also, students got to gain first-hand experience with modern 3D modeling and design technologies like Autodesk® Fusion 360.

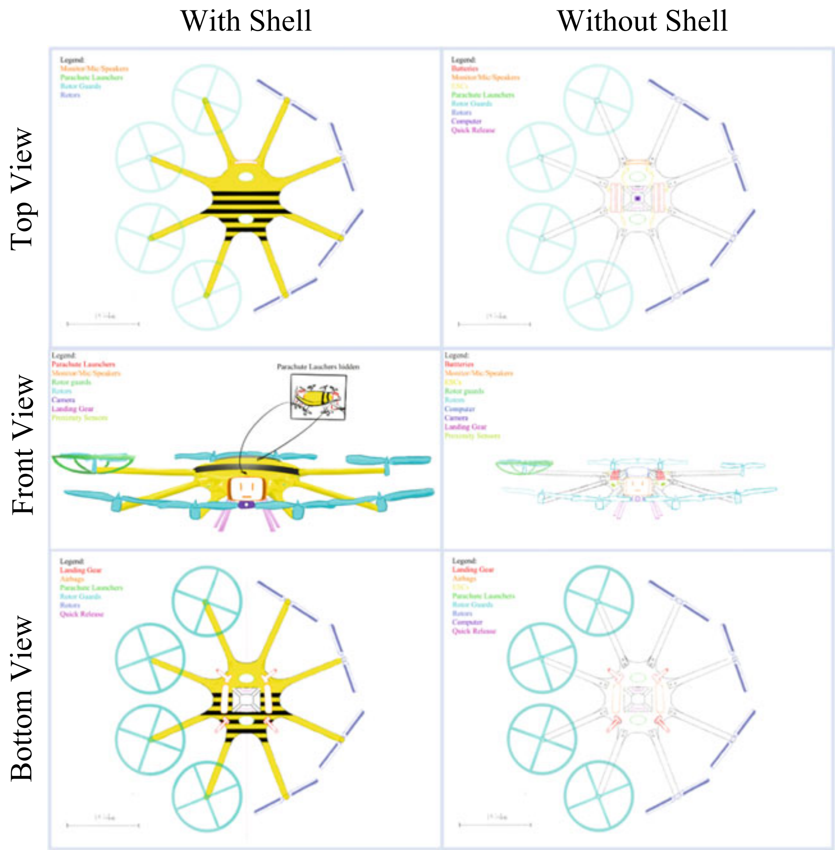

Fig. 1 Conceptual drone design

3.4 Virtual Reality Implementation and Drone Integration

The students selected Unity® as their game engine to serve as their intermediary between the digital model and VR. As new models were finalized, they were exported as compatible files and given animations with controls in a virtual environment. With a modeled drone, a realistic environment was best suited to symbolize a real-world scenario of a drone on the built environment (Fig. 3). The students utilized all resources?? to enhance the virtual implementation of the drone, interconnecting the information from the literature review with all parameters defined in the sketches and models as well as demonstrating programming and model skills alongside their communication and organizational workflow. Through the integration of the environment with drone controls, simulations of accidents, actions, features, and achievements were recorded and visualized as the final project result to be presented at the end of the semester.

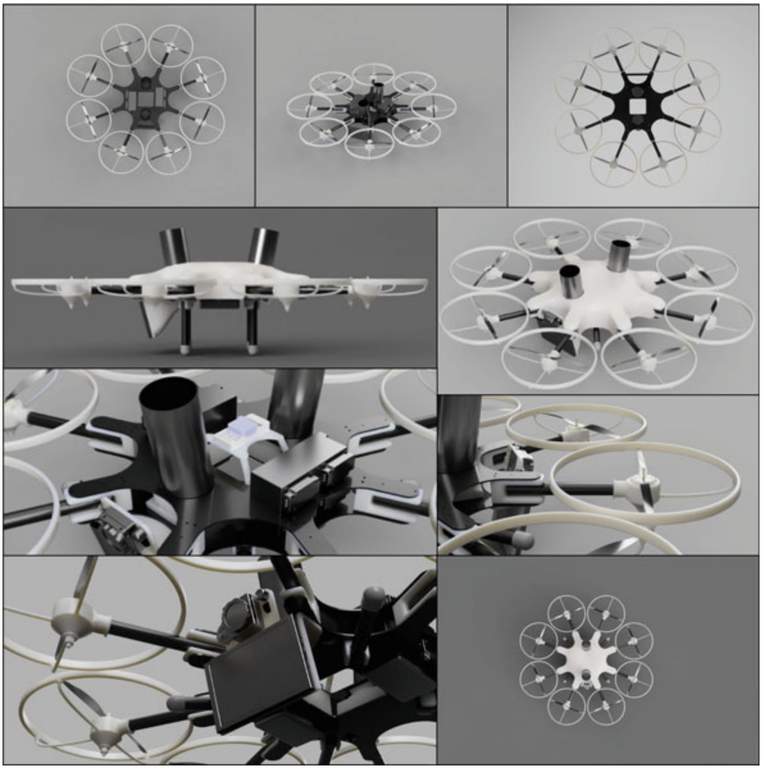

Fig. 2 Developed 3D drone model

Fig. 3 Unity® game development and drone integration

The students took a stepwise approach towards the implementation of the Unity® environment with the previous developed material. Multiple aspects were considered when producing the final product: models, physics, controls, automatic interactions, and outputs. After importing the models, each model was colored, scaled, and configured with their appropriate physical properties: collision, gravitational influence, and custom scripts. Once physical collision metrics were established and tested, the drone was programmed with controls for both manual and automatic functionality. Then, features were added to provide visible and audible interpretation of the drone's capabilities: propeller and collision sounds, obstacle avoidance detection, drone checkpoint system, and startup/shutdown procedures. By performing this virtual environment implementation, students were able to increase their ability to adapt their skills to suit new technologies and how to transpose prior work to updated integrations. They also gained experience using game engines like Unity® alongside sound generation software for virtual effects. Finally, simulations were produced with parameters that would demonstrate the drone's features for presentation purposes.

3.5 Project Presentation

To finalize the project, the students presented their work to the instructors of the course. By bringing these ideas together, the presentation encapsulated all efforts from the collaboration and interdisciplinary work. It included the iterative process, starting from the literature review and ending with the Unity® implementation. Each student presented their contributions, demonstrating the collaborative process and dynamic interaction amongst the group. As with the collaboration, multiple topics were implemented in the presentation: project purpose, required sensors, safety features, anthropomorphic features, limitations, and future research. The limitations and next steps section considered many facets, discussing the project management side and technical skills/technologies required for future development. These wide-ranging explanations demonstrated the efficacy of the interdisciplinary work and collaboration in the classroom setting.

4 Lessons Learned and Conclusion

This paper reflects on an interdisciplinary project conducted in a research-oriented undergraduate honors course with the aim of encouraging group work among second semester freshman honors students from different STEM disciplines. With this implementation, the students demonstrated several notable factors influenced by the class structure. The level of involvement and interest from the students to invest time and effort towards topics like research, drones, virtual reality, game engines led to more progress over a shorter period, exceeding expectations from initial outline and allowing for more time committed towards smaller details in the process. With several technologies involved and multiple perspectives from diverse students, they considered information from multiple backgrounds in different topics influencing several sections like the literature review, modeling software, virtual requirements, factors that yielded higher quality results. The quality of work accounted for factors or features that were out of scope before the implementation of diverse technologies like digital versatility and edge case handling. This led to more efficient solution integration: sketches were produced at a higher caliber and significantly assisted the 3D modeling process, the generated 3D models easily transitioned into the Unity® virtual environment, and the simulations and renderings reflected initial expectation due to the initial planning already accounting for such needs. Not only did collaboration efforts influence the final deliverables, but the diverse topics also involved in the process led to students finding support for their decisions through multiple facets, bolstering their choices while developing a newer level of understanding surrounding interdisciplinary work.

With the outcomes of the project defined, limitations impacting several aspects were identified. Specifically, factors surrounding the study could be manipulated to produce more results or change the accuracy: class size and project duration. The class size consisted of only seven students, with four students selecting this project and forming a singular group. This meant that all data and metrics produced and analyzed resulted from the work of four individuals, which could have restricted the extent of the underlying work. With a bigger class size, more groups and results would be produced, assisting in the identification of trends, and leading to more refined conclusions. The time associated with the project was limited to one half of a semester (7–8 weeks). This short time period, although challenging students to be more effective in decision-making and critical thinking, led students to become concerned about the final product being influenced by the rapid progression of the initial outline. With a longer project duration, more correlations and validation could be generated between sections of the project with higher level of development of the overall result, and students would have more time to explore the complexity of individual topics, creating the possibility for deeper connections and understanding.

Future work could focus on these limitations. Replicating this study with more students would allow for several groups and more results to compile and compare, allowing for higher validation and accuracy. Extending the duration of the project would result in better understanding of the impact of interdisciplinary work, potentially reaching improved quality outcomes. In addition, having a higher level of student diversification would enable the involvement of more topics, increasing the interdisciplinary effort. This could be accomplished by, for example, including art and psychology students, which allow for topics like anthropomorphism and presentability to be enhanced by relying on more specialized backgrounds and experience. By manipulating the selected topics involved with drones in construction, different subsets could be focused on and analyzed when discussing the effectiveness of interdisciplinary work. Instead of focusing on building a drone specialized for construction, the focus could be on topics surrounding the human interaction aspect which would result from higher level of development in different topics like social sciences and psychology.

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The Integration of 4IR Technologies in Architectural Education for Upskilling the Workforce in the Nigerian Built Environment

Chika Okafor, Clinton Aigbavboa, John Aliu, and Ornella Tanga

Abstract There is an increasing awareness and adoption of Fourth Industrial Revolution (4IR) technologies in the Architectural, Engineering and Construction, Operations and Management (AECOM) industry. This has placed significant pressures on academia to develop and produce graduates who are equipped with literacy skills to seamlessly transit into the world of work after graduation. However, universities in developing nations such as Nigeria have struggled to integrate 4IR technologies such as visualization tools into their curricula. This study filled this gap by exploring the various 4IR technologies that are relevant for teaching architectural designs and 3D visualization in the architecture discipline. This study further explained how these technologies can be employed in architectural education to improve students understanding of the design and building processes, thus equipping them for the world of work. The objectives were achieved by reviewing existing theoretical literature on how 4IR technologies can promote the upskilling of architectural students learning. Findings from this study revealed that the integration of 4IR technologies in architectural education can enhance students understanding of the design and construction processes and upskill them for greater productivity in the industry. This study therefore recommended the integration of 4IR technologies in architecture education and generally in AECO disciplines for improved learning outcomes and employability of the students. This study also offers a reference point as well as directions for future research in exploring other 4IR technologies for technology-enhanced architecture pedagogy.

Keywords Architectural education · Pedagogy · Virtual reality · Employability · Digital skills · Digitalisation

C. Okafor (✉) · C. Aigbavboa · O. Tanga
Centre for Excellence and Sustainable Human Settlement and Construction Research Centre, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: chikanonyelum.okafor@unn.edu.ng

J. Aliu
Institute of Resilient Infrastructure Systems, College of Engineering, University of Georgia, Athens, GA, USA

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1 Introduction

Industry 4.0 has changed several important industries, including how work is done and how students are educated. For instance, it has changed the nature of activities that are currently performed manually by replacing them with tasks that are handled by machines [10]. According to Zhao et al. [53] the one who owns the newest knowledge, gets more understanding, develops the up-to-date knowledge, and creates the use-value, including more expertise will be able to obtain a higher position in the future. To create a workforce that is well prepared and qualified to work in the current technologically driven period, the education system must provide its current students with the essential and appropriate skills and competencies [10] that will make them ready for the world of work. Maintaining speed with the rapid developments in professional practice around the world is a problem for architectural education [29]. Thus universities and professional organizations have a responsibility to advance architectural education, support architectural careers, and improve the abilities of practicing architects [39]. Likewise, academia must consider continuing education, and also periodically evaluate and assess the prospective practitioners' knowledge regarding the most recent developments in architecture-related areas. These developments include the newest applications, construction techniques and materials among others that are required in advancing the AECOM [34] industry. This will motivate the students and practitioners to continue their education, improve their abilities, and self-learn in order to meet the demands of the world of work [24].

Higher education institutions (HEIs) are perceived as a center for producing skilled labour for social and international consumption. This is predicated on the idea that instruction at this stage is essential for enhancing human capital, which expands job options for graduates in the construction industry [3]. The knowledge-based economic indicators in societies are one of the true markers of developing a professional job and making a livelihood using the knowledge acquired via university education [24]. HEIs have the responsibility to continually evaluate the systems that enable architects to effectively continue their education so that they can adapt to changes in the field of architecture and in the Architectural, Engineering, Construction, Operations and Management sector as they occur. Educators frequently rely on traditional methods to impart knowledge to students, which typically involve lecturing students who are to pay attention and take in the information presented [47: 554]. New technologies may not always be adopted in this context. Tarling and Ng'ambi [47: 556] explained that new content (curriculum update) and abilities (technological skills) must be developed to stay up to date with the changing technologies in the context of education. Tarling and Ng'ambi [47: 556] also described the significance of sustainable advancement in terms of diverse pedagogies that may and should be applied in varied circumstances to accomplish deep and meaningful learning. Venter and van der Wath [49] highlight that there is a common good relationship among professional and educational environments, as emerging technological skills will need to be developed in studios if educators wish to train professionals who are proficient in these developing technologies. Demirkan [17] challenges educators to be forward planning about how to educate, train, and excite the coming generation.

Technological application in the design studio does, however, enhance interaction, active learning, and socialization, which are evident in students' acquisition of design knowledge, in certain settings like studio educational settings, according to Demirkan [17]. The student is put at the center of the learning process due to substantial progress of user modeling and personalization processes, according to Bacca et al. [12]. More so, with the advancement in technology, students are now able to work together and simulate or view the different stages of construction works in real time. The development of software, video conferencing, use of emails, online learning and other tools that facilitate better teamwork and communication during construction projects have been beneficial in this [2]. This facilitates the dismantling of social barriers between students as well as between them and academia. As a result of the fact that technologies are constantly changing, students must become familiar with the numerous types of technological and computer applications used in their fields in order to analyze, design, and communicate effectively [36]. Despite its drawbacks, emerging technologies can play a catalytic function in transforming pedagogy, as much as they can also be utilized to support the transmission of pedagogies, as Tarling and Ng'ambi [47: 270] remind educators. Technology has a big impact on how we teach and learn, yet educators who do not trust new technologies can frequently make them less effective. It is possible to criticize emerging technology as over- hyped and insignificant [7], but their relevance in the current era is revolutionary and will define how learning and the industry work henceforth.

The current study identifies the fourth industrial revolution technologies (4IR) that are relevant for teaching architectural designs and 3D visualization in the architecture discipline and how they can be employed in architectural education to improve students understanding of the design and building processes, thus equipping them for the world of work. This study is focused on architectural education and the fourth industrial revolution technologies review, identifying the 4IR technologies' that can be integrated in architectural education for enhanced students' learning outcome and also for preparing architecture students for the world of work.

Method

Secondary data was adopted to accomplish the objective of this research study. Keywords including architecture, education, built environment, and 4IR were used to search for similar literature on the IEE, ISI Web of Science, Emerald, Taylor and Francis, and SCOPUS databases. These databases were selected because they are the most well-known and frequently utilized databases for scientific study [20]. After the search, over 200 publications were found which were carefully assessed to determine their relevance to the subject of this study. A total of 65 articles were found eligible as the search was restricted to journals articles and conference publications between 1996–2022. Additionally, other 4IR publications such as [38, 53] and [26] were adapted for this study. After thorough examination, a total of 37 articles were finally considered relevant and significant for this study as they discussed the application of 4IR tools in architecture education for improved student's understanding of the design and construction process that will equip them for the workforce.

2 The Fourth Industrial Revolution Technologies in Architectural Education

Our world has undergone an enormous transformation because of the digital era. Digital tools have completely changed how architectural designs are created, as well as how structures are envisioned, optimized, evaluated, and built. However, the current advancements in computer power are forcing design and architecture to deal with new, smarter technologies and automated systems [46]. Today, digital technologies are being used more and more in architectural design. These new technologies are employed in the design process for simulation, visualisation and clash detection and in the construction phase for project monitoring and also in facility management, among other varied uses. These technologies are reshaping our societal ideas, infusing new values into our culture, and altering our way of life [46]. Demirkan [17] states that using technologies in design studios enhances interaction, active learning, and socialisation, that are reflected in students' growth of design knowledge, in certain settings, like studio educational settings. In addition, Soulikias et al. [46] stresses that the form-finding procedures are made easier by the 4IR (digitization), as well as designs which adapts to location and climate needs. A new era of computer technologies has been ushered in by the movement of media from the manual to the digital, which has profoundly altered the perception of scale and the relationship between the human body and architecture (anthropometrics) [46]. Therefore, to advance the learning and appreciation of architectural design principles, educators should ensure that students learn to draw using the traditional methods in their early undergraduate years and fully employ the BIM and other Industry 4.0 technologies in their works and projects in their second and subsequent years of study. The 4IR technologies applicable to architectural education will be discussed in the following sections.

2.1 Virtual Reality (VR)

Virtual reality is a great tool which offers students a fresh perspective and real life experience of what they are studying without even being there directly. According to Mandal [30], VR is a computer-simulated environment that enables users to engage, whether that environment is a representation of the real world or a fictional one. Additionally, Pope [38] defines VR as the use of technology to create the illusion of being in a non-existent environment. By providing information to several senses, like sight and sound, the students' brains are tricked into thinking they are perceiving a virtual object. The collaborative approach used in architecture education, which comes from the contexts of design studios and apprenticeships, is well known [38]. As teaching architecture is a visually focused profession that mixes imagination, VR technology promises an enhanced imaginative ability of the student. In the current technological age, virtual reality has become one of the methods used in architecture education in a variety of ways. VR can be employed to provide students with a form of experienced based learning where virtual tours to non-existent sites can be taken using the technology, where students are taught the construction processes without having to visit an on-going real world construction site. The utilization of VR here includes using virtual reality equipments such as headsets, and lenses and making a tour of a building model in a virtual environment [40]. Architecture is one of the fields that could profit from virtual reality as it enables visualizations of design models in 3D. Virtual reality technology was originally used to help architecture students with its ability to visualize in three dimensions, which is undoubtedly the most difficult component of architecture education [43]. This is one way that 3D software programs (such as Revit and ArchiCAD) that have influenced design in the architecture school curriculum can impact on VR (when integrated) in architectural education [40]. According to Mateu et al. [32], in the description of the virtual world, information is acquired through learning by doing in an atmosphere that creates a sense of immersion that seems real [32]. [1] opines that in architecture field, virtual reality has surpassed all other methods as the "go-to" method for enhancing a building's appearance. Virtual Reality makes the process of design analysis significantly simpler and less expensive [1].

Potential of Virtual Reality as a Paradigm for Collaborative Learning in Design Studios

Virtual Design Studio: The design studio have earned recognition for promoting teamwork up till today. By utilizing technologies like video conferencing, email, internet publishing, Web3D, and digital modeling, students gain a greater understanding of new modalities of media integration and cooperation in design practices. Virtual design studios will be beneficial for collaborative learning between institutions in various regions, with the original design studio's teamwork orientation [40]. Furthermore, students can learn without utilizing paper in these workshops. This is accomplished by giving virtual-based software, headsets, and lenses to the creators of the new virtual environments. Students can participate in designs, virtually walk through the models to access progress, review their designs' outcomes, flaws, and the details [9, 40]. Additionally, instructors use VR to access and grade students' projects. Commercial plugins are utilized to easily convert the model from the simulation software (Revit) to the VR immersive environments [48]. According to Maghool et al. [28], by simulating a building construction process for example, students can better assimilate the knowledge gained through the virtual experience. Maghool et al. [28] further opines that the LADUVR application is one of the interactive VR tools that is useful for teaching architectural detailing and the building process. This tool has three main areas of application, one for depicting the systematic process of building construction, the next for clearly showing the architectural details to learners, and the other for practice, Maghool et al. [28] explains. VR application in architectural design would provide a visualisation in real life scale of the model, thereby providing architecture students a clear view and understanding of the model [51]. VR gives the full impression of the size of the space, the room height, luminance of the space among others, affording the young designers an imaginary feel of the space. This is an advantage over the traditional 2D plan view of drawings, according to Williams III et al. [51]. In Bashabsheh et al. [13]'s case study at Jordan University, the authors developed a software for teaching the building process using VR. The process involved selecting a 2D drawing with structural details which were developed into 3D models, exported to 3D max for rendering and then imported in the VR game engine software for the VR experience. Students are able to view the design from various angles including the aerial perspective by a click of a button. According to Bashabsheh et al. [13], with a video button, the building process can be replayed by the student or a pdf download of the process can be made using the document button. Leal et al. [25] notes that the immersive environment in VR offers learners the opportunity to assess the quality of the building work. Similarly, the instructor can employ VR in simulating the building process such that the students can have a near real site experience in the virtual world. Sirror et al. [45], also confirms that designers are able to understand spatial relationships, make better choices of the building finishes, colour and texture and the aesthetics of the building generally with the use of VR. These are very relevant in architectural studies.

2.2 Augmented Reality (AR)

Augmented reality has the potential to dramatically improve interactive learning, augmented reality (AR) is a cutting-edge learning tool that is growing in popularity in educational settings. Because it may be utilized in addition to more traditional learning tools like text, photos, video lessons, and the internet, augmented reality has also made a big contribution to blended learning as its use can be combined with the traditional learning methods such as books, graphical representations, video, among others [22]. Venter and van der Wath [49] highlights that there is a common good relationship among professional and educational environments as emerging technological skills would need to be developed in studios if educators wish to foster professionals who are proficient in these developing technologies. Demirkan [17] challenges educators to be think inwardly on ways to educate, train, motivate and excite the coming generation of professionals.

Architectural Education* via *Augmented Reality

Although AR is a relatively new technology (created in the 1960s), it is a dynamic tool for training and instruction that is gaining a lot of pace. Bacca et al. [12] opines that it can help students become more motivated to learn [12]. Similarly, Lee [26] notes that AR is indeed a particularly effective technological advancement in higher education since it may enhance students' theoretical and practical understanding.

Lee [26] further asserts that augmented reality (AR) can actively engage students by incorporating rich contents from computer-generated) 3D surroundings and/or models. Gurevych et al. [19] opines that AR provides the benefit of "self-study," which raises the interest of the students in the teaching materials and, as a result, helps to stimulate a desire to use contemporary interactive media. Wu et al. [52] emphasize that AR has the ability to enhance student knowledge and skills, by improving their investigative skills and so they get a more precise understanding of the subject. According to Lee [26], AR education lends itself more to constructivist learning, where students can generate and manage the building of their own knowledge by leveraging both their prior experience and their own initiative. This can result in a genuine form of education and training where a context exists and what is intended by contextualization could be redefined by AR technologies, which can blur the lines between informal and formal environments as well as inside and outside of the classroom Wu et al. [52]. The use of AR in architecture design studios can promote learning as the incorporation of machine-generated 3D environments or models can be engaging, promoting understanding of the content as well as motivating students to learn, thereby bridging the gap between theory and practice. Riera et al. [42] developed an AR application that can be utilized on mobile phones. The authors asserts that the AR application is able to show several 3D models simultaneously, thereby making it easy for learners to make a comparison of many design options. This tool offers the flexibility of switching and flipping the model displayed. Megahed [33] opines that AR promotes interactive and collaborative learning in the architecture discipline. With AR, students are able to visualize their design in AR setting by the use of special AR HHDs and HMDs displays. The interface provides students the avenue for viewing 3D models which are incorporated in real life settings in a more imaginative way. Leal et al. [25] suggests the use of an AR application like the Skope to take the students on a site visit that mirrors a real life site visit where an explanation of building construction mechanisms and the structural components of a building are made. The AR magic book can also be employed to enhance learning, Leal et al. [25] asserts. According to Billinghurst [15], this technology will enable students to view the magic book as 3D computer-generated models popping out of the book pages. This technology can assist architecture students in visualizing in 3D. Hajirasouli and Banihashemi [21] put forward that AR can be adapted as a form of experiential learning where students apply theoretical knowledge (the building construction) in an AR environment. Therefore, architecture students in this way get a practical knowledge of the design and building process without necessarily being engaged in the industry.

2.3 Mixed Reality (MR)

Another technology that can be integrated in architectural education is mixed reality. MR essentially refers to a sliding immersion scale where, on one end, the observer is viewing reality through a machine with minimal layouts of virtual information and augmentation, on the other end, virtual reality, where there is a total immersion into the digital world with little to no reality [22]. Typically, academics refer to virtual items as superimposing, coexisting, or merging [12]. It is important to remember that augmented reality and virtual worlds are not the same thing [11]. It should be clear that AR is not like a virtual environment, in which the user is fully submerged in a created environment, but rather enhances (rather than replacing) reality [11]. AR enables interaction with virtual items that are two- or three-dimensional and merged into the real world [22]. With the help of the mixed reality technology known as Virtual Touch, students may create 3D virtual collaboration spaces and actively take part in problem solving. Utilizing this technology, students are able to set up workgroups where they can produce and share materials. Furthermore, the manipulation of real-world things can have an impact on the virtual environment because of the Virtual Touch's tangible interfaces. Students can interact and experiment in a learning environment using physical manipulations so that they may visualize the immediate effects of their actions [32, 40]. Hosny and Kader [23] opines that MR not only involves the visualisation and the auditory sense but it also arouses the student's sense of touch and feel for an all emcompassing design experience and learning. According to Hosny and Kader et al. [23] architecture students can sit round a table and are able to visualize 3D models of their design collaboratively, utilizing transparent headsets. Therefore, MR promotes collaborations and students' interactions on a project,

2.4 Building Information Modeling (BIM)

BIM is the design and simulation tool which is key to architecture education in the technologically advancing age. The implementation of BIM has various benefits for the educational sector. The easiest way to visualize building systems and components in three dimensions is learning-through-building. Digital portfolios with BIM projects are used by graduating architectural students when they apply for jobs or graduate programs as it gives them an advantage and better chances of being recruited or admitted respectively [27]. Additionally, the built environment industry employers value graduates who are knowledgeable in the most recent BIM tools and can utilize these techniques to address integrated design difficulties. Moreover, increased employment rates are one indicator of BIM's influence on BIM ready graduates [27]. In order to improve the built environment industry as a whole, BIM instruction in architecture programs strives to give the aspiring AECOM leaders learning programs that can better equip them to deal with cutting-edge technology and procedures [27]. A successful design workflow depends on being able to switch back and forth between hand sketching and BIM. At an even higher level, a BIM model's completion serves as a starting point for more complex analysis software, construction management methodologies and post-occupancy as well [27]. BIM integration in architecture curricula is cost-effective, universities cannot accomplish the change necessary to conduct efficient BIM training programs without investment and cooperation between the industry and government. According to Casasayas et al.

[16], AECOMs must be actively involved in a collaborative culture shift and establish relationships with HEIs. This will make the investment necessary for architecture graduates to gain entry to the workforce with the skill sets needed for the BIM-related employment of the future. Additionally, government support is also necessary [16]. Since BIM is an environment that allows many kinds of simulations, it can also be used as a teaching tool to teach project management using real world scenarios. It is very effective, especially when compared to more traditional methods of designing in the field [35]. Mutai and Guidera [37] points out that with the global BIM trend, it can be anticipated that there will be an expectation among AECOM professionals that construction curriculums will be integrating BIM skill development so that graduates joining the industry will have developed competencies in BIM technology.

Vinsova et al. [50] proposed a framework for fully integrating BIM in the architecture curriculum of Czech technical university in Prague. The author proposed that architecture students utilize BIM for the presentation as well as working drawings and detailing. Knowledge of BIM application for simulations, analysis and collaborations as well as for building services and structures were also recommended by the author. Similarly, Leal et al. [25], proposes the use of BIM in architectural education for teaching structural analysis and building materials properties. Furthermore, the authors opine that BIM can be utilized in assessing the performance of structures, therefore, determining the best method to be used in construction of buildings. BIM can also be used to relate the different stages of construction to students by showing the assembling of the different parts of the parametric model [25]. An advanced level of BIM learning was recommended for architecture students by Vinsova et al. [50] such that the students learn to utilize all BIM features owing to its many benefits. According to Aksamija [4], the application of the BIM levels of detail (LOD) established by the American Institute of Architects is recommended in architectural education. The LOD 100 for massing, simulation of overall dimensions and volumes, LOD 200 for simulating the building elements as a whole, LOD 300 for simulating the building elements with their precise shapes and sizes as parts for assembly, LOD 400 for modeling building elements as parts that can be assembled with precise dimensions, locations in the building and number, giving clear information for their details, fabrication and assembly and L0D 500 for modeling building elements as completed structures with precise shapes, sizes and orientation. Aksamija [4], further proposes the integration of BIM courses into core compulsory architecture courses across architecture departments due to the benefits that it offers. Similarly, Schroeder [44] proposes the integration of BIM across the architecture curriculum. Schroeder [44] stresses that learning of building components using a modular approach (creation of precise representation of a building prefabricated components) will improve students' as well as educators' conception of building materials and their assembly. The use of node based modeling software such as Dynamo for Revit in architecture schools was recommended by Schroeder [44] to analyze difficult geometries, minimize students errors and save student's time through the automation of repetitive procedures (revisions of sheets). Additionally, Leal et al. [25] asserts that BIM 4D, 5D and 6D videos can be used to teach students, scheduling, costing and site planning.

2.5 Internet of Things (IOT)

In the building industry, the practice of architecture involves other professions for decision-making, including civil engineering, mechanical engineering, and electrical, sanitary, or environmental engineering. However, the education of architects lacks a systematized foundation to connect to knowledge in fields other than the conventional ones of construction [18]. As a result, to advance in this area, knowledge integration (KI) processes is advocated. KI demands the integration of unique IoT hardware, software and devices for architectural design where user inputs are displayed within the design space. The IoT gadgets' low cost makes it possible for them to be used in many different institutions, and their quick adoption enables students to learn via discovery [8]. One of the design challenges have been the use of geometrical variables and abstractions, without taking the surroundings, constraints, and limitations of the spaces it occupies into account. A conceptual model that has the potential to transform education and move it toward intelligent education is the use of IoT as a teaching tool [18]. The IoT paradigm in architecture pedagogy will make it easier to customize devices for academic purposes and guide the users through each stage and will represent a significant advancement in the teaching of architecture. The BIM parametric modeling tool that is frequently used in architecture is the focus of this implementation in architecture education, as it lowers the implementation complexity [41]. IoT can be applied in the design development of smart homes and smart cities according to Bayani et al. [14]. This will enable better data flows and the control of the building. Furthermore, students in general including architectural students can apply IoT on a daily basis as it can be employed in monitoring the classroom and design studios air-conditioning, it helps better remote communication between students and lecturers and it is employed in promoting campus security (web cameras). IoT is also applied in providing digital campuses as it was especially utilized during the COVID-19 pandemic. The technology also improves information access for all students for a better learning environment [5].

3 Lessons Learned

The mode of teaching in architecture in Nigeria universities is still the traditional passive system, where students pay attention to the instructor and assimilate the information passed on without the infusion of technological tools. The adoption of new technologies will promote active learning whereby interactions and socializations can take place and this will result in a more efficient learning of the design process and the acquisition of technical as well as collaborative and communication skills. Furthermore, with technology integration in architecture education in Nigeria, students can learn to collaborate on design projects, perceive and understand the different phases of construction as in real site construction work processes. The simulation softwares, video conferencing applications, use of email, e-learning and other project collaborative and communication tools has been instrumental in achieving this in the developed country context. Some school of thoughts in academia opine that in order not to lose the sense of application and to have an appreciation of the architectural design principles, architecture educators still advocate for the learning of hand-drafting and sketching in the early design years of architecture students' education and the uptake of technological design and simulation tools in the following years to ensure that HEIs produce well-grounded architects for the twenty-first century Architectural, Engineering and Construction, Operations and Management industry. At the technological level, BIM, VR AR and IOT can be applied for enhanced learning outcomes as well as in preparing architecture students for the digitally advancing world.

As teaching 3D visualizations with 2D representations is often difficult for educators and understanding of the concept difficult for undergraduate students in their early study years, VR integration in architectural design studio will be beneficial. VR application in architecture design studios creates the impression of a virtual studio, which is paperless, where students can try several design options without the use and discarding of several drawing sheets as in the traditional design studios. Presently, the industry is in high demand of BIM ready architecture graduates who can effectively utilize BIM technology in the design and construction processes, therefore, creating opportunities for architects who are BIM proficient for employment after graduation from HEIs. BIM is not only a design and construction tool in the AECOM industry but also a useful teaching tool. It is considered a powerful tool for teaching design, construction processes, scheduling, building materials and building services as well as for structures. IOT is also relevant for teaching building services which involves the collaborations and inputs from other design professionals like the structural, electrical, mechanical (plumbing), HVAC engineers and also the specialty contractors. Therefore, architecture students will have a grasp of the work processes in the discipline as well as a versatile knowledge of allied professionals' input, for better coordination of the design and construction works.

HEIs therefore, have a role to play in upskilling architecture students, the prospective industry practitioners in the digital era in order for them to excel in practice in the industry. Students are tasked to be efficient in the use of the emerging technologies in their disciplines for design and construction processes in order to maintain their relevance in the industry. Professional practice and education are inter-related therefore, to promote the use of the 4IR technologies in the industry, the applications first need to be implemented in architectural studies in HEIs. There is need for industry-academia-professional bodies collaboration as the application of the 4IR technologies needs to cut across all HEIs in Nigeria, moreover, their adoption and integration in architectural education has cost implications which require support from the industry and the government.

4 Conclusions

The integration of 4IR technologies in architectural education will be beneficial to the students, the educators and the industry. Many students especially undergraduates find the comprehension of geometries, visualizations of buildings in 3D, massing, proportion, and balance challenging. Therefore, concept formation and innovative designs becomes a difficult task for them especially for students with no prior technical orientations. This results in most students copying designs from the internet, past students and even their colleagues as the jury date approaches and they have neither concept nor the basic design drawings required for presentation. The integration of the 4IR technologies will greatly improve understanding and visualizations that will lead to creative and innovative designs. Furthermore, the use of VR in teaching design will help students visualize their proposed concepts and try out different design options in immersed environment, thereby being more original in their design. Similarly, AR actively engages students in the design by the application of rich-contents from the digitalized 3D environment or models that would excite their imaginations and boost their creativity [26]. BIM technology, the simulation, visualization and modeling tool can multi-functionally aid students in understanding and undertaking design, trying out different design options with different concepts, geometries and materials. It also helps in achieving proportion and massing, the understanding of building components and the construction processes during the modelling process and it also increases the speed of drafting as opposed to the traditional hand drawing and or two-dimensional (2D) CAD drafting.

As architectural design is not complete without the involvement of other building professionals; the structural engineer, mechanical engineer with specialty in heating ventilation and air-conditioning (HVAC), electrical engineer, sanitary engineer, in the architectural education context, knowledge integration model using IoT specialized devices for architectural design where users' actions are integrated and interacted within the digitized design environment is beneficial [18]. This aids the design students to understand the processes and the building services required to be imputed for a complete construction drawing and documentations preparation. The adoption and integration of 4IR technologies in architectural education will greatly enhance learning, creativity, output and employability of architectural graduates. These 4IR technologies which are applicable in the built environment industry should be applied to architectural education for enhanced learning outcomes, innovativeness and upskilling of architectural students for the work force in the Nigerian built environment.

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Visualization (nD,VR, AR)

Interactive BIM-Based VR: A Case Study of Doors

Sou-Han Chen and Fan Xue

Abstract The adoption of virtual reality (VR) in the construction industry provides an immersive experience for users to view and interact with Building information modeling (BIM). However, in the current practice, the VR experience is created manually, which is time-consuming and does not refer to other validated data. This study proposes an automatic BIM to interactive VR method based on Revit and Unreal Engine in three steps. First, a bounding box-based segmentation is conducted in Revit through Dynamo for classifying the motion-bearing components. Then the BIM along with the segmentation results are imported to Unreal Engine for components mapping and interactive behavior selection. Finally, Oculus Quest presents an interactive BIM-based VR experience to users. A case study of BIM doors was conducted to validate the proposed method. In the output VR models, users can control and interact with swing doors through the touch controller of the VR headset. Four interactive behaviors of the door were realized for interactive and experiencing user interactions. The findings confirmed the feasibility as well as automation of the proposed method, for faster BIM-to-VR content creation.

Keywords Building information modeling · Virtual reality · Interactive · Motion-bearing components · Revit · Unreal engine

1 Introduction

The architecture, engineering, construction, and operation (AECO) sector is seeking an efficient visualization approach to enhance the interpretation of construction projects. The rapid growth of urbanization has fastened and increased the construction complexity in architectural features, construction methods, and smart facilities management [1]. With such a high complexity, the traditional design approach gradually cannot meet the users' expectations of visualization and interaction. While all

S.-H. Chen (✉) · F. Xue
The University of Hong Kong, Pokfulam, Hong Kong SAR, China
e-mail: souhan@hku.hk

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the information and 3D geometry are presented on the 2D screen, users sometimes have difficulties visualizing the special environment of the project, especially for complex projects [2]. As a result, design faults and inappropriate space utilization [3] still occur and lead to a low reputation in the sector.

To reduce and alleviate the problems caused by visualization, virtual reality (VR) technology was introduced and adopted throughout the project lifecycle. Academic research and industrial applications have been conducted and validate the VR implementation. For example, facilitating the design process [4–6]; providing immersive visualization [7–10], safety training [11], and providing a virtual environment for users to interact with the building elements [12, 13]. However, the VR content creation process is resource-intensive and requires designers to have both AECO and VR knowledge. Without sufficient domain knowledge, the VR content might be unrealistic and cannot provide a good experience and leading to the failure of the VR applications. Therefore, an efficient approach to generating VR content is vital.

Building information modeling (BIM) has been increasingly adopted in the AECO sector due to its integrational capability. BIM is a comprehensive digital representation of the physical and functional characteristics of a facility [14]. The benefits and impacts of BIM have been widely agreed upon by researchers and industries [15–17] and have become mandatory in many regions [18]. BIM provides a systematic information hub for all the involved parties to collaborate at the same project pace. With the capability of storing accurate, semantic, and detailed data, BIM can represent a digital twin of reality, where architects, engineers, contractors, and end-users can simulate and manipulate the design and construction details. Although BIM can be considered to be a solid foundation of VR content, users cannot have any interaction with the objects as there is no mechanism and physic engine inside BIM software. Therefore, there is still a gap between BIM and digital twin applications.

In addition, gaming technology has demonstrated its ability to produce high-end visualization of architectural features and to provide various interactive scenes for users to experience the virtual built assets [19–22]. Moreover, many gaming companies provide great tools for users in the AECO sector to import and link their BIM projects to the game engines. For example, Epic Games provides an add-on, Datasmith, for automatically transferring and synchronizing BIM with Unreal Engine (UE) projects [23]; Unity provides Unity Reflect for real-time collaboration across platforms and applications [24]. Although such tools can minizine the information lost during data transformation, the transferred information is not automatically utilized for further applications. After importing BIM into the game engine, designers still need to spend effort on setting the interaction of the objects and configuring the parameters. This process is time-consuming and not suitable for large-scale projects. As a result, an automatic workflow for the interaction settings is desired.

This research aims to present a preliminary method to exploit the potential of using BIM and gaming technologies for automatically facilitating VR content and experience. The proposed approach is designed to (1) facilitate the VR content creation process, (2) explore the interactive ability of BIM, and (3) provide a realistic and diverse VR experience to the users through the game engine.

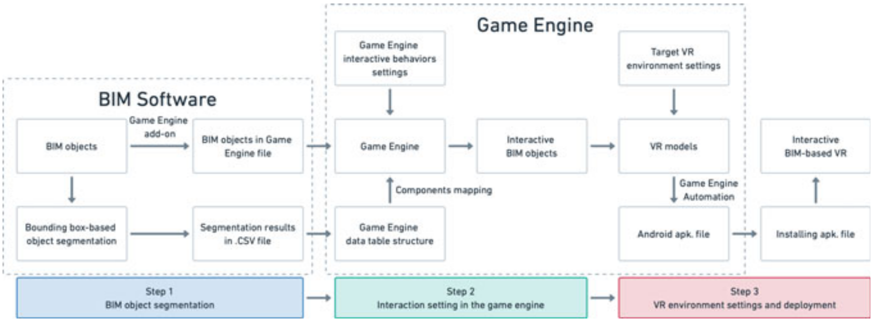


Fig. 1 Method of the proposed three-step automatic BIM to interactive VR process

2 Methodology

2.1 Overview

The proposed method is described below (Fig. 1) and includes three major steps: (1) object segmentation in BIM software, (2) interaction setting in the game engine, and (3) VR configuration and deployment.

2.2 Step 1. BIM Object Segmentation

The first step of the method is to classify the motion-bearing components which will be used as the physic constraints, also known as hinges, in the game engine. Since BIM can be considered a well-structured information hub [25], the object data and parameters can be retrieved and analyzed in a systematic approach. For example, Dynamo, a Revit plug-in for managing and extracting data, can be used to identify the elements that contain certain text, tags, or under specific categories. Therefore, users can easily classify the motion-bearing components and stored the information in a CSV file. However, since the properties of the BIM objects might not be comprehensive, a bounding box-based segmentation approach can be used to identify the motion-bearing components.

The bounding box is an invisible cube that contains all model elements, annotation elements, and datum elements [26]. The motion-bearing component can be identified by checking if its bounding box is intersecting with two or more connected components. Using the door as an example, hinges can be identified correctly as their bounding boxes intersect with the panel's bounding box and the frame's bounding box, while the frame will not be classified as motion-bearing components as its bounding box contains the panel's bounding box. This essential approach is favorable for segmenting the BIM objects into different parts as objects in the AECO sector are generally uncomplicated and more typical.

2.3 Step 2. Interaction Setting in the Game Engine

The target of this step is to transfer BIM objects to interactive objects with the option that designers can select the interactive behaviors of the objects (Fig. 2). Unlike the traditional mesh models in OBJ or FBX files, which mainly focus on the geometry of the model, BIM contains more metadata, such as category names, custom labels, and unique BIM IDs. Through mapping metadata with the segmentation results generated in Step 1, key motion-bearing components and other parts of the BIM objects can be recognized by the game engine and the interactive behaviors can be applied to the corresponding components. There are two advantages of adopting this pre-defined interactive behavior, applicable to large-scale transformation and can provide users with a diverse interactive experience.

Firstly, the interactive behaviors can be custom-built and applied to all the same object types. For example, once the designers define an interactive behavior of a push/pull window, all the push/pull windows can be applied to the same settings and designers don't need to configure them one by one. Even though the shape or the size of each push/pull window might be different, the game engine can still use the segmentation results to recognize the motion-bearing components along with other parts of the objects and perform the correct behaviors of the objects.

Secondly, through applying different interactive behaviors, the same BIM objects can perform differently. For example, a BIM furniture can be lifted either by one touch controller or two touch controllers; a BIM swing door can be opened either by a simple push or need a key to open it. With the ability to quickly change the behavior of the objects, designers can effortlessly try out different settings for providing the most realistic experience to the users.

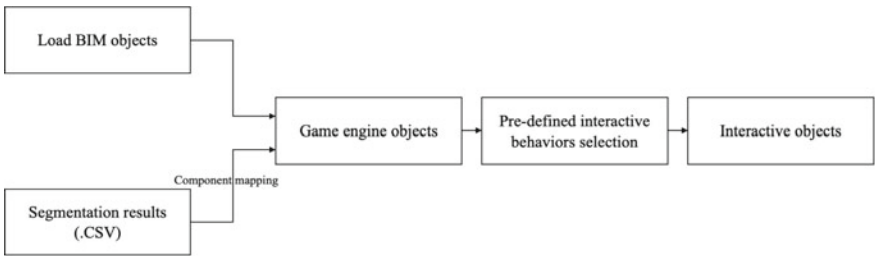


Fig. 2 General framework of transferring BIM objects to interactive objects

2.4 Step 3. VR Environment Settings and Deployment

To successfully develop and deploy the VR content inside the game engine, proper VR configuration should be set. Generally, there are three essential settings needed to be configurated sequentially before packing all the content into an Android Package (APK) file: (1) VR operating system configuration; (2) touch controller settings; (3) interactive game object settings.

First of all, since different VR companies have their own VR operating system, designers need to determine which VR headset will they use to provide the interactive experience. Based on different systems, some plug-ins, packages, or software development kits needed to be installed in advance. Secondly, based on the VR operation system, designers need to define the action of each bottom on each touch controller. The actions can be classified into two categories: locomotion system and hand interaction system. Typically, the locomotion system can be set to either be continuously moving or teleporting, while the hand interaction system contains various actions. For example, holding/releasing game objects, controlling game objects to perform specific behavior, and pausing the game. Finally, the priorities of the interactive game objects should be modified to match the touch controller settings so that the objects can behave correctly based on the users' input.

3 Results

3.1 Case Study of BIM Door

Doors are one of the most important object types for fire safety checking during the preliminary design of building works. Besides the appearance of the door, deciding its opening direction and planning the exit route are crucial works for the designer. Although the adoption of VR technology can provide an immersive experience for the user to interact with doors, the interactive behavior is still manually designed. As a result, this research used a BIM door from the UK National Building Specification (NBS) BIM Library [27] as a case study for validating the proposed method in Fig. 1. Table 1 lists the software used in this case study.

3.2 Bounding Box-Based Segmentation Results

Figure 3 shows the Dynamo scripts for door segmentation. Based on the general structure of the door, all the components can be segmented into one of the following categories, Door_Panel, Door_Hinge, or Door_Frame. To correctly segment the decorations and handle on the panel to Door_Panel, the bounding box of the panel was extended on the y-axis. Then, by comparing each bounding box of all the components

Table 1 Software list

Software	Version	Description
Revit	2022	Loading BIM door in Revit family document (.rfa) and the supporting the environment for Dynamo
Dynamo	2.12	Performing the bounding box-based segmentation and exporting the results in CSV file
Unreal Engine (UE)	4.27.2	Creating interactive behavior of the BIM objects; setting VR environment; Packing the VR model into APK file
SideQuest	0.10.32	Installing the APK file into Oculus VR

with the bounding box of the panel, their relationships with the panel can be known. Figure 4 shows the segmentation results of the test BIM door. The first three rows show the segmentation results and list out the unique ID of each component, while the rest rows show the locational data of all the hinges, including the X-axis, Y-axis, and Z-axis. The unit is in centimeters.

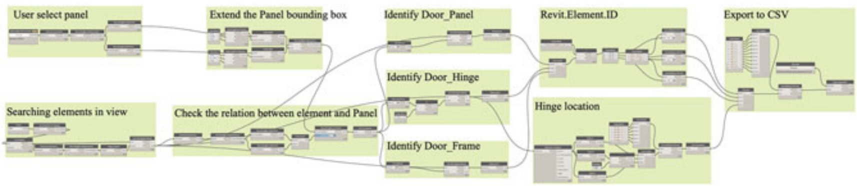
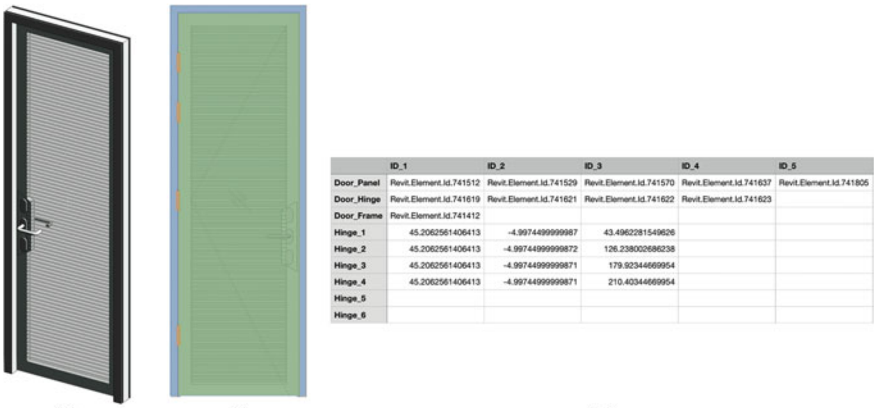


Fig. 3 Dynamo script of bounding box-based segmentation



	ID_1	ID_2	ID_3	ID_4	ID_5
Door_Panel	Revit.Element.Id.741512	Revit.Element.Id.741529	Revit.Element.Id.741570	Revit.Element.Id.741637	Revit.Element.Id.741805
Door_Hinge	Revit.Element.Id.741619	Revit.Element.Id.741621	Revit.Element.Id.741622	Revit.Element.Id.741623	
Door_Frame	Revit.Element.Id.741412				
Hinge_1	45.2062561406413	-4.9974499999987	43.4962281549626		
Hinge_2	45.2062561406413	-4.99744999999872	126.238002686238		
Hinge_3	45.2062561406413	-4.99744999999871	179.92344669954		
Hinge_4	45.2062561406413	-4.99744999999871	210.40344669954		
Hinge_5					
Hinge_6					

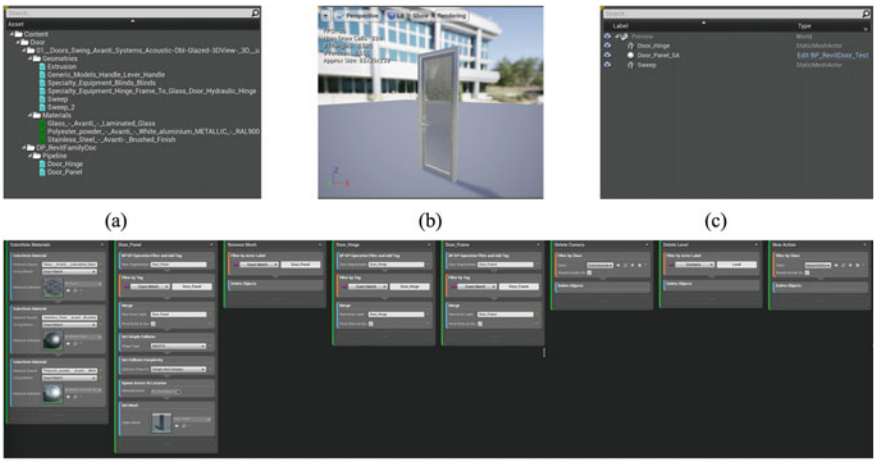
Fig. 4 Segmentation results. (a) Test BIM door; (b) Illustration of the segmentation results; (c) segmentation results in CSV file

Besides the segmentation results, the BIM object was exported as a Datasmith file, which is a file type created by Epic Games and used for importing BIM into Unreal Engine (UE).

3.3 Interactive Behaviors

Unreal Engine provides a visual system, called Dataprep, for designers to pre-process the Datasmith file before the actual BIM object is imported to the scene. Figure 5 shows the Dataprep system used in this case study. The core of this Dataprep system is shown in Fig. 5d. These blocks enable designers to select and modify the components. For example, designers can select all the components with native BIM material, Glass_-_Avanti_-_Laminated_Glass, and change their material to native UE material, which is more realistic and detailed. In this case study, the Dataprep system is formed by four main steps: (1) substituting materials; (2) merging components based on the segmentation results; (3) adding the interactive behavior to the door; (4) deleting unwanted data. With such a pre-defined Dataprep system, designers can effortlessly filter unwanted data and reorganize the data structure.

By changing the interactive behavior setting, users can experience different interactions with the door. These interactive behavior settings were pre-defined in Blueprint, a visual gameplay scripting system in UE. Designers can make use of the Blueprint system to custom-build users' interactive experiences. In this case study,



(d)

Fig. 5 Dataprep system for transferring a BIM door to an interactive game object. (a) original BIM door data hierarchy in Datasmith file; (b) interactive BIM door preview; (c) interactive BIM door data hierarchy preview; (d) data processing blocks for transferring BIM door to interactive BIM door four interactive behaviors were created in advance (Table 2). The Blueprint of each interactive behavior is provided in Fig. 6.

Once all the VR models are properly placed in the scene and the VR configurations are done, UE can pack the contents into an APK file, which can be used for installing VR models into Oculus VR. In this case study, SideQuest is used for the APK installation. The final interactive BIM-based VR is presented to the users through Oculus Quest 2. Figure 7 shows two screenshots of the interactive BIM-based VR. Figure 7a shows the initial status of the VR model, while Fig. 7b shows the scene after 7 s with some doors already performing different interactive behaviors. This clearly reveals the great potential of the interactive ability of BIM.

Table 2 Interactive behaviors description

Name	Trigger	Description
Physic door	Physic	The door contains physic priorities. Once there is any external force applied to the door, the physic engine will stimulate its movements and behaviors automatically
Automatic door (1)	Timer	The door will follow the pre-set movements and behaviors based on the internal timer
Automatic door (2)	Collision	The door will open automatically once there is any object with the collision priorities entering the specific area and will close once the object leaves
VR locking door	VR settings	The door will behave based on the pre-defined conductions. The door can only be opened once the key is in a specific location

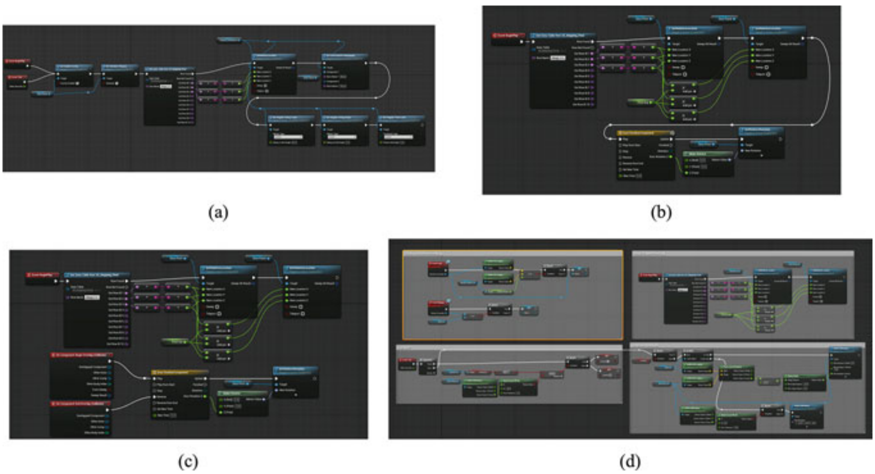


Fig. 6 Blueprint for different interactive behavior settings. (a) Physic-based interaction; (b) Time-based interaction; (c) Collision-based interaction; (d) VR-based with locking function interaction [28]

Fig. 7 Screenshots of the interactive BIM-based VR. (a) The initial scene; (b) Scene after 7 s

4 Limitations

In contrast to the manual VR creation approaches, the case study has validated the feasibility of the proposed automatic method. However, there are three limitations in the proposed method that shall be overcome in future studies.

First, this method only works for Revit family documents. Due to the Revit system data hierarchy, the bounding box-based segmentation approach cannot perform correctly as detailed components inside family documents will not be passed to the project document. For example, door hinges might be invisible inside the Revit project.

Secondly, the bounding box-based segmentation relies heavily on the accuracy of the model. If the geometric and the location of objects and components are not accurate, the segmentation results would be affected, and the final VR experience might not be realistic.

Last but not least, in the current practice, the major panel of the door must be selected manually. Since the appearance of the door might be diverse, the door panel cannot be accurately identified by its geometry. Some small experiments were conducted in Dynamo to automatically identify the panel. For example, based on the largest volume; based on the largest surface area; based on the components with nearby components. However, all the segmentation results are still not ideal and not general.

5 Conclusion

Virtual reality technologies have provided the AECO sector with an immersive experience of visualizing and interacting with the construction project. However, the process of VR content creation is time-consuming and requires great domain knowledge in both VR and ARCO knowledge. This study presents an automatic BIM to interactive VR method with the adoption of BIM and gaming technology. A case study of BIM door was implemented and validated the proposed method. The results showed the proposed method can facilitate and fasten the VR content creation process and provide a more interactive VR experience.

To improve the process of BIM to interactive VR, several research directions can be explored. First, the adoption of the Revit project document can improve the scalability of the VR experience. Furthermore, a more efficient method of segmentation and auto-BIM-detailing can be developed and investigated. Also, a standardization of the interactive behaviors can be explored and shared across both academia and industry.

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Leveraging Virtual Reality for Improved Construction Health and Safety Training

Damien Smuts, Ashvin Manga, and John Smallwood

Abstract The International Labour Organisation estimates, that on average, 60 000 fatal accidents occur on construction sites annually. The importance of developing and providing health and safety (H&S) training that allows trainees the best opportunity to understand and appreciate the hazards and risks present on construction sites as well as to understand and implement the policies and procedures in place to promote a healthy and safe working environment are fundamental to H&S training practices. Virtual reality (VR) is an emerging technology with practical applications to significantly improve understanding and appreciation of H&S training. This study employed an experimental quantitative approach to evaluate the effectiveness of VR H&S training by conducting VR training sessions with H&S practitioners within the construction industry. The VR training software was provided by research and innovation company 3M and included 3 different training sessions. The training sessions included fall protection and harness inspection, working from heights awareness, and general construction site H&S induction. A total of 14 construction and H&S practitioners participated in the study including H&S agents, and site agents. Results from the study indicate that participants found the training experience engaging and realistic aiding their learning experience. Additionally, participants experienced limited difficulty interacting with the platform and navigating within the VR environment with no participants experiencing any discomfort from the experience.

Keywords Construction · Health and safety · Training · Virtual reality

1 Introduction

Commercial construction constitutes a broad range of shareholders working collectively on a single project often under constraints inclusive of cost, time, and quality. This unique manufacturing process has recognised the construction sector as an

D. Smuts · A. Manga (✉) · J. Smallwood
Nelson Mandela University, Port Elizabeth 6031, South Africa
e-mail: ashvin.manga@mandela.ac.za

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industry in which health and safety is paramount to project success [1]. Several health and safety (H&S)-related research projects have emphasised that most accidents on sites could have been mitigated or prevented by implementing the correct and consistent H&S management processes and a programme that includes planning, education and training, and inspection [1]. H&S training can leverage visualisation technology such as virtual reality (VR) to significantly improve the effectiveness of H&S training. Furthermore, traditional on-site training often interferes with construction activities thereby reducing productivity and ultimately costing the client more [2]. A VR approach to construction H&S training allows for improved comprehension and understanding by providing information in a visual format and offering virtual off-site hands-on training, mitigating the risks of on-site training and loss in productivity [2].

Given the status of H&S in South African construction, and that limited, if any research has been conducted relative to the impact of VR delivered construction H&S training in South Africa, a study was conducted, the aim of which was to assess the potential of adopting VR H&S training as an alternative to that of traditional H&S training. The objectives of the study were to determine the:

- effectiveness of traditional H&S training programmes;
- effectiveness of VR H&S training programmes;
- effectiveness VR H&S training compared to traditional H&S training, and
- extent to which six forms of discomfort were experienced during the VR training applications, and
- potential to implement VR H&S training.

2 Review of the Literature

2.1 History of Virtual Reality (VR)

In 1957 Morton Heilig designed and patented the Sensorama, a device that allowed users to mimic riding a bicycle. The user sat in the machine, which exhibited a 3D city, and could hear city noises, feel wind, and seat vibrations, and even smell individual odours. The Sensorama was the first move toward the commercialisation of VR [3]. The first head-mounted display was the Philco HMD. It did not use a simulated world, but instead used a video displayed at a distance creating the effect of telepresence, a VR application that is still in use today [3]. The next VR related technology worth mentioning is the development of haptic and gesture feedback by using wired gloves. The first one developed was the Sayre glove in 1977, by Tom DeFanti and Daniel J. Sandin, which functioned courtesy of fiber-optics. Thomas G. Zimmerman worked in the early 80 s to develop the Data-glove, which significantly influenced other devices, such as the Power Glove. It was manufactured by Mattel for the Nintendo Entertainment System, available at an affordable price, although it was considered a commercial failure [4]. The Oculus Rift was the first headset focused on gaming. It provided an extended field of view of 110°, stereoscopic vision, and fast head tracking. It does that by processing data that passes through a 3-axis gyroscope, accelerometer, and magnetometer, giving the user a fast image update, meaning no visual latency. To date, several companies have entered the VR space, most notably Meta investing significantly into the VR space.

2.2 *Virtual Reality Training*

Workplace conditions and practices have deteriorated because of industrialisation, owing to inexperienced, unskilled, and uneducated workforces [5]. As a result, workers may learn the proper approach to interact with machines and their working environment through training modules that employ technologically sophisticated methodologies. Furthermore, smart industry 4.0 deployments have added a new dimension to productivity by providing operators with cost-effective and time-effective off-site H&S training [6].

Workers in industries receive on-site and off-site H&S training to gain the necessary hands-on skills and practical experience. This leads to an increase in workers' skill levels, which helps to avoid high-risk accidents in the workplace. However, statistics suggest that 30–40% of industrial accidents are due to inexperienced and unskilled operators [6]. This is because current H&S training techniques fail to: replicate the dynamic interaction in a socio-technical system; increase cognitive performance learning that is more engaged and knowledge that is retained for a longer amount of time and provide an interactive platform for determining a strategy for effective preventative measures [7]. Furthermore, due to variables such as time and space constraints, organisational costs, and a lack of expert knowledge, these techniques failed to deliver instruction in a real-world environment [8]. With these limitations in mind, VR based training, one of the major dimensions under the umbrella of Industry 4.0, has emerged as a potential solution due to its ability to provide real-time visualisation, dynamic accident causation modelling, risk-free human-machine interaction, and an increased learning rate.

VR-based H&S training has provided a pervasive and persistent platform for developing perceptual experience and cognitive capacity for problem-solving and decision-making in complicated stressful circumstances without exposing employees to real-time hazardous or environmental conditions [9]. Furthermore, H&S training in an immersive VR environment will aid in the enhancement of process comprehension and awareness, the emergence of unanticipated issues, the evaluation and anticipation of errors in decision making, and the detection of workplace dangers. The usage of VR-based training has replaced traditional training techniques with a user-friendly and adaptable training platform [10].

Construction workers can now be trained without risk of injury by leveraging virtual reality technology. Furthermore, when compared to traditional training methods that rely on movies and handouts, VR is a significantly more immersive and realistic alternative [11]. As the construction industry is a high-risk industry for occupational injury, VR H&S training has been targeted with interest by both academia and industry [11]. A published review of the literature regarding the effectiveness of VR training in 2017 indicated that the technology showed significant potential, however, the main pitfall regarding the use of VR technology according to the researchers was access to VR content [12]. Furthermore, it is notable that in only four years the cost barrier to obtain and develop VR content has decreased significantly and will continue to decrease as companies such as NVIDIA and Meta are making massive investments in bringing the metaverse into fruition [13]. The successful use of VR to improve H&S training is evident across other industries that require extensive scenario-based training. Then, research concluded that VR 'drills' had improved the self-preparedness and self-efficacy of nursing professionals dispatched to respond to chemical disasters [14]. Research has determined that there is a cost barrier preventing companies that have limited funds for research and development to invest in VR [15].

2.3 Learning with Virtual Reality

Recent research provided substantial evidence to suggest that the visual fidelity of a head mounted display did not impact the users' learning experience as significantly as hypothesised by the researcher. Instead, the results indicate that the degree of interaction and seriousness of the VR experience significantly increased the participants' H&S knowledge [16]. The findings from this research are significant as there is evidence to support the use of affordable VR solutions such as Google Cardboard which retails in South Africa for approximately R400.00. educators should focus on the development of interaction and problem-solving type VR environments that can be experienced using affordable VR displays [16]. One of the drawbacks of using VR as an educational tool is that users may experience various symptoms that are similar to motion sickness, disorientation, nausea, pallor, sweating and headaches leading to vomiting. These symptoms are related to a conflict within the biology of the brain [17]. However, results provided by researchers [18] indicate that immersive and interactive learning environments increase learning motivation. A notable finding is that learning motivation plays a substantial role in learner engagement and retention of the content.

To uncover the usefulness of VR resources in engineering studies, researchers developed varied surveys that were circulated during seven academic courses to determine the opinion of students enrolled in diverse engineering degrees at different universities [19]. The results from a database of 200 students surveyed considered that the most important features in VR application are interactivity, realism (including immersion), motivation, ease of use, and educational usefulness. From these results, several conclusions are listed below:

- Interactivity and realism are the most important features for motivating students to engage with VR learning;

- The students were impressed by the realism of the VR applications developed by the researchers. However, students demand the use of VR resources as much as possible to improve their learning experience, according to survey results. Thus, collaboration between experts in a specific subject and VR technicians are necessary for designing a useful and attractive VR environment for students, and
- VR is not useful as a stand-alone learning aid, therefore, revised learning methodological approaches must be developed to maximise the effectiveness of VR learning.

3 Research

The aim of the study was to determine the effectiveness of VR H&S training compared to that of traditional H&S training within the construction industry. The purpose of VR H&S training is to provide employees with realistic workplace experiences and allow them to learn from taking risks while working in difficult conditions. The empirical study was conducted using an experimental quantitative design using a self-administered pre and post questionnaire designed to determine the impact of the VR training. The experiment was conducted in a large lecture room at Nelson Mandela University. Participants partook in three VR applications, which were supplied by 3M™, who created and developed the VR H&S training applications. The three VR environments included H&S aspects that are common hazards and risks on a construction site, which included the fundamentals of fall protection, working at heights awareness, and fall protection harness inspection. Participants were informed before the start of the VR training that they might experience some discomfort during the training, namely dizziness, sweating, or a headache, and that the experiment can be terminated at any stage should the participant experience any discomfort.

The participants spent about 20 min wearing a VR headset while receiving the H&S training. The participants' performance in the VR environment was recorded with their knowledge, but the footage of the actual participants was not captured. After the VR session was completed, the participants were then given a self-administered questionnaire to complete, which entailed a series of questions relative to the objectives of the study.

A total of 14 participants were subjected to the experiment and completed the questionnaire. The questionnaire was developed in Google forms and used open-end questions together with Likert Scale and check boxes. In terms of e industry experience, 6/14 (42.9%) participants had '1–10 years', 42.9% had '11–20 years', and 2/14 (14.2%) had '21–30 years'. In terms of injury experience, 71.4% of respondents indicated they have not been injured on site, while 28.6% have been and 85.7% of participants had no experience with VR, while 14.3% had.

In response to the question 'Is there a need for an improvement in H&S training?' all the participants responded in the affirmative. Table 1 indicates the effectiveness of traditional H&S training in terms of realising compliance with H&S legislation and regulations in terms of percentage responses to a scale of 1 (Very ineffective) to 5 (Very effective), and a MS ranging between a minimum value of 1.00 and a maximum value of 5.00. Given that all the MSs are >2.60 to ≤3.40, the effectiveness of traditional H&S training in terms of realising compliance with H&S legislation and regulations can be deemed to be between less than effective to effective/effective.

Table 2 indicates the participants' learning experience from training application (TA) 1 'PPE Inspection', TA 2 'working at heights', and TA 3 'harness and fall protection' in terms of percentage responses to a scale of 1 (Not at all) to 5 (Substantially), and a MS ranging between a minimum value of 1.00 and a maximum value of 5.00. All the MSs are >3.00, which indicates that the participants' learning experience was between somewhat to substantial. However, given that all the MSs are >3.40 to ≤4.20, the respondents' learning experience from the TAs can be deemed to be between somewhat to a great extent/great extent.

Table 1 The effectiveness of traditional H&S training in terms of realising compliance with H&S legislation and regulations

Aspect	Response (%)						MS	R
	Unsure	Very ineffective.......Very effective						
		1	2	3	4	5		
Workers wearing PPE	0.0	11.1	11.1	0.0	66.7	7.1	3.36	1=
Workers identifying hazards & risks	0.0	11.1	11.1	0.0	66.7	7.1	3.36	1=
Workers operating plant and equipment	0.0	0.0	22.2	33.3	33.3	11.1	3.33	3
Workers following safe work procedures	0.0	0.0	33.3	33.3	22.2	11.1	3.11	4 =
Workers committing unsafe acts	11.1	0.0	11.1	33.3	33.3	11.1	3.11	4=
Workers reporting unsafe conditions	0.0	11.1	33.3	33.3	11.1	11.1	2.78	6

Table 2 Extent to which participants learnt from the three types of VR H&S training

Training type	Not at all.................Substantially					MS	R
	1	2	3	4	5		
Working at heights	0.0	0.0	28.6	28.6	42.9	4.14	1=
Harness and fall protection	0.0	0.0	21.4	42.9	35.7	4.14	1=
PPE inspection	0.0	0.0	28.6	42.9	28.6	4.00	3

Table 3 Extent to which the site felt realistic

Training type	Response (%)					MS	R
	Not at all………………..Extremely						
	1	2	3	4	5		
Working at heights (Cherry picker)	0.0	0.0	0.0	35.7	64.3	4.64	1
PPE inspection	0.0	0.0	0.0	42.9	57.1	4.57	2
Harness and fall protection	0.0	7.1	21.4	21.4	50	4.14	3

Table 3 indicates the extent to which the participants felt the training application (TA) 1 'PPE inspection', TA 2 'working at heights', and TA 3 'harness and fall protection' sites felt realistic in terms of percentage responses to a range of 1 (Not at all) to 5 (Extremely), and a MS ranging between a minimum value of 1.00 and a maximum value of 5.00. All the MSs are >3.00, which indicates that the participants felt that the respective training type scenarios were between somewhat to extremely realistic. However, given that all the MSs are >3.40 to ≤4.20, the respondents' learning experience from the TAs can be deemed to be between somewhat to a great extent/great extent.

78.6% of respondents opine that it is easier to learn using VR as a tool, while 14.3% responded in the negative, and 7.1% were unsure. Respondents were required to indicate whether VR training is more beneficial than traditional training. 71% responded in the affirmative, 14.3% in the negative, and 14.3% were unsure.

Table 4 indicates the extent to which various contentions apply in terms of percentage responses to a scale of 1 (Minor) to 5 (Major), and a MS ranging between 1.00 and 5.00. All the MSs are >3.00, which indicates the potential is more major than minor. However, four of the MSs are >4.20 to ≤5.00, which indicates the extent to which the contentions apply is between a near major to major/major extent—'learning is easier using VR as a tool', 'there is a need for an improvement in H&S training', 'the VR training application simulated a real site' and 'VR training enhances appreciation of workplace risks'. Given that the MS for 'VR training assists in terms of understanding hazards' is >3.40 to ≤4.20, the extent to which the contention applies is between some extent to a near major/near major extent.

Table 5 indicates the degree of ease experienced in terms of navigating around the VR site in terms of percentage responses to a scale of 1 (Not at all) to 5 (Extremely), and a MS ranging between 1.00 and 5.00. Given that the MS is >4.20 to ≤5.00, the respondents experience can be deemed to be between very easy to extremely/extremely easy to navigate around the site.

Table 4 Extent to which various contentions apply

Aspect	Response (%)					MS	R
	Minor…………………………..Major						
	1	2	3	4	5		
Learning is easier using VR as a tool	0.0	0.0	0.0	27.3	72.7	4.73	1
VR training is more beneficial than traditional training	0.0	0.0	9.1	18.2	72.7	4.64	2
There is a need for an improvement in H&S training	0.0	0.0	14.3	28.6	57.1	4.43	3
The VR training application simulated a real site	0.0	7.1	7.1	35.7	50	4.29	4
VR training enhances appreciation of workplace risks	0.0	7.1	14.3	28.6	50.0	4.22	5
VR training assists in terms of understanding hazards	0.0	7.1	21.4	28.6	42.9	4.07	6

Table 5 Degree of ease experienced in terms of navigating around the VR site

Response (%)					MS
Not at all ……………….Extremely					
1	2	3	4	5	
0.0	0.0	14.3	28.6	57.1	4.43

Table 6 Extent to which the respondents were immersed by the VR surroundings

Response (%)					MS
Not at all …………………..Major					
1	2	3	4	5	
0.0	0.0	14.3	28.6	57.1	4.43

Table 6 indicates the extent to which the respondents were immersed by the surroundings in the VR training application in terms of percentage responses to a scale of 1 (Not at all) to 5 (Major), and a MS ranging between 1.00 and 5.00. Given that the MS is >4.20 to ≤5.00, the extent of immersion in the surroundings can be deemed to be between a near major extent to major/major extent.

Table 7 indicates the extent to which six forms of discomfort were experienced during the VR training applications in terms of percentage responses to a scale of 1 (Not at all) to 5 (Substantially), and MSs ranging between 1.00 and 5.00. All the MSs are <3.00, which indicates the extent to which discomfort-related factors were experienced by the respondents during or after the VR simulation is negligible as opposed to substantial. Sweating achieved the highest MS (1.64), followed closely by eyestrain (1.43). All the MSs are ≥1.00 to ≤1.80, which indicates that the experience of the six forms of discomfort during or after the VR simulation are between not at all to very little.

Table 8 indicates the potential for the use of VR for training in the construction industry in terms of percentage responses to a scale of 1 (Minor) to 5 (Major), and a MS ranging between 1.00 and 5.00. The MS is >3.00, which indicates the potential is more major than minor. However, given that the MS is >4.20 to ≤5.00, the potential for the use of VR training in the construction industry can be deemed to be between near major to major/major.

Table 7 Extent to which six forms of discomfort were experienced during the VR training applications

Form	Response (%)						MS	R
	Unsure	Not at all…………………Substantially						
		1	2	3	4	5		
Sweating	0.0	50.0	35.7	14.3	0.0	0.0	1.64	1
Eyestrain	0.0	64.3	28.6	7.1	0.0	0.0	1.43	2
Fatigue	0.0	92.9	7.1	0.0	0.0	0.0	1.07	3
Headache	0.0	100.0	0.0	0.0	0.0	0.0	1.00	4 =
Nausea	0.0	100.0	0.0	0.0	0.0	0.0	1.00	4 =
Dizziness	0.0	100.0	0.0	0.0	0.0	0.0	1.00	4 =

Table 8 The potential for the use of VR for training in the construction industry

Response (%)					MS
Minor………………………..Major					
1	2	3	4	5	
0.0	7.1	7.1	28.6	57.2	4.36

4 Discussion

This research was conducted in 2021, a year in which the world was recovering from a global pandemic in which nationwide lockdowns impacted businesses across South Africa. The construction sector was no exception to the economic turmoil Covid-19 brought and subsequently most construction entities were under operational and financial strain limiting their willingness to participate in academic research. Furthermore, the research ethics clearance process introduced time constraints and tight timelines. However, the convenience sample adopted for the study managed to garner 14 active construction H&S practitioners, therefore, the findings can be deemed indicative as opposed to representative. A notable finding is that 85.7% of the participants had never experienced any form of VR or VR delivered training. Additionally, not a single participant experienced discomfort of any sort. This indicates the improved comfort head mounted display (HMD) VR headsets have made in improving user comfort which was once a significant issue for HMD's. As stated in the literature the main benefit of VR training is exposing users to immersive, dynamic and dangerous scenarios in a safe and secure environment. This affords the trainee the opportunity to make mistakes and experience the consequence of their actions. This level of immersion promotes appreciation of the dangers on a construction site, understanding of the procedures established to keep workers safe and holistic awareness of the task. New findings from this research indicate that VR technology within the construction health and safety training sector is in its infancy in terms of adoption.

5 Conclusions

Given the effectiveness of traditional H&S training in terms of realising compliance with H&S legislation and regulations relative to six aspects, it can be concluded that traditional H&S training is not effective as it should be. This conclusion is reinforced by the unanimous affirmative response relative to the need for an improvement in H&S training. Given the extent to which the participants learnt from the VR H&S training applications, the extent to which VR sites felt realistic, the benefits of VR H&S training, the extent to which various contentions apply, and the potential for the use of VR for H&S training in the construction industry, it can be concluded that VR H&S training is realistic, preferable to traditional H&S training, and VR H&S training has the potential to improve H&S compliance, and H&S performance.

Visual fidelity did not have a significant impact on the learning experience as per the findings of previous research [16]. However, the degree of interaction and seriousness of the VR experience had a significantly greater impact on learning retention and understanding [16]. The findings of this study corroborate with the findings of other studies reported on in the review of the literature confirming the importance of interactivity and realism in positively influencing the VR learning experience [14]. Furthermore, the findings of this research underscore the findings of previous research [14] in that subject matter and VR specialists are required to develop impactful VR learning experiences to enable the research methodology adopted, which entailed collaboration with 3 M™ who developed the VR training used in this study.

6 Recommendations

VR assisted H&S training should be adopted in construction as it transforms the presenter's role from information deliverer to facilitator, assisting trainees in their exploration and learning. This allows trainees to explore a virtual world where they may learn experientially and at their own pace, avoiding the situation where trainees are left behind during the training session, and spend the remainder of the session trying to catch up. The resources available to create virtual environments are significantly more abundant. The development of VR environments is a skill that should be present within a AEC business as vertical integration of digital skills is easy to accomplish compared to supply chain integration.

Employer and professional associations, and statutory councils in the construction industry should raise the level of awareness with respect to Industry 4.0 technologies and promote the adoption thereof. Stakeholders that adopt industry 4.0 technologies, VR assisted H&S training included, should interrogate, and quantify the benefits of such adoption. Tertiary education institutions should collaborate with such stakeholders, in addition to spearheading such research, and exposing students to VR H&S training during their studies. In closing, previous research opens the door for future research in terms of the development of affordable VR learning solutions such as Google Cardboard, which places an emphasis on interaction and seriousness, averting the procurement of expensive high-fidelity HMD [11].

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Concept and Implementation of BIM-to-World Co-registration for Mixed Reality Applications

Marat Khairtdinov, Fulya Tasliarmut, and Christian Koch

Abstract Mixed reality tools have witnessed a surge in meaningful applications within the construction industry. A critical prerequisite for these tools is the proper alignment or co-registration of the real world with the virtual and digital content, a process referred to as co-registration at the beginning, and tracking during users' movement. Notably, the majority of showcased use cases focus primarily on superimposing innovative virtual design content onto tablets (AR) and see-through devices (MR) that have already been accurately registered and aligned, without providing insights into the registration process. Although most of the available MR devices perform well in tracking the device's position and orientation during user movement, the co-registration procedure is usually manual, tedious, and constitutes a significant shortcoming in the overall user experience and MR tool adoption. This paper presents a distributed client-server concept for a co-registration process for MR devices. The server process is bifurcated into a semi-automated rough registration part that uses minimal user input, and a fully automated fine registration part employing the Iterative Closest Point algorithm. The client part runs the projection, visualization, and tracking process utilizing the initial co-registration data. The presented concept is implemented and tested on the Microsoft HoloLens as the MR-client and a software server that runs a dedicated Python script. Experiments and results demonstrate that the presented concept and implementation effectively support the co-registration process with minimal user input, offering reasonable accuracy and latency, even when the corresponding part of the real world has not been captured previously.

Keywords Augmented reality · Mixed reality · Building information modeling · Co-registration · HoloLens

M. Khairtdinov · F. Tasliarmut · C. Koch (✉)
Chair of Intelligent Technical Design, Bauhaus-Universität Weimar, Weimar, Germany
e-mail: c.koch@uni-weimar.de

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1 Introduction

The concept of Building Information Modeling (BIM) implies the creation, integration, and continuous use of digital data throughout the entire life cycle of a facility including design, building, operation, and maintenance [1]. Often visually represented with the MacLeamy curve, the BIM workflow aims to shift the effort and cost related workload from the later stages of construction to its design phase [2]. While this enables enhanced architectural, structural, and financial planning, the application of BIM to on-site construction management is still in the developmental stage. Next to digitization, automation is one of the most important aspects of the BIM workflow. Within the context of the Architecture, Engineering and Construction (AEC) industry, many solutions rely on extended reality (XR) technologies including virtual, augmented, and mixed reality (VR, AR, MR). The integration of XR tools with BIM not only play an important role in terms of better spatial understanding through real-time data visualization, they also contribute to improving the communication on-site and to enhancing decision-making processes [3].

Despite advancements in the sector, progress monitoring remains labor-intensive and time-consuming. To this date, it is more often performed by manually acquiring data on-site for later evaluation. To automate progress monitoring, the most straightforward approach is to compare geometric structures between the as-modeled 3D data with the as-built shape through superimposition. Incorporating digital information into the real-world surroundings of a user is the core of MR experiences. For real-time inspection and monitoring, MR devices such as the head-mounted Microsoft HoloLens or hand-held tablets can be utilized. To overlay as-planned models as holographs on the corresponding as-built environment, an accurate and precise positioning of the virtual and the physical objects is essential. The process of aligning a set of captured points from a MR device to a corresponding set of points from a given as-planned model defines the task of co-registration. This process usually involves either the detection of pre-defined markers in the captured environment or considerable user input to estimate a suitable initial guess for the registration algorithm.

In this work, we demonstrate our approach to conduct a semi-automated co-registration of the as-built and as-planned BIM data. We employ the Microsoft HoloLens hardware and a performance-efficient client-server architecture to offload the computation-intensive task of initial pre-registration and fine-registration of the environment with the as-planned building information model. We commence with an overview of current registration methods and related work, followed by an outline of the methodology of our proposed approach. Furthermore, we verify the concept on experiments by creating synthetic and world point cloud data of a real facility.

2 Related Work

Point set registration defines the task of aligning two (i.e., pairwise or co-registration) or more (i.e., group-wise) set of points. An overview of registration algorithms has been shown in the works of Zhu et al. [4]. The objective of point set registration is to detect correspondences between point sets and calculate the transformation needed to map one point set onto another. Registration can be performed between images, from a 2D image to a 3D point cloud or between point clouds. Raw data for 3D point clouds are often obtained from sensors like 3D laser scanners, RGB-D cameras, Time-of-flight (ToF) cameras, or from photogrammetric reconstruction algorithms such as Structure from Motion (SfM). The computation of a rigid transformation between sets of points can be decomposed into a translation and a rotation, while the calculation of non-rigid transformations poses an arduous challenge including affine transformations (e.g., scaling, shearing) [5]. Depending on the use case, the registration process is typically divided into two main stages: (i) the coarse and (ii) the refined alignment [6].

The traditional way to coarsely register a scanned point cloud to a reference model is by manually adjusting the point set to be registered onto the physical counterpart until a sufficiently accurate alignment is achieved. The process is complicated, time-consuming, and there exists a chance to introduce inaccuracies due to human error. For the initial co-registration of a point cloud, corresponding points are either manually selected or 3D descriptor-based or descriptor-free methods are applied [7]. After extracting salient key points through feature detection algorithms, the interest points are computed with incorporation of their local neighborhoods, which can then be matched through a similarity metric. Robust 3D descriptor methods include Fast Point Feature Histograms (FPFH) [8] and Signature of Histograms of Orientations [9]. One prominent example by Mahmood et al. combined FPFH as a feature descriptor with the Random sample consensus (RANSAC) algorithm to filter out false correspondences during the pre-registration process [6]. Descriptor-free methods aim to perform a global co-registration through the use of Principal Component Analysis (PCA) with which the rotation for the alignment is estimated [7]. The translation is then calculated by computing the centroids of the respective point clouds.

Another approach is to utilize markers that are attached to other objects within the device camera's field of view and apply pose estimation algorithms to calculate the relative distance between markers and the camera. However, marker-based methods are not robust when occlusion or varying lighting conditions are introduced [10]. In particular, overcoming viewpoint and pose deformations within different models as well as filtering out noise in the form of occlusion and outliers is notably cumbersome with markers.

Following the initial coarse registration, a refinement stage can further improve the accurate superimposition. One of the most widely used methods for fine point set co-registration is the Iterative Closest Point (ICP) algorithm [11]. The optimization approach calculates the rigid transformation in an iterative manner to align an unregistered point cloud to a reference cloud. In an initial step, corresponding data points are identified under the assumption that the closest points correspond. The aim is to minimize the objective function, which defines the distance between two corresponding points in their respective point sets. By computing the center of mass, the scanned point set is shifted to the target point set and subsequently rotated by using singular value decomposition (SVD). After each iteration, the correspondence is updated and the procedure is repeated either until a maximum number of iterations or a threshold is reached. Being sensitive to the initialization, one of the main shortcomings of the ICP algorithm is that it can get stuck in local minima under adverse conditions [12]. In addition, due to the explicit calculation of the closest points, the time complexity scales quadratically with the number of the corresponding points [13]. Many variants of the ICP algorithm have been developed to overcome its limitations. One often utilized metric for better performance of ICP is the point-to-plane distance coupled with the least squares approach instead of the point-to-point measurement [14].

3 Methodology

The task of co-registering as-built data with as-modeled data can be expressed as aligning two 3D shapes under the rigidity constraint. Given two 3D shapes in arbitrary positions within the same Euclidean coordinate system, we aim to find a transformation of the first shape that aligns it with the second.

The task of co-registration of as-built data with as-modeled data using a portable MR-device implies that the system needs to obtain the shape of the environment (as-built data) and the initial transformation of this shape. As depicted in Fig. 1, in the proposed method, the process of co-registration is divided between a client and a server application that share the overall tasks as follows.

The client application deployed on the MR device (Microsoft HoloLens) reconstructs the 3D-shape of the real room (world point cloud) and performs tracking of

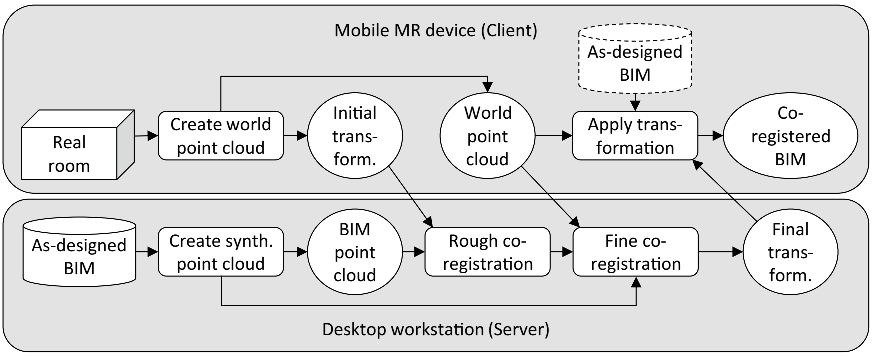

Fig. 1 The process of semi-automated co-registration divided between the client and the server application

its camera inside of this environment. It also contains the 3D shape of the corresponding model (e.g. as-designed BIM) that has to be transformed to align it with the environment (co-registered BIM).

On the server side, the shape of the as-designed BIM is used to create a synthetic point cloud (BIM point cloud) that is, firstly, manually and roughly aligned using an initial transform of the MR device, and secondly, automatically and accurately aligned during the fine co-registration process using the world point cloud. The latter process results in a final transform that is sent to the MR device to align the as-designed BIM with the world environment (co-registered BIM).

3.1 Creation of Synthetic Point Cloud

3D solids have surface boundaries, which represent the geometry of the as-designed BIM. These surfaces can be transformed into 3D meshes that consist of points or vertices that are grouped into polygons, for example, triangles. This process is called tessellation. The result of the tessellation is a synthetic point cloud of the as-designed BIM. In order to create a certain compatibility between the world and the synthetic point cloud in terms of point density, the synthetic point cloud must be up-sampled. The process of up-sampling is depicted in Fig. 2, and is performed on the server.

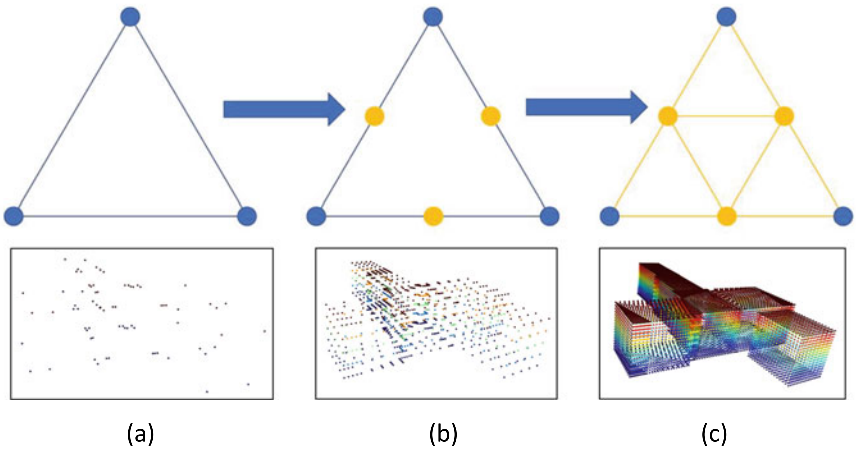

Fig. 2 The up-sampling process of a triangular mesh with the corresponding effects in the 3D point cloud. **(a)** Original resolution of the point cloud. **(b)** Point cloud up-sampled by two times. **(c)** Point cloud up-sampled by four times

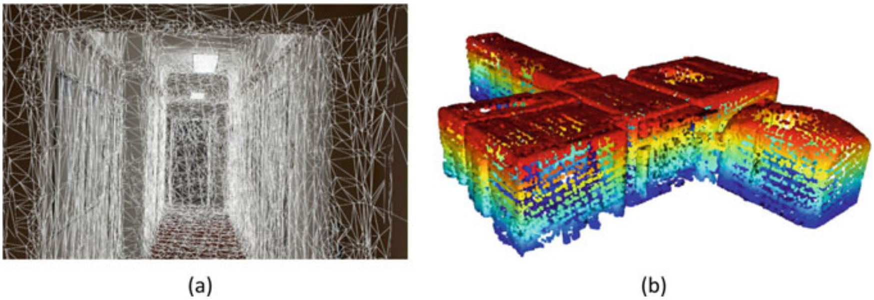

Fig. 3 Spatial mapping of the environment using the HoloLens results in a mesh **(a)**, or point cloud **(b)**, respectively

3.2 Creation of World Point Cloud

The creation of the world point cloud can be performed using MR devices. In case of the HoloLens, this process is called spatial mapping (Fig. 3a) and results in a mesh that represents the inner surface of the environment, e.g. a real room. Accordingly, the vertices or points of this mesh form the world point cloud (Fig. 3b).

3.3 Co-registration

As mentioned above, the co-registration process is a semi-automated process as it is divided into a manual client-based rough alignment and a server-based fine registration procedure.

The idea is that the user enters the construction site and obtains the 3D scan of the environment using the device's built-in sensor as described in Sect. 3.2. This 3D scan lies in the coordinate system defined by the device: the position of the device at the initial moment of tracking is the origin of this coordinate system (see Fig. 4).

After the user has entered the first room, they must initiate registration by scanning the environment to obtain the 3D world point cloud. Then, the user informs the system of their location and the pre-defined direction (e.g., north) they are facing. Knowing both the direction (Fig. 4b) and the room on the floor (Fig. 4c), the system aligns the center of the corresponding room with the position and orientation of the camera, assuming the user to be at the center of the room. The position and orientation can be easily tracked in the real environment by the MR device. The obtained initial transform is then sent to the server and provides the basis for the fine registration process.

The process of fine registration is carried out on the server using the ICP algorithm [11], which takes two point clouds of similar shape and density at arbitrary positions as input. In our case, it strives to align or co-register the world point cloud with the synthetic BIM point cloud.

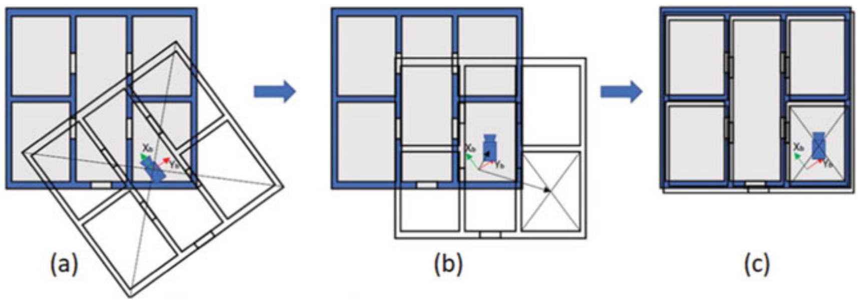

Fig. 4 The process of manually and roughly co-registering the as-designed model with the real world environment on the client MR device

4 Implementation

This section describes the actual implementation of the proposed method. In order to share the computational load of scanning and co-registering, a client-server architecture has been chosen (Fig. 5).

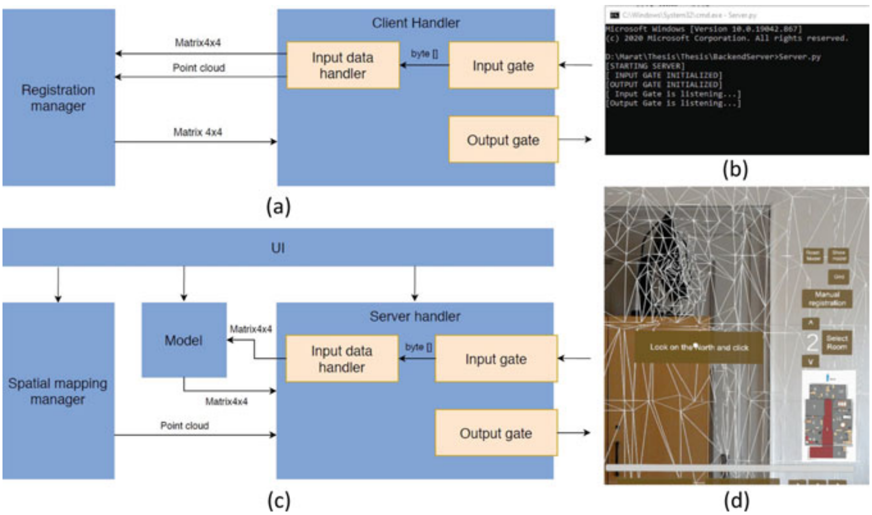

Fig. 5 Software design for the server running a Python script **(a)** and the client running a Unity3D program **(c)**. User interface of the server **(b)** and the MR client **(d)**

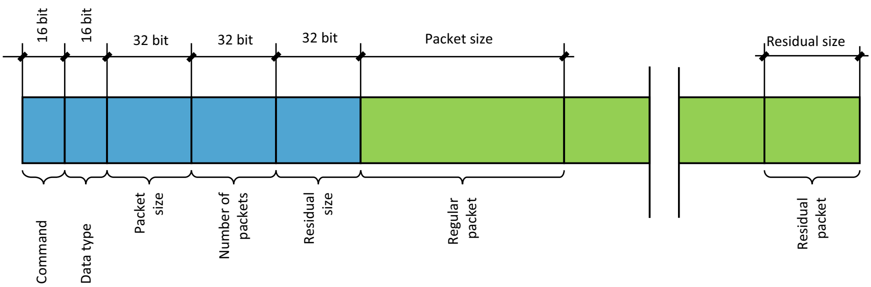

Fig. 6 Structure of the data transfer protocol for sending data between client and server

4.1 Client-Server Architecture

The co-registration tasks are separated as follows. The server app performs the ICP algorithm (Registration manager) based on the initial transform and the world point cloud (Fig. 5a), and the client app runs the spatial mapping and the initial registration based on user input (Fig. 5c). For that purposes, corresponding input data handlers and input/output gates have been implemented. The server runs a dedicated Python script (Fig. 5b), whereas the client is based on a Unity3D program using the MR HoloLens library (Fig. 5d).

4.2 Data Transfer

Figure 6 depicts the structure of the data protocol used for the transfer of the transformation matrices (initial transform from client to server; final transform from server to client) and the world point cloud data that is sent from the client to the server.

5 Case Study and Results

This section describes the case study that was used to test the proposed method as well as the results of the co-registration process.

5.1 Case Study

The experiments were conducted on the Bauhaus-Universität Weimar campus, as shown in Fig. 7. A specific room was selected for this purpose; in this case, room number 2 in Fig. 7.

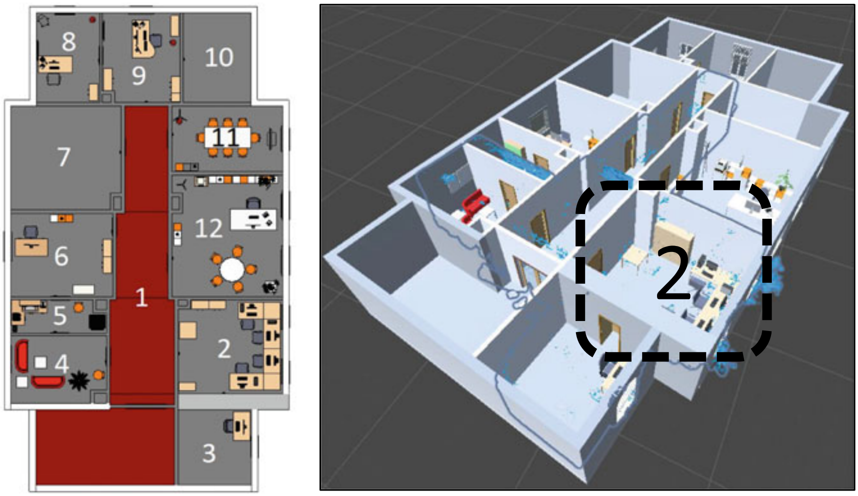

Fig. 7 Floor in a university building used in this case study, highlighting the specific test room (number 2)

Figure 8 gives an impression on both the user interface of the HoloLens app (Fig. 8a) as well as the qualitative results of co-registration (Fig. 8). In Fig. 8b, it can be observed that the real and virtual objects of both the cupboard and the table appear to be aligned and co-registered. However, a slight misalignment can also be recognized, which is in this particular case, also related to the imperfect as-designed modeling dimensions.

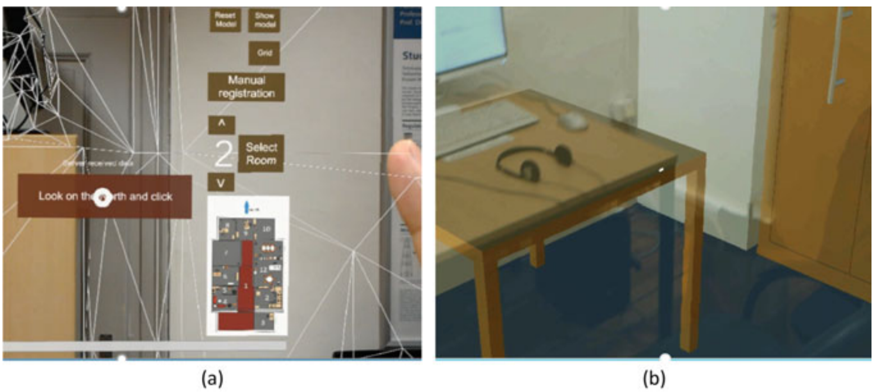

Fig. 8 (a) User interface of the HoloLens MR device. (b) Qualitative result of the co-registration process showing the superimposed as-designed BIM model onto the real world scene

6 Results

Figure 9 illustrates the exemplary results of the manual, initial, and rough registration process that, as previously described, is based on user input. It can be observed that a simple user input, here room and orientation, can be used to roughly co-register virtual and real content, and then serve as qualified input for the next step.

The results of the fine registration process are quantified as the distance error between world scan points and surface planes in the as-designed BIM based on Eq. (1)

$$RMSE_{point-plane} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} n_{t,i} \bullet (p_{s,i} - p_{t,i})^2} \quad (1)$$

where n_t represents the normal unit vector of the target point cloud (BIM surface plane) associated with its point p_t, and p_s represents the closest point of the source point cloud (world) while n represents the number of points.

Figure 10 highlights the results of the fine registration process, while distinguishing a different number of rooms on the same floor. The rough registration is based solely on the scan of one room. However, if more than one room is scanned, the fine registration can be performed on the respective point clouds of more than one room, e.g. one room (Fig. 10a), two neighboring rooms (Fig. 10b) or even three neighboring rooms (Fig. 10c). It can be observed that the overall co-registration error does not improve with an increasing number of rooms or point clouds, respectively, used within the ICP algorithm.

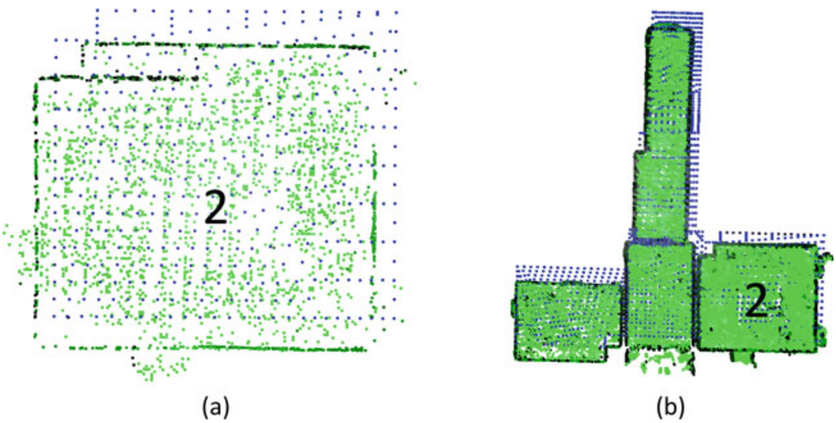

Fig. 9 Results of the manual, initial and rough registration process

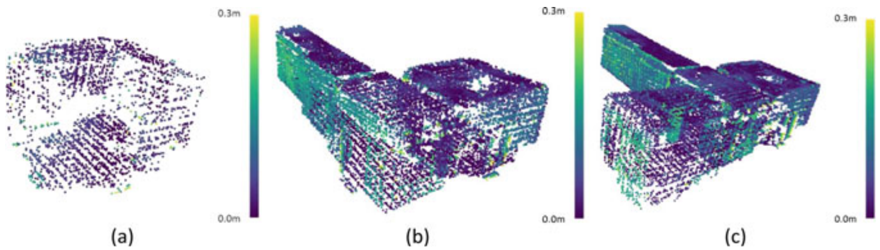

Fig. 10 Results of the fine registration process, using **(a)** One room. Point-to-plane RMSE = 0.114 m. **(b)** Two rooms. Point-to-plane RMSE = 0.109 m. **(c)** Three rooms. Point-to-plane RMSE = 0.112 m

7 Conclusions

This paper presents a concept and an implementation of a semi-automated BIM-to-World co-registration process for mixed reality applications using the Microsoft HoloLens as the MR device. This process is divided into a client and a server process in order to balance the computational load. While the rough, initial and manual registration is performed on the MR device, a dedicated Python server application implements the ICP algorithm that takes the initial transformation of the scene as input. A specialized case study demonstrates that the proposed method provides feasible and practical results.

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Safety and Training Implications of Human-Drone Interaction in Industrialised Construction Sites

Adetayo Onososen, Innocent Musonda, Molusiwa Ramabodu, and Christopher Dzuwa

Abstract Over the past decade, the development of construction robots, such as drones, has increased, given the need to apply emerging technologies and innovations in enhancing occupational health and safety on construction sites. The usage of these innovations is not without safety concerns for human-robot interaction. Previous studies have highlighted the importance of training in enabling a safe collaboration between human workers and robots in the construction environment. However, the cost of acquiring these novel innovations makes training cost expensive. This study, therefore, examines the safety and training implications of human-drone interactions based on the simulation of drones for material handling in a virtual environment. The findings of this study would help construction stakeholders and designers identify critical factors towards enabling an effective virtual reality training approach to building safe adoption of robots and ensuring workers' health is assured.

Keywords Human-drone interaction · Human-robot collaboration · Human-robot interaction · Construction safety · Collaborative robots · Training

1 Introduction

Drones, also known as Unmanned Aerial Vehicles (UAVs), have increased in usage and adoption in the Built environment and on construction sites, given their merits in progress monitoring, health and safety monitoring, security, progress tracking, surveillance, and inspection, aerial data collection etc. [1–4] These efforts at digitalising the sector through the adoption of drones, however, is not without its demerits

A. Onososen (✉) · I. Musonda · C. Dzuwa
Centre for Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: adetayoo@uj.ac.za

M. Ramabodu
Department of Construction Management and Quantity Surveying, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa

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[5]. Among these are safety issues in human-drone interaction, ergonomics, workers' privacy and the cost of training to facilitate adoption [6, 7]. Previous studies have mentioned that while drones are important and would be more adopted, they nonetheless bring in a wider spectrum of unwarranted risks and hazards [8–10]. While training to ensure safe adoption has been advocated by previous studies [11, 12], the cost of training arising from crashes of drones limits investment and discourages adoption [13, 14].

Therefore, recent advances have seen virtual reality as a more effective platform for human-drone training. Virtual Reality (VR) mimics real-life scenarios and helps train users on drone operations, and it has been identified as a highly effective training approach [11, 12]. Experts have employed VR in the built environment to help visualise city operations, buildings, and design since roughly the 1990s [15, 16]. Users may evaluate prototypes realistically, beginning with the earliest design phases, thanks to the concept of virtual prototyping or virtual design review. Several firms perform design reviews to find errors or areas of improvement in their innovations before the actual product is built [17]. Studies have also mentioned that Virtual reality (VR) has demonstrated its capacity to improve communication, early project planning and coordination in several sectors [18, 19]. It creates a unique environment where stakeholders can intuitively visualise and interact with 3D representations of a product before it is manufactured [20].

While VR has these merits, its use in construction is limited. For effective human-drone interaction in industrialised construction sites where all workers will not have a similar degree of understanding and involvement with drones on the construction site, their training implementation is inevitable [21]. Adoption of drones in itself can be a safety risk as previous studies mentioned that while a drone user with a background in civil engineering can understand certain drone actions fitted for their expertise, an artisan might otherwise be concerned about the advent of drones and could get distracted and interpret it as spying tools [21]. This unfamiliarity with the operation of drones on-site causes concern with non-users and close communities. While drones are operated around them, this may bring discomfort and anxiety to their working environment [22, 23].

While drone collision deaths and injuries are rare, safety risks will always be a concern. Also important is a collision with wildlife, properties, distraction, violation of privacy, or trespassing. All of these speak to the need for a VR-Based drone training approach to ensure adoption safety and lower training costs. Therefore, studies on appropriate safety and privacy management to accompany drone integration on-site are important to facilitate adoption and improve training efforts.

A human-computer interaction in which the computer generates a sensory experience is known as virtual reality, a setting that reacts to and is interactively modified by user behaviour [24, 25]. Experiences in virtual reality settings come from three different places: immersion, interaction, and multi-sensory feedback. With immersion, the user is completely engulfed in the setting, giving them the impression of being real in the world portrayed. At the same time, interactivity can be seen as the ability to control events in the simulation environment by using human body movements, which initiate responses in the simulation environment as a result of these movements [24].

The safety implications of drones in construction have recently received much attention from researchers and practitioners. The ability of drones to be airborne and be controlled remotely or autonomously has only increased the safety implications of utilising such technology in a construction environment. Therefore, while adoption benefits are immense, the safety implications limit the construction environment sector adoption. Therefore, the challenge remains aiding drone users with knowledge and expertise on underlying safety risks associated with flying drones and eliminating these risks through repetitive training in a virtual environment [26, 27]. The presence of onboard mounted cameras continues to raise reasonable suspicions and privacy concerns in most environments and therefore has implications on training to ensure drone users keep to strict ethical conduct during drone flying. UAV technology is fairly new in construction, and the full scope of the negative outcomes has yet to be addressed and further investigated [8, 28, 29].

Without adequate training, workers may exhibit unsafe actions, leading to dangerous outcomes (i.e., catastrophic accidents). As stated in previous studies, unsafe work behaviour has been mentioned as one of the main influences of workplace hazards in construction [8]. Privacy issues such as the invasion of drone hovering workers can startle workers and lead to loss of focus which can cause trips, falls and other potential accidents, hence the need for training on the safe usage of drones on-site [22, 30].

Hence, this study examines the safety and training implications of human-drone interactions based on the simulation of drones in material handling in a virtual environment. The phases involved in the study are presented based on a pilot study's output. The study provides insights on users' behaviour in the environment which are critical to inform training and education of users in using VR, and also on how people perform given tasks in the virtual environment.

2 Method

The research method involved designing and developing a virtual reality environment with human participants interacting with drones in an immersive environment. The first stage in the method approach consisted of 3D modelling of the assets necessary to set up the scenario for the virtual environment. The assets modelled in 3D included the construction site, construction vehicles and materials on construction sites, Drones, and tasks to be carried out. In the second stage, the 3D models were transformed into assets.

The drone simulator was implemented in Unity® 2022.1.16 using the C# programming language. Following the import of the model into unity®, design parameters, i.e., weight, gripping mechanism joint friction, rotation, retraction and expansion speed, were assigned to the drone. The flight environment was a construction site with four uncompleted buildings. Other objects commonly found on construction sites were also added to the scene. The third stage involves integrating the different assets to create the whole environment and integrate them. Furthermore, the lighting system ensured a good degree of photorealism.

The fourth stage involved interaction programming using C++ to ensure the Oclus® touch controllers and thumbsticks can help users navigate the environment, perform tasks and interact with other humans in the environment. Task management was designed to allow the participants to pick materials (bricks in this case) between a lower point on site and deliver them at a much higher level (On the top of a structure). After the design and development of the drone, a pilot study was conducted with thirteen built environment professionals from diverse disciplines. The users began by learning to control the drone, navigate it without weight, pick the material and deliver it through vertical and horizontal flight patterns. To study what users were doing in the environment and provide insight for further development and improvement, an automatic data collection system was integrated into the application to provide indices on the user's performance based on different factors. Each interaction in the environment is further supported by associating sounds with actions in the environment to improve the overall realism; before the tests, participants were taken through a training session that involved guiding users on the controls to navigate the environment and manually fly the drone (Fig. 1).

For the experiment, the Oculus® Quest 2 was adopted. Participants were required to sign ethical consent forms before participating in the experiment. Afterwards, the workings of the Oculus® quest 2 were briefly explained to the participants. Participants were advised to adjust the HMD to their comfort. Participants calibrated their eye gaze to ensure accurate eye-tracking data. The study began after a successful eye calibration was achieved. Participants were immersed in the learning environment, where they completed tasks involving the delivery of construction materials

Fig. 1. 3D model-conceptual view

(bricks in this case). The use of delivery drones as a means of transporting goods is becoming increasingly common in today's society. By incorporating the use of delivery drones in the task stated above, we were able to simulate a practical and meaningful real-world scenario. The task of material pickup and delivery using a drone allowed us to assess participants' ability to navigate the drone, manipulate it, and deliver a package to a specified location. This task also enabled us to evaluate the effectiveness and efficiency of the drone as a delivery vehicle. Furthermore, the use of delivery drones in the task allowed us to investigate the potential benefits and limitations of using such technology in the transportation industry. Overall, the inclusion of delivery drones in our study provided a relevant and practical application for the use of drones in the real world. This procedure was repeated in the same order for all participants. The data for the study was collected by the virtual application based on each participant's behaviour in the environment. The parameters used to retrieve the data were Payload, Collision object, Time, Drone speed, Drone Position, Drone Orientation, Safe Distance, Pilot Position, Command, Drone Range and Battery life (Figs. 2, 3 and 4).

Fig. 2 Flight environment with drone

Fig. 3 Participants in the study

Fig. 4 Participants in the study

3 Results and Discussion

3.1 Altitude Distribution and Velocity Distribution

The frequency of the altitude and velocity distribution of the experiments are shown in Fig. 5 and Fig. 6. The frequency distribution along an altitudinal gradient revealed that most of the participants were flying at low altitudes. This is not unusual for first-time drone users who, at initial flight operations, focus on being able to control the drone. However, the altitude of flight is critical to human-drone interaction. It indicates users' ability to maneouver around different building heights, fly at heights that will not cause noise and distraction to site workers, and fly drones to deliver materials at a given height. This is critical to inform drones of virtual training in understanding the behaviour of participants in the environment and how this transfers to developing skills in real-life scenarios.

Furthermore, the velocity distribution of the experiment also revealed very low flight speeds of 1–2 m/s. While this indicates users' understanding of the drone's control, the graph further shows participants improved on speed as they improved on controls of the drone. Hence, for safety training in virtual drone environments, the speed and altitude that participants can fly safely depend on the skill level associated

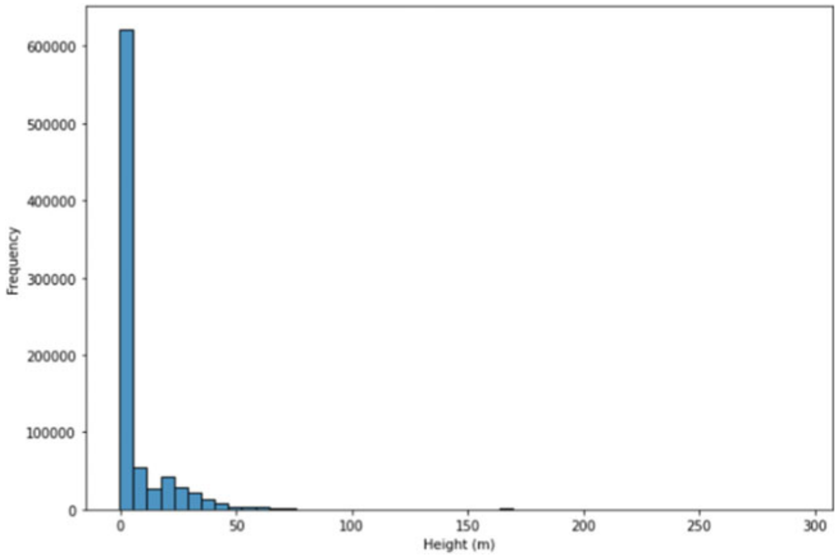

Fig. 5 Altitude distribution of experiments performed by participants

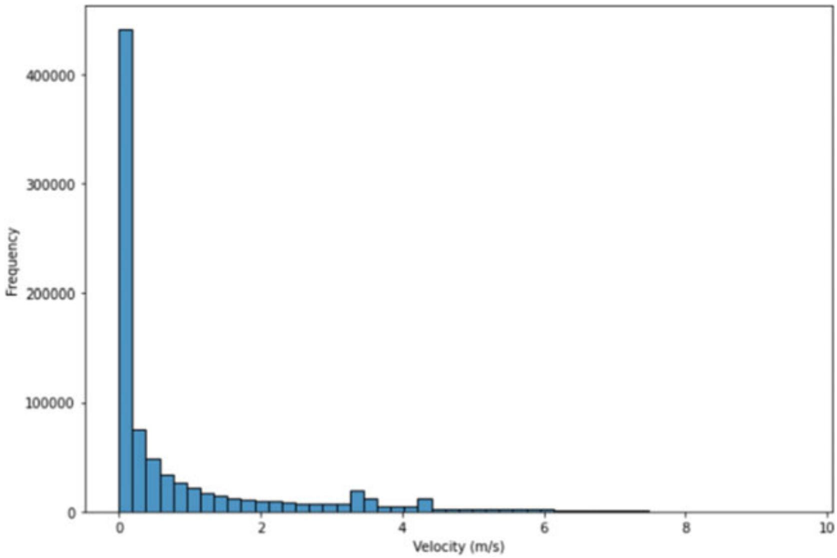

Fig. 6 Velocity Distribution of experiments performed by participants

with drone control. While drones are expensive and prone to crashes when used in training, a virtual environment can aid users in honing their skills to understand drones' directional behaviours before being placed with drones in real-life scenarios. This helps the confidence level of trainees, improves skills level before physical flights and reduces the cost of replacing drones.

3.2 Collisions Per Experiment

The collision per experiment for the study was generated from the application and indicated the frequency of collisions experienced by users in the virtual environment. As shown in Fig. 7, the reveals a high number of collisions by participants in the environment. Collisions are an important indicator to measure the risk of losing drones and the safety of flying drones without risk to humans around the site. While the results are not unusual given that the participants are new to flying, the ability of the virtual environment to integrate object and human contact avoidance in participants, especially in adverse weather conditions, is important for training. This addresses salient issues raised on the safety of integrating drones with humans present on site. Furthermore, a virtual platform allows users to repetitively conduct training on collision avoidance before uptaking physical drone flights.

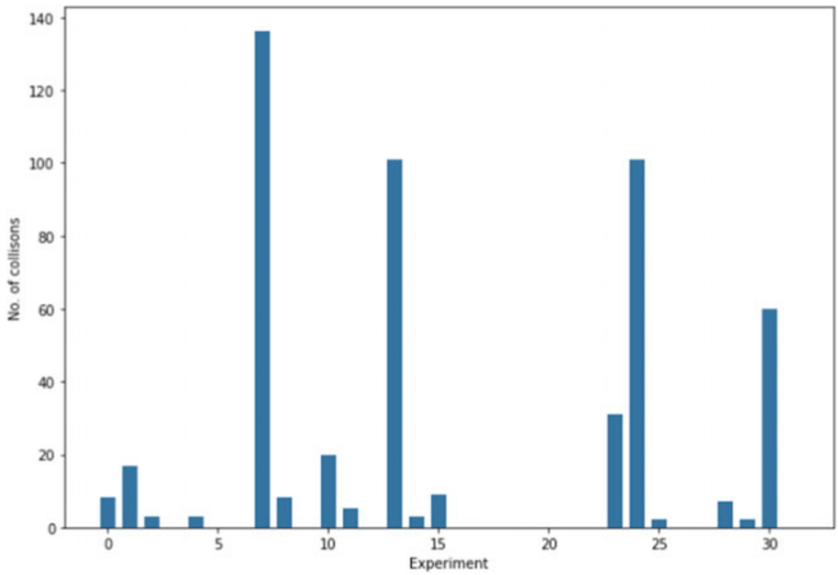

Fig. 7 Frequency of collisions in the Experiment

3.3 Collisions Frequency Based on Time

The collision frequency based on time indicates the chances of colliding during the experiment based on periods. Figure 8 revealed that time periods less than 200 m/s had more collisions compared to other time periods. This indicates that the collision occurred while the users were just starting. This is expected as users struggle to control the drone when starting and could fly at high speeds, colliding with objects while learning the controls. This is further justified by the results showing that the collisions reduced as participants progressed in the study. This implies that more training hours are needed for drone training. Given the ability of VR to aid repetitive training without the risk of losing the drone, it is imperative for training guides to ensure users learn drone operations control firstly in a VR environment before actual deployment on-site.

3.4 Collisions Frequency Based on Velocity

The collision frequency based on velocity indicates how active the participants are in the environment and could also indicate the level of idleness. Figures 9 reveal that most collisions happened at about 4 m/s. At the initial stage, most of the collisions happened at lower velocities. This could indicate that users collided with objects while attempting to pick the materials.

3.5 Drones Command

To further confirm the users' activities in the environment with the previously discussed results, the command directed to the drone was analysed using word cloud and revealed that at various instances in the virtual environment, users did not send any command to the drone. This indicates idleness for most participants. Discussions with participants after the experiments revealed some likely reasons, such as users pausing to check out structures in the environment and having virtual walkthroughs. To improve supervised learning and reduce idleness in the virtual environment, further development of the virtual training platform will have multiple users collaborating in the same environment.

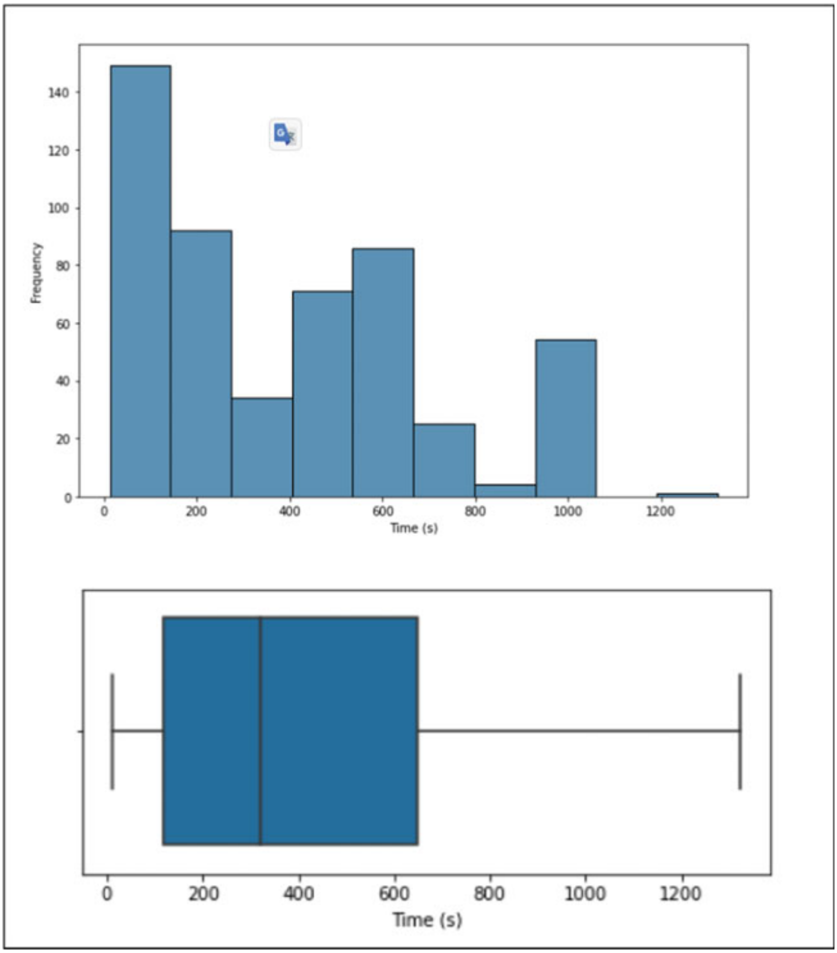

Fig. 8 Collision Frequency based on time

3.6 Collision Frequency Based on Height

The collision frequency based on height revealed that most collisions happened under 7 m, as shown in Figs. 10. This indicates that the users often collided at this range due to the challenge of picking the bricks to be delivered in the task. The challenge of picking the objects is also attributed to understanding how to control the drone. As previously stated, this could be improved through repetitive virtual environment training.

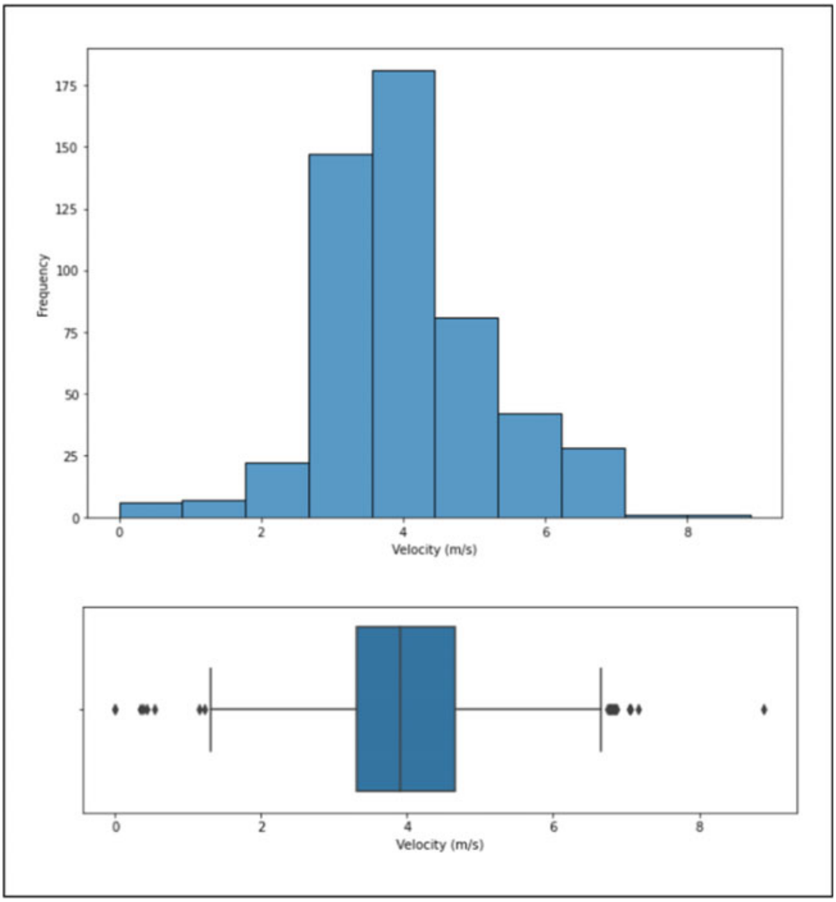

Fig. 9 Collisions Frequency Based on Velocity

Fig. 10 Drone command word cloud

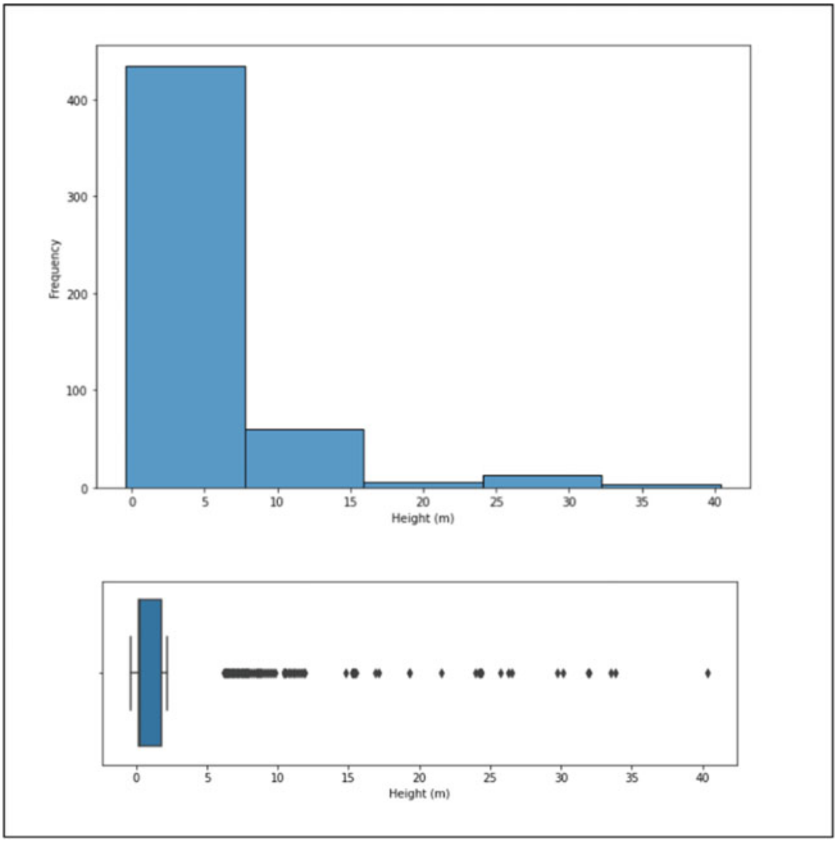

Fig. 11 Collision frequency based on height

3.7 Percentage Out of Boundary

Privacy issues are critical barriers to drone adoption, as drone operations can capture areas beyond the target point. This has led to various litigations, which have impacted the interest and adoption level of drones in construction. To train participants on ensuring drones stay within controlled bounds and to ensure users do not spy on neighbouring structures, the study collected data on the boundaries incursion tendencies of the users and discovered that for most parts of the experiment, people were within the boundaries with only one user straying away as shown in Fig. 11. Pilots are liable to pay for damages and their flight license suspended over privacy issues, so this training is critical to eliminating privacy issues associated with drone operations on site (Fig. 12).

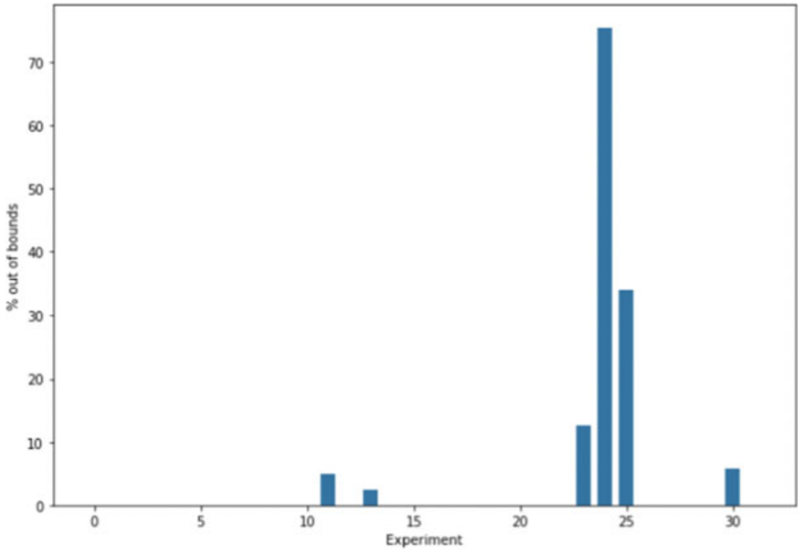

Fig. 12 Percentage out of boundary

4 Conclusion

The study designed and developed a virtual reality training platform to examine drones' safety and training implications for material handling on construction sites. While the study revealed the high number of collisions, this was explained as usual with initial training experiences with physical drones and demonstrated the importance of virtual environments as a testing platform before the physical deployment of robots with humans. This critically reveals that virtual environments offer users the ability to understand skills level, identify likely safety and performance errors able to be committed in real-life scenarios, utilise virtual reality to eliminate those risks and improve performance before physical interaction with robots on site. For construction organisations and training institutions, this helps appreciate the reduced initial capital investment achieved when robot such as drones are adopted with virtual training platforms. The study also revealed the issues associated with the idleness of participants in the virtual environment and how virtual reality can help correct unsafe behaviour and privacy concerns associated with drones application on construction sites. Further design and development options are raised and discussed in the study. The use of delivery drones is identified as a limitation of the study and future studies will incorporate other drones use cases.

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Task Performance to Understand the Effectiveness of Visualisation Technology-Based Training for Human-Drone Interaction Learning

Adetayo Onososen, Innocent Musonda, Molusiwa Ramabodu, and Christopher Dzuwa

Abstract Drones' adoption in the Architecture, Engineering and Construction (AEC) sector is increasing with the need for digitalizing construction processes and workflows. However, the investment cost does not match the cost of replacing drones from crashes and accompanying safety and privacy challenges resulting in litigation. Therefore, this study examines visualization technology-based training to study human-drone interaction for learning. To achieve the objectives, drones were modelled in 3D alongside a virtual construction site for participants in the experiment to perform tasks. The attached tasks gave indicators of the effectiveness of such learning platforms in drone training. The results noted that while virtual reality is excellent as a form of training, the low number of delivered items indicates the need for more training time. The findings of the study are useful for those in academia, policy-making and industry buy-in.

Keywords Human-drone interaction · Human-robot collaboration · Visualisation · Virtual reality · Construction safety · Task performance · Learning

1 Background to Study

Unmanned Aerial Vehicles (UAVs) or drone applications have the potential to provide value-driven solutions for a wide range of applications that need a variety of capabilities [1–3]. Recent technological developments in unmanned aerial vehicles have significantly aided in improving the diverse application of drones in construction

A. Onososen (✉) · I. Musonda · C. Dzuwa
Centre for Applied Research and Innovation in the Built Environment (CARINBE), Faculty of Engineering the Built Environment, University of Johannesburg, Johannesburg, South Africa
e-mail: adetayoo@uj.ac.za

M. Ramabodu
Department of Construction Management and Quantity Surveying, Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa

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[5]. Drones in construction are increasingly being adapted for site security, thermal imaging, progress monitoring, building inspection, building surveys, equipment tracking, photography and material handling, amongst others [4, 7]. Firms are beginning to maximise opportunities associated with digitalising processes and workflow in the sector through drone adoption. Still, they are constrained by a lack of training resources given the high initial investment required to acquire drones [6, 8, 9].

To solve this problem, recent innovations are pushing the boundaries of visualization to provide training for users of digital technologies in an immersive environment mimicking real-life scenarios and equipment [10]. The term "virtual reality" (VR) describes the artificially produced three dimensions using a computer system to create an environment with the use of sensors [11]. This use case extends to areas such as; VR in various safety contexts, including identifying risks, educating the workers, transferring skills, and ergonomics. With the introduction of VR, the use of sophisticated VR tools to produce a visualization of difficult working circumstances and risk mitigation Knowledge and education have increased [12–14]. Rokooei et al. [12] highlight that the use of VR in training is gaining momentum with examples including virtual reality (VR) as a teaching tool for roofers since it poses no danger and can replicate high-altitude scenarios real hazards of falling.

This advantage has placed VR at the centre of the emerging nature of training for workers in the built environment, especially for high-risk tasks. With the increasing adoption of technologies, virtual reality training absorbs the risk of losing or damaging digital tools, which comes with high investment costs. Also important, virtual training provides users accessibility, availability and affordability to repetitive learning with no danger and the ability to self-learn. Therefore, while large construction firms can invest in these digital innovations, virtual training is still required to ensure investment costs are maximized, and loss is eliminated. Platforms for training, monitoring, and control are provided by VR technology, enhancing the safety of building projects and fewer accidents at building sites [15, 16].

The technologies of augmented reality (AR) and virtual reality (VR) in the Architecture, Engineering, and Construction (AEC) industries are important since the built environment is fundamentally reliant on information related to three-dimensional (3D) space and a strong dependence on images for communication and progress monitoring [17]. Constructivist learning is supported by VR's immersive character [18]. As mentioned by Abdelhameed [18], the theory of constructivism is a learning approach whereby people create knowledge by taking lessons from their experiences. Human learners get knowledge from the world via experiences and the use of their senses. VR uses computer-generated sensory input in place of real-world sensory input simulation to facilitate learning by giving users a setting where they may explore situations rather than just envisioning things. Therefore, this study investigated the use of visualization-based technology with a specific focus on virtual reality training to examine effectiveness of task performance in human-drone interaction learning to improve safe adoption of drones in industrialised construction sites. The overarching research question in this study was to explore how effective VR is in training users on drone flight operations with an additional focus on aerial material transport on construction sites. Results based on the data generated by the virtual training platform is presented.

2 Research Method

The main objective of this study was to determine the efficacy of virtual reality (VR) training for drone flying operations measured based on task performance in the virtual environment. The research technique entailed creating a virtual reality environment where people may interact with drones in a realistic setting. The elements required to set up the scenario for the virtual environments were modelled in 3D as the first step in the technique approach. The construction site, construction trucks, supplies on building sites, drones, and jobs to be completed were among the 3D-modelled assets. The 3D models were turned into assets in the second stage. The drone simulator was developed using C# as a programming language with Unity 2022.1.16. The design characteristics, such as weight, grasping joint mechanism friction, rotation, retraction, and expansion speed, were assigned to the drone. The flying environment was four unfinished structures on a construction site. The training scene was supplemented with other items frequently seen on building sites. In the third stage, the various assets are combined to form the overall environment and are integrated.

Furthermore, a good level of photorealism was produced using the lighting system. For the Oculus touch controllers and thumbsticks to assist users in navigating the scene, carrying out activities, and interacting with other people in the environment, this level of interaction was achieved using C++ . The purpose of task management was to enable participants to choose materials (in this example, bricks) between a lower point on the job site and deliver at a much higher level (On the top of a structure). A pilot study with experts in the built environment was carried out after the design and development of the drone. The users first learned how to fly the drone vertically and horizontally, control it without any weight to pick up the material, and deliver it. An automatic data gathering system was included in the program to offer indices on the user's performance depending on various parameters. This allowed researchers to investigate what users were doing in the environment and provide information for future development and improvement. Associating sounds with environmental actions further supports each interaction to increase the level of realism. Before the testing, participants had a training session that involved instructing users on how to operate the controls to fly the drone and navigate through the area manually.

The Oculus Quest 2 was chosen for the test. Before participating in the trial, participants had to sign paperwork requesting their ethical consent. After that, the participants quickly explained how Oculus Quest 2 functions. Participants were advised to adjust the HMD to their comfort. To ensure precise eye-tracking data, participants calibrated their eye gaze. After a successful ocular calibration, the trial got underway. Participants were immersed in the environment with activities requiring the delivery of building materials while fully immersed in the learning environment (bricks in this case). For everyone, this process was performed in the same sequence. Based on each participant's behaviour in the setting, the virtual program collected the data for the research. The parameters used to retrieve the data were Payload, Collision object, Time, Drone speed, Drone Position, Drone Orientation, Safe Distance, Pilot Position, Command, Drone Range and Battery life.

Tasks given to users in the VR environment involved (1) learning the controls to understand how to fly the virtual drones, (2) flying the drone in the environment within the boundaries of the site to ensure privacy, (3) safe flying of the drone to avoid collisions with objects and humans (4) using the drone to transport materials vertically and horizontally without dropping the materials (5) learning safe navigation of the drone with materials handling at high altitude (6) controlling the drone in adverse weather conditions to simulate real-life scenarios (7) maintaining contact with the drone by ensuring it is not lost (8) safe and effective delivery within a given period (9) beyond visual line of sight learning to adopt skills required for the drone in out of sight or night operations. To validate the virtual environment developed, it was tested by industry experts such as drone pilots in practice and drone design experts to ensure the applicability and correctness of embedded components and required actions.

3 Results and Discussion

3.1 Number of Task Deliveries in the Experiment

As shown in Fig. 6 the frequency of deliveries in the environment by participants using drones for material handling was low. In testing the task performance of the experiments, most could not successfully deliver 3 tasks within the specified 10-min duration. While this is surprising, it is not unusual for first-time drone users who are inclined to initially understand the drone controls and virtual settings before performing the required tasks. However, the successful deliveries revealed that virtual environments could efficiently train users in learning operations of drones for material handling. The low number of deliveries also indicates the level of rigour ensured in demonstrating the drone mimics real-life scenarios. This was further supported by a post-experiments discussion with licensed drone pilots who participated in the experiment (Figs. 1, 2, 3, 4 and 5).

Fig. 1. 3D model-conceptual view

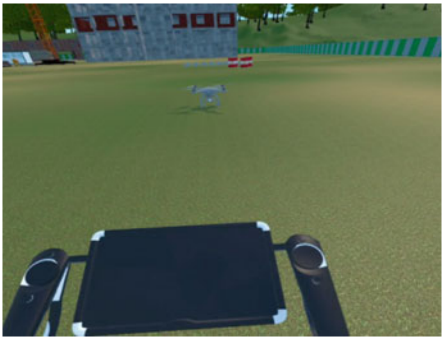

Fig. 2 Image showing VR environment

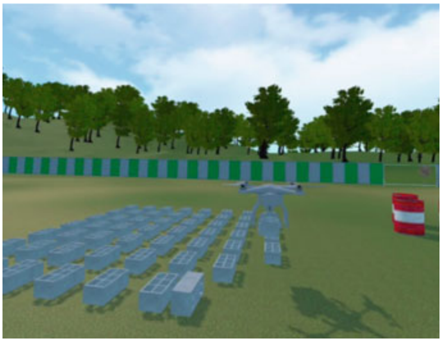

Fig. 3 Image showing materials in VR

3.2 Delivery Distribution Based on Time-Taken

The delivery distribution based on time-taken, as shown in Fig. 7, revealed that the tasks performed took about 40–60 s for most of the tasks performed successfully. Given the high number of materials transported daily on the construction site and the battery span for most commercial drones in operations, this was considered critical to be measured. It is important as it can justify the cost-benefit use of adoption drones for material handling on-site against current traditional approaches. With the current drone battery span of an average of 20 min, the number of tasks to be performed

Fig. 4 Participants

Fig. 5 Participants

before recharging is vital to convincing stakeholders of the cost-benefit of adoption and returns on investment that integrating drones in daily construction operations bring. However, collisions were also measured to ensure, in an attempt to maximise the use of drones in delivering tasks, that this is done in a safe and healthy approach with no risk of hazards to humans, animals, aircraft and other objects.

3.3 Mean Drone Velocity Distribution

Mean drone velocity distribution, as highlighted in Fig. 8, is vital to measure the successful flight behaviour of users in the environment and indicate what velocity levels are adequate for successful and safe flight operations. While there are standard speed levels for drone flights, with drones handling materials on construction sites, a safe velocity level at which the materials can be well handled and tasks delivered

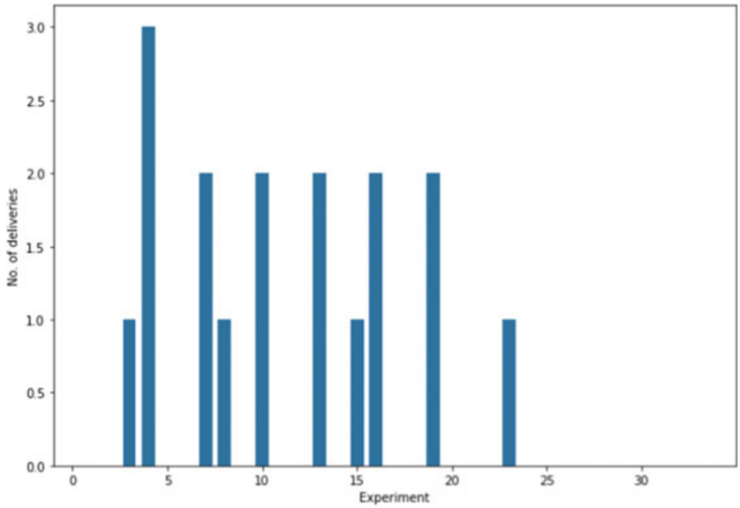

Fig. 6 Number of tasks delivered successfully in the experiment

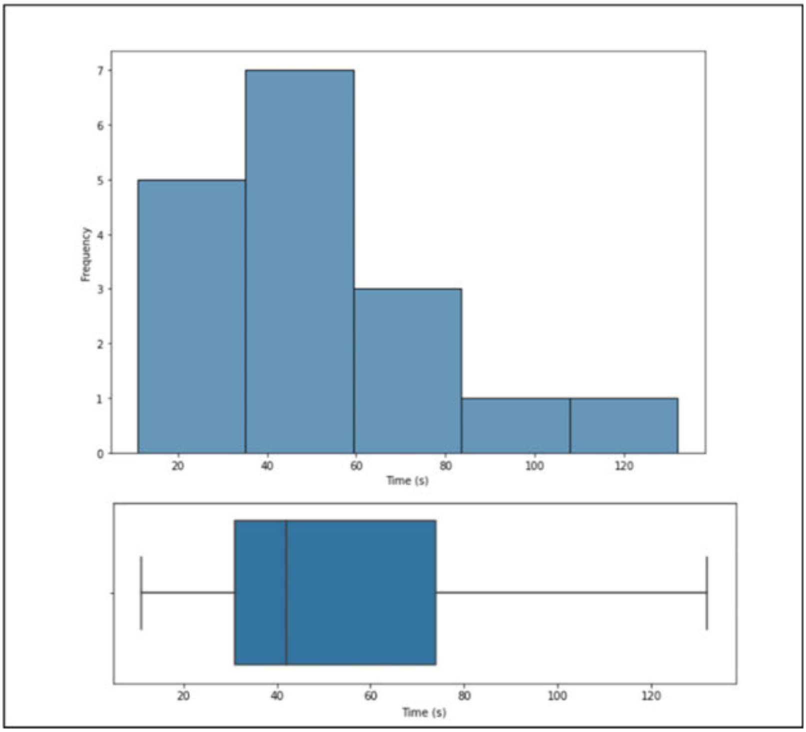

Fig. 7 Frequency of delivery distribution based on time taken

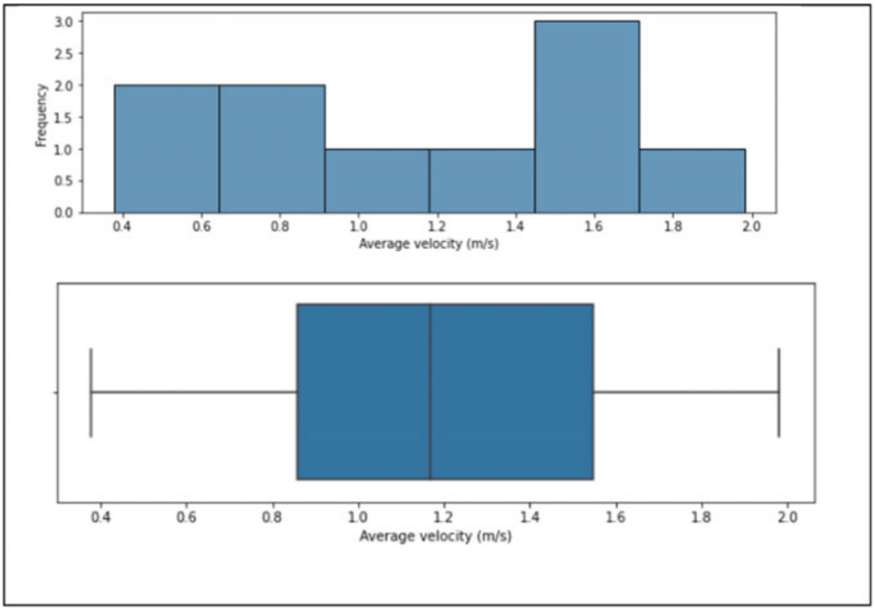

Fig. 8 Mean drone velocity distribution.

successfully is vital to training insights in directing users and ensuring the safety of human-drone operations on site. This is important for drones carrying payloads for non-military uses in a construction environment, given the presence of humans and properties at close proximities.

As shown in Fig. 9, the low-velocity distribution at which unsuccessful experiments flew reveals that velocity was not a major criterion in the ability to deliver tasks but depends on the users' skill to control the drone. Hence, this reveals that virtual environments are important in drone flight operations to increase skills before interacting with drones in a real-life setting.

3.4 Mean Drone Altitude Distribution

Figure 10 reveal the frequency of the mean drone altitude distribution of unsuccessful experiments, while Fig. 11 reveal the mean drone altitude distribution of successful experiments. They revealed that altitude is not a significant factor in the ability to deliver tasks in the environment. They also show that depending on the altitude level, tasks are delivered successfully or unsuccessfully based on the participants' skills level in using the drone to execute the task given. As identified previously, this reveals visualisation's effectiveness in building skills before physical human-drone interaction on site.

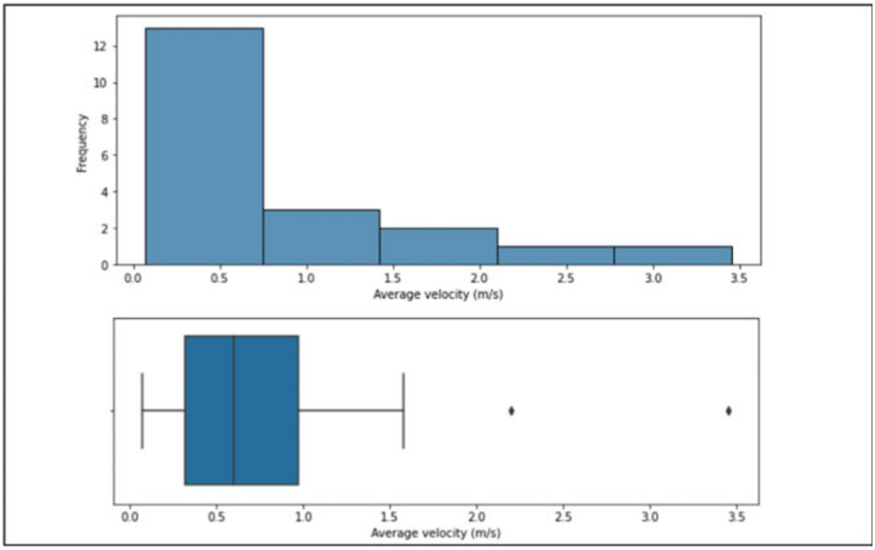

Fig. 9 Frequency showing mean drone velocity distribution of unsuccessful experiments

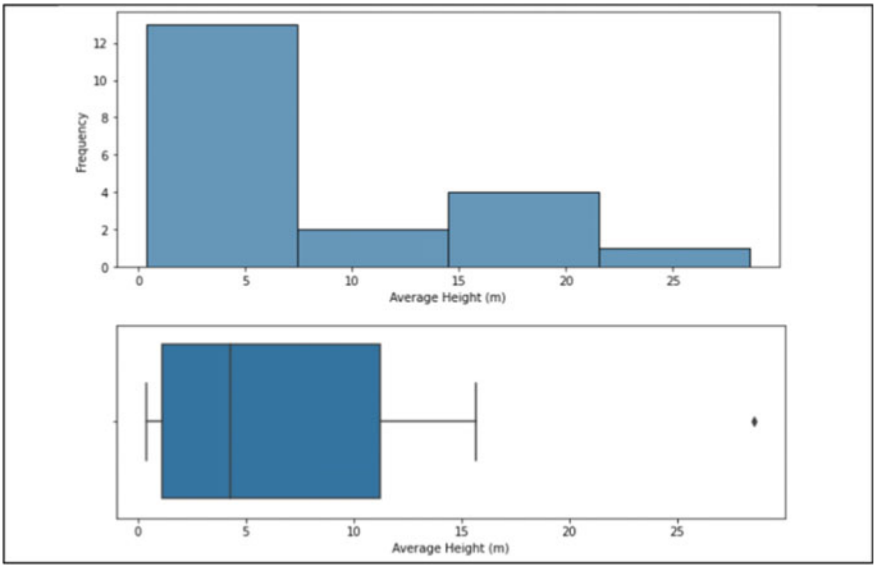

Fig. 10 Frequency showing mean drone altitude distribution of unsuccessful Experiments

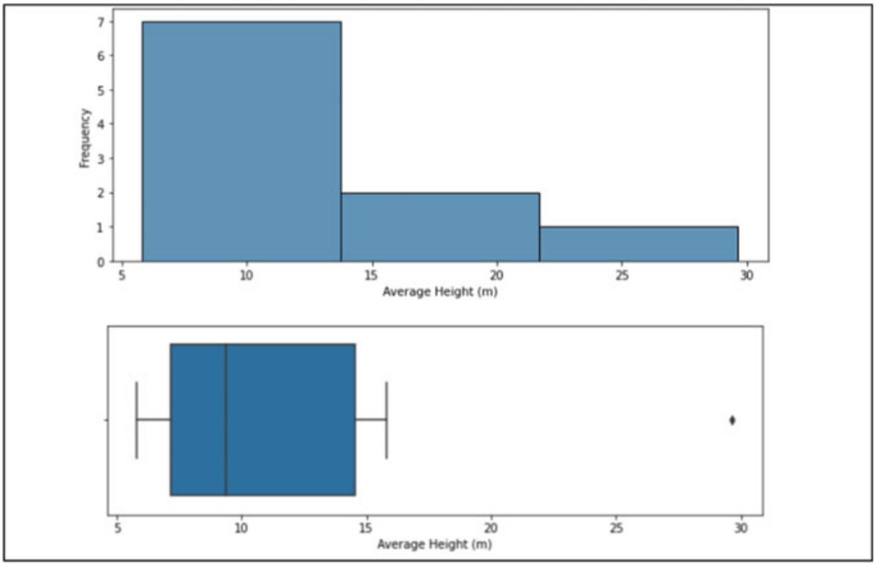

Fig. 11 Frequency showing mean drone altitude distribution of successful Experiments

3.5 Delivery Altitude Distribution

Figure 12 reveals that most of the delivery made were done at 35.5 to 40 m height. At the same time, some deliveries were also made at heights lower and higher than this. This further supports the previous discussion stating that pilots can deliver tasks at specified heights when the drone operator's skill level is ensured. Further testing on this will examine the difference in delivery altitude of users using a visual line of sight in drone operations and those using beyond visual line of sight (BVLOS). This is further important to improve the usage of drones to deliver tasks and materials at any altitude. The success of this would be critical for deploying drones in hazardous construction sites beyond physical reach [19, 20].

4 Delivery Velocity Distribution

Figure 13 revealed that the delivery velocity for the experiments was under 2.5 m/s. This is not surprising, given that users can fly at much higher speeds until they pick up objects or materials with the drone. Therefore, the materials reduce the velocity of the drone. This is critical to two factors. Firstly, it demonstrates the rigour of the virtual training platform to mimic real-life scenarios, which is important to justify the ability of virtual environments to precede physical training exercises. Secondly, it informs drone operators and first-time users on what to expect concerning velocity

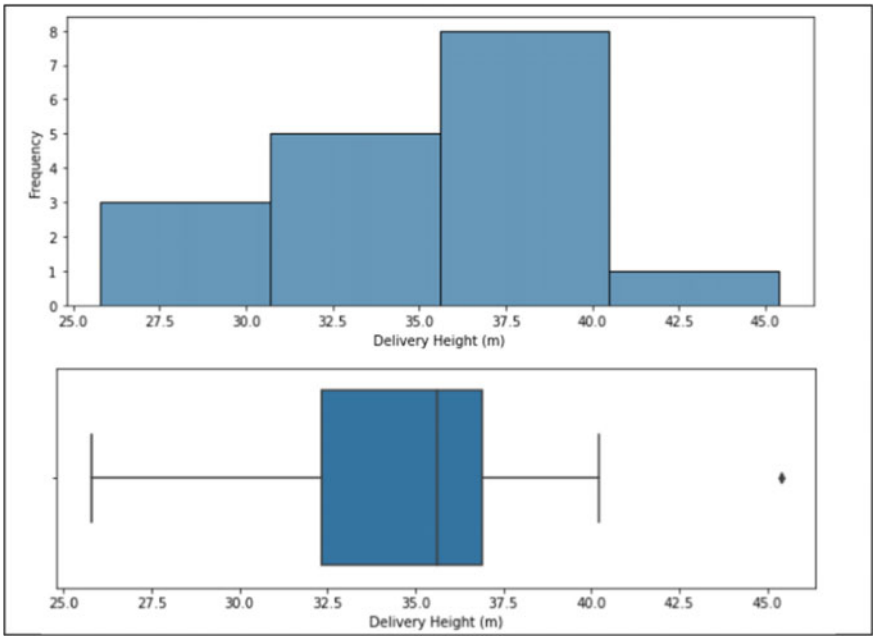

Fig. 12 Frequency showing delivery altitude distribution

in using drones with payload and those without payload. This is important, especially for BVLOS operations and flying drones in adverse weather conditions. Users can adjust flight plans based on understanding the difference in velocity between a loaded drone and a non-loaded drone. This knowledge is essential to not losing drones and payloads during adverse flight situations and to ensuring safe and successful flight task performance [20–22].

5 Typical Flight Paths (Altitude)

Graphical representations of typical flight paths (altitude) for successful and unsuccessful experiments are revealed in Fig. 14. The results revealed that successful users had a progressive flight pattern by first learning the drone control at lower altitudes and progressively flying to higher altitudes. However, this is different from unsuccessful flights, which revealed users were starting out at high altitudes and coming down to low altitudes. The implication of this shows that when users fly at high altitudes at the initial commencement of the drones, they find it difficult to understand the drone's controls, affecting the experiments' success. This seriously impacts flying safety and collision with aircraft, animals and properties. This provides critical insight for training guides in directing users' learning [23, 24].

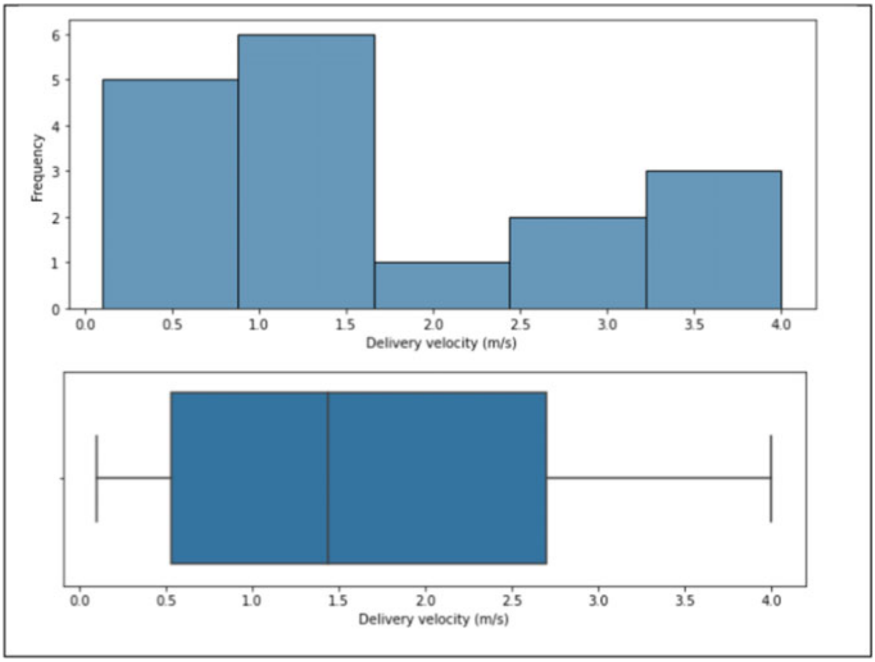

Fig. 13 Frequency showing delivery velocity distribution

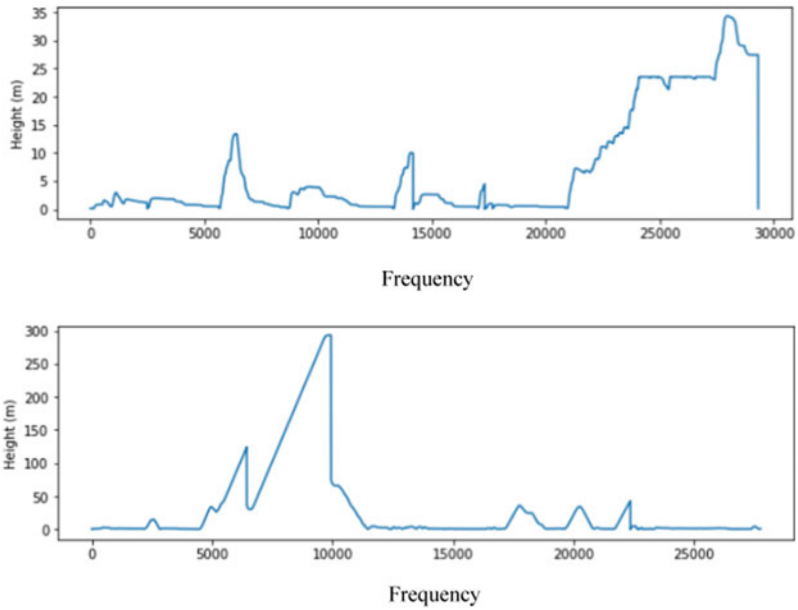

Fig. 14 Graphical representation of typical flights paths (altitude) for Successful experiments

6 Conclusion

While drones have been considered for material handling in other sectors such as logistics, Health, manufacturing etc., they are underexamined in construction environments. Using drones to handle construction materials is an emerging drone research area. They are important for risky situations such as the delivery of robotic systems/equipment in hazardous environments, which makes using drones in material handling on construction sites inevitable. However, they are also prone to health risks from dropping objects, colliding with properties and humans, and mishandling materials transported. Therefore, this study examined virtual reality's use for safe drone flight operations through task performance in an immersive environment.

With time, due to the latest technological innovation, drones are becoming cheaper and more accessible, but not without accompanying safety and privacy concentrations. This work demonstrates the effectiveness of using VR as a training platform for drone usage on construction sites. The study revealed that VR is an effective platform in task performance training involving drones such as robots. Also, the study identified safe flight behaviours and patterns based on altitude and velocity.

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Real-Time Inference of Temporal Emotional and Behavioral Conditions of Learners in Problem Solving Within Mixed Reality Environments

Édouard Castets, Ivan Mutis, and Gady Agam

Abstract Using new affordances of Machine Learning (ML) and Mixed Reality (MX) technology, the presented research looks at how learners' decision-making in problem-solving can increase with the technology interaction. The approach empowers users for enhanced problem-solving outcomes by enabling them to perform adapted actions in an MX environment. For example, present an adapted user's view of 3D design components in the immersive space for any action (locking and moving) in problem-solving (e.g., design interpretations). The aim is to incorporate ML to tailor the user's ability to problem-solve complex 3D design components by capitalizing on the flexibility of MX immersive environments. The system uses a collection of physiological and pupillometry data to create real-time inferences of the user's state (emotional and physiological conditions). This paper focuses on the first phase of developing the MX and ML system for the augmented technology-user interaction to allow inference of the data in real time.

Keywords Spatial and temporal information · Spatial and temporal ability · Problem-solving

É. Castets
Department of Mechanical, Materials, and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL 60616, USA

I. Mutis (✉)
Department of Civil, Architecture, and Environmental Engineering, Illinois Institute of Technology, Chicago, IL 60616, USA
e-mail: imutissi@iit.edu

G. Agam
Department of Computer Science, Illinois Institute of Technology, Chicago 60616, USA

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1 Introduction

Significant limitations in the current pedagogy in construction engineering (CE) include ineffective application, analysis, and synthesis of any form of design representations to situational and physical contexts**.** The abundance of variable [1] in "real-life" construction sites impacts learners' abilities to effectively manage and comprehend significant amounts of *spatial* (how to design components or resources are related to one another in the 3D space) and *temporal* (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task information) information [2]. Limited or no ability to process spatial and temporal information (i.e., lack of spatial and temporal cognitive ability [3–7]) hinders the understanding of designs and management of the varying local conditions (e.g., unplanned conditions) that transpire during construction processes. The limitation leads to a suboptimal integration and internalization of complex spatial and temporal information, hindering decision-making tasks in problem-solving. Research challenges emerge in the processing and integration of complex spatial information effectively from image-based visualizations [8–12] effectively.

This research addresses these challenges by focusing on the capability of new technologies to enhance users' cognitive processes. The approach explores the users' use of cognitive and physiological responses during problem-solving by examining how learners' decision-making in problem-solving can increase with technology interaction. The approach empowers users for enhanced problem-solving outcomes by enabling them to perform adapted actions in a mixed reality (MX) environment—e.g., present an adapted user's view of 3D design components in the immersive space for any action (locking and moving) in problem-solving (e.g., design interpretations). The aim is to incorporate ML to tailor the user's ability to the complexity of 3D design components in problem-solving by capitalizing on the flexibility of MX immersive environments. The system uses a collection of physiological and pupillometry data to create real-time inferences of the user's state (emotional and physiological conditions) (Fig. 1).

This paper focuses on the first phase of developing the MX and ML system for augmented technology-user interaction. The design incorporates methods to collect

Fig. 1 MX experience with engineering design components

and treat data that could be used to build models for inference of the user state (temporal emotional and behavioral conditions) in problem-solving (e.g., the user's realization of difficulty—or moments of impasse when problem-solving). The state changes are characterized by physiological stimulation (symptoms, e.g., rapid heartbeat, muscle tension) or behavioral indicators (e.g., rapid hand movements) as the users (physical bodies) face a situation (e.g., difficulty in addressing a solution in problem-solving). The states change as the situation from an activity fade—they are temporal conditions.

The presented approach develops a ML model to predict and infer the users' states as users (learners) may experience different states in response to various triggers about a particular situation or activity. The model will enable manipulation of the temporal conditions, thereby facilitating decision-making in problem-solving.

For this first phase of the approach, the designed system is an enhanced OST-HMD through sensors (visual sensory-motor and bio-metric sensors) and accompanying computing power for an adaptive human-computer interaction (HCI). For instance, the system will capture the user's activity in the MX environment during simulations using wearable sensing technology and eye-tracker devices in real time and predicts the users' state while manipulating MX reality objects. It addresses the technical challenge of modeling the users' physiological and behavioral responses by taking advantage of one of the users' free body motions in the MX environment when manipulating MX objects. This system will be used for the problem-solving task using MX to address the users' cognitive ability in real-time. The contributions of this paper are (i) method for data collection with unobtrusive and open-source technology; (ii) framework for inference in real-time to assess the user's state during problem-solving.

The organization of paper this paper arranges the presentation with a summary of the main contributions to the collection and use of biometric data, a description of the MX problem-solving task, and the technology architecture and experimentation outputs.

2 Related Work

Many studies have been conducted to assess or observe subjects' abilities and psychological states based on physiological signals. There is a lack of studies on the exploration of studying the user and augmented, virtual, or mixed reality technology interaction using physiological data. The interaction is founded on tracking physiological signals together with eye features signals (i.e., pupillometry).

In 2018 P. Schmidt et al. [13] introduced the most extensive open-source dataset related to stress using physiological features. Their study aimed to measure subjects' physiological features (Table 1) as they were exposed to different affective stimulation (stress, resting, and amusement). The outcome provided data to classify the emotional state of the subject. Their data was collected using unobtrusive collection wearable sensing devices to measure the Blood Volume Pulse, Electrodermal

Table 1 Physiological features

Feature	Device position	Frequency
Electro-cardiogram	Chest	700 Hz
Electrodermal activity	Chest	700 Hz
Electro-myogram	Chest	700 Hz
Body temperature	Chest	700 Hz
Acceleration XYZ	Chest	700 Hz
Respiration	Chest	700 Hz
Acceleration XYZ	Wrist	32 Hz
Blood volume pressure	Wrist	64 Hz
Electrodermal activity	Wrist	4 Hz
Body temperature	Wrist	4 Hz

Activity, body temperature, and the 3-axis acceleration. The study presents their classification results on their data, with up to 80% accuracy with a 3-class classification problem (amusement, stress, neutral state) and up to 93% with a 2-class classification problem (no stress, stress).

Pupillometry has proved itself useful for the classification of emotional states. In 2014 Pedrotti [14] and his team presented a method based on wavelet transformation on pupillometry signal to predict with a neural network the psychological stress of a subject. They realized a data collection during a driving session on a simulator where the subjects had to drive normally or in a stressful situation. They tracked pupil diameter and electrodermal activity, and after training their neural network, they predicted the psychological stress level with a precision of up to 79%.

Yamada et al. [15] propose to detect mental fatigue while watching a video from eye tracking. The study presents a method based on a neural network with feature selection to predict mental fatigue from data collected (pupil diameter and eye gaze saccades features) during an experiment. Their final model succeeds in predicting mental fatigue state with an accuracy of up to 91%.

One of the challenges of data collection system is to make the data usable for inference in real time. For example, it appears that on some wearable sensing devices for data collection, such as Empatica E4 used in the Philip Schmidt paper [16], the motion artifact is interfering with the Blood volume pulse signal, resulting in a noisy blood volume pulse signal. An important aspect of the blood volume pulse is that a clean signal contains most of the electrocardiogram features, including heart variability, which has been revealed to be an important feature in the Smith's and colleagues' study [13]. Two notable articles tackle the question of cleaning the blood volume Pulse signal. The first one is a study from Reiss [17]. Their study presents a large dataset of physiological signals recorded during various activities with motion artifacts. The data included acceleration, blood volume pulse, and electrocardiogram. Moreover, their study presents activities based on a convolutional neural network to predict the heart rate from time-frequency spectra of the noisy BVP signal and 3-axis acceleration with a mean average error performance of 7.65±4.2 bpm, which outperforms many other methods in 2019.

In 2021, Chang et al. [17] provided a study where they proposed to train a convolutional neural network to reconstruct a clean BVP signal from a noisy signal. Then they offer a method to predict heart rate with a frequency spectra analysis. Their final model predicts the heart rate with an average mean error of 1.65 bpm.

3 Problem-Solving Tasks Using MX and ML Ecosystem

The design is a problem-solving task that incorporates spatial and temporal abilities. The problem-solving task is an experiment that enables the collection and treatment of data to be used to build models of the ML inference of the user state (behavioral conditions. An example of the behavioral conditions is the user's realization of difficulty—or moments of impasse when problem-solving (as shown in Fig. 2). As the behavioral conditions analyzed on data collected on problems with simple MX visualizations features, the same conditions should easily translate to more complex CE problems with MX visualizations. The conditions will be used to indicate the users' spatial and temporal ability performance.

The approach allows MX users to experience different states in response to various triggers about a complex task on problem-solving. The state changes are characterized by behavioral indicators (e.g., rapid hand movements) as the users (physical bodies) face a situation (e.g., difficulty in addressing a solution in problem-solving). The states change as the situation fade—they are temporal conditions.

The problem-solving design of the experiment consists of a cube puzzle (similar to Tetris game features), where the users are required to move pieces into a grid to complete a whole cube. Users must move around to select, move, and fit pieces into the grid to complete the puzzle. Records of each user's movements for spatial and temporal information (e.g., time to relate MX objects to one another in the MX space) for each user are collected for further analysis. Figure 2 illustrates the sequence the user followed for the cube puzzle, each scene indicating the embodiment (moving pieces, walking in the physical space) for the MX objects in the associated problem-solving.

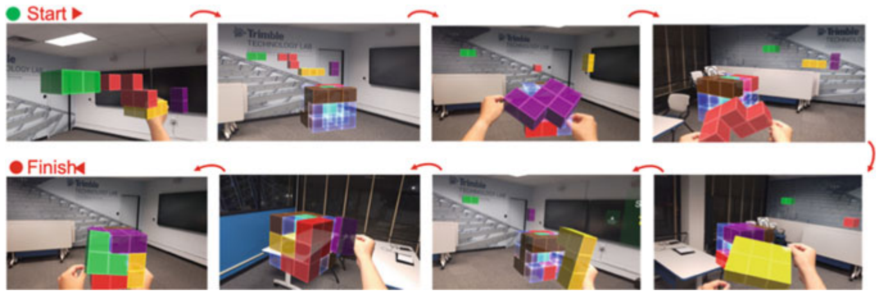


Fig. 2 Foundational experiment for problem-solving on spatial and temporal cognition: individuals move and lock MX objects (actions) as they experience different states in a process (from start to finish) in response to various triggers about a complex task in problem-solving

4 System Design

For this first phase of the approach, the system design consists of an enhanced OST-HMD through sensors (visual sensory-motor and bio-metric sensors) for human-computer interaction (HCI). The system will capture the user's activity in the MX environment during simulations using wearable sensing and eye-tracker devices in real-time for the prediction of the users' state while manipulating MX reality objects.

The first device used for data collection is the wearable sensing technology device to collect physiological feature data. (Table 2).

The system design incorporates an OST-HMD as an MX Headset (MS Hololens2). The MX device is a sophisticated ecosystem with multiple sensing and tracking technology functioning in a system to make high-quality MX experiences possible. Although the MX device incorporates advanced technology to engage the user in scenarios with a needed degree of awareness in the MX experience, user-computer interaction research is a challenging activity due to still limited sensing, computing capabilities, and the narrow field of view—as factors of portability (untethered device) and affordability may come into place for this type of market-ready device.

The researchers address this challenge by incorporating additional computational and sensing capabilities without reducing the ability of the user to move freely within the physical environment with unbearable weight, heat, and battery life for lab activities. The researchers were able to build a new MX technology ecosystem for ML and MX user-interaction research, facilitating activities such as data collection methods

Table 2 Initial collected features

Feature	Device
Blood volume pulse	Empatica E4
3 axis acceleration	Empatica E4
Body temperature	Empatica E4
Electrodermal activity	Empatica E4

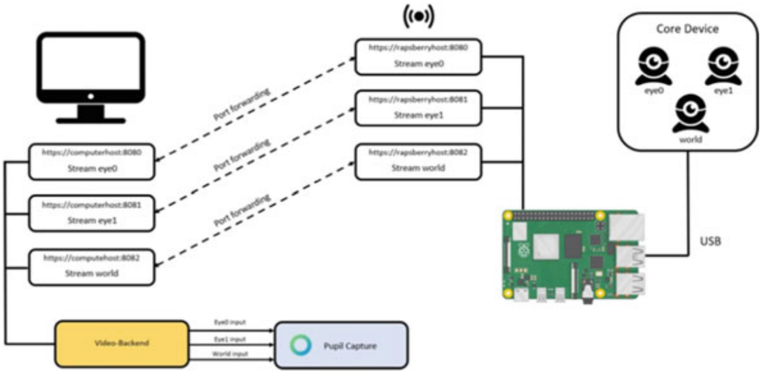


Fig. 3 Wireless communication framework between Pupil Core mounted on OST-HMD device and a computer

to data treatment, such as using an eye tracker with the use of open-source data (see Fig. 3).

The technology ecosystem was designed using the following specification factors: (1) portability (e.g., maintaining untethered OST-HMD feature); and (2) stability (e.g., no- demand for intensive computations to the OST-HMD). (3) reliability (e.g., no-demanding peripheral performance in the OST-HMD).

The developed ecosystem consisted of wearable sensing technology devices connected via Bluetooth Low Energy protocol. The ecosystem included eye trackers connected to a companion computer (e.g., Raspberry PI 4) powered by a low-consumption battery. The design was conceived to permit the functionality of additional fix eye tracking cameras on the OST-HMD. The system is depicted in Fig. 3 and Fig. 4.

One of the major challenges was obtaining full wireless mode operations in each of the sensing devices. For example, the pupil tracking software is robust and accurate but uses many resources, including a GPU, to compute the eye tracking features in real-time. Hence a wireless mode can't use a companion computer to run the pupil tracking software. Thus, the researcher chose to make the companion computer redirect the video stream of the cameras (see Fig. 4) via a TCP protocol.

Important technical design considerations for the ecosystem were: (i) the additional eye tracker sensors must function at the same time as the OST-HMD; (ii) additional wearable sensing technology should be synchronized with the OST-HMD as data will be collected in real-time and wirelessly for inference and real-time-feedback to the OST-HMD.

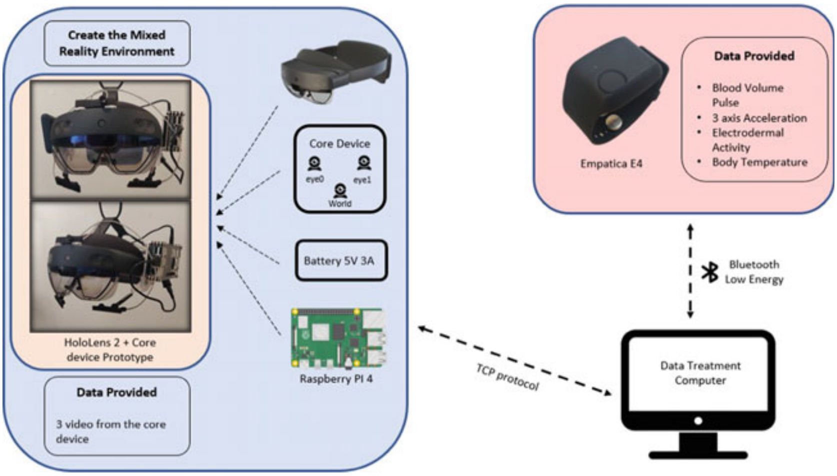


Fig. 4 Prototype OST-HMD + Core Device

5 Data Collection and Treatment

A summary of the collected data (features) is summarized in Table 3. The collected data will be treated to feed the ML models.

Some of the features, like pupil diameter, can differ from one person to another. Thus, the researchers developed a baseline moment during the collection to compare the value from one moment to another.

The eye gaze velocity was computed from the Cartesian coordinates (x, y, z) of the eye gaze point converted into spherical coordinates (r, θ, ψ), as expressed from Eqs. 1, 2, 3 and 4.

$$r = \sqrt{x2 + y2 + z2} \tag{1}$$

$$\theta = arcos\left(\frac{y}{r}\right) \tag{2}$$

Table 3 Collected features

Feature	Device
Blood volume pulse	Empatica E4
3 axis acceleration	Empatica E4
Body temperature	Empatica E4
Electrodermal activity	Empatica E4
Pupil diameter	Pupil Device
Eye gaze velocity	Pupil Device

$$\psi = (\vec{u}_1, \vec{u}_2) \tag{3}$$

where $u{\rightarrow}_1 = (1, 0)$ and $u{\rightarrow}_2 = (z, x)$

$$\omega = \frac{\sqrt{d\psi^2 + d\theta^2}}{dt} \tag{4}$$

with ω, the gaze velocity

There was the need to pre-process the eye-tracker data. Firstly, as the pupil size is very different from person to person, the pupil diameter signal at time $Pd(t)$ was compared to the mean pupil diameter during baseline, as in Eq. 5.

$$Pdrelative(t) = \frac{Pd(t)}{Pd_{meanbaseline}} \tag{5}$$

The eye tracker provided eye-tracking data, including pupil diameter and eye gaze position, even during blinks. Sensing issues occurs such as the no detection of pupil data during blinking moments and, at other time, due to unusual eye position. Hence these data need to be corrected during these moments. The employed method to address this challenge was discarding the outliers and realizing a linear interpolation for the missing data.

The pupil tracking software associates a confidence index between 0 and 1 for each recorded data. Hence the retained data were data with a confidence index above 0.85. For the pupil diameter, the data that must be discarded was data where the pupil diameter drops to 0 due to a lack of detection of pupil data. The remaining data that was in the 2nd percentile was discarded. Also, for the eye gaze velocity, the remaining outliers that must be discarded were high-velocity values due to a lack of detection of the pupil. When the position of the eye gaze was moving with a high velocity, the values not included in the 98^{th} percentile were discarded.

On the clean blood volume pulse signal, it was possible to compute the heart rate and the heart rate variability, which are features that have demonstrated their impact on the classification of human emotional states [13]. The researchers considered that the motion artifact strongly affects the blood volume pulse signal. To extract the heart rate from the blood volume pulse signal, the researchers developed a framework on a Deep Neural Networks model. The model will inform the different states of emotional status (e.g., higher levels of stress) based on the physiological signal while the user solves the problem (see problem-solving task in Sect. 3). This network model was

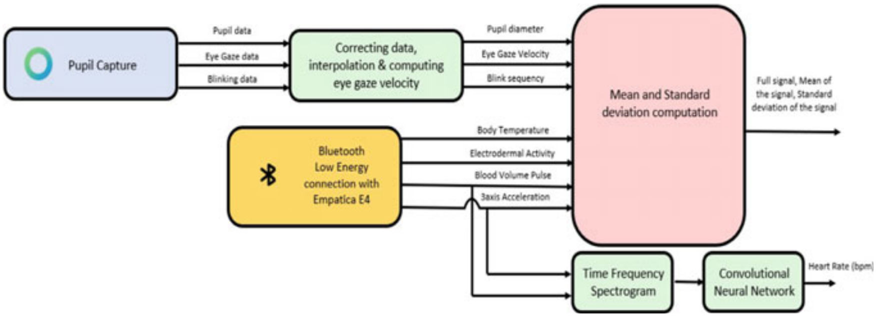


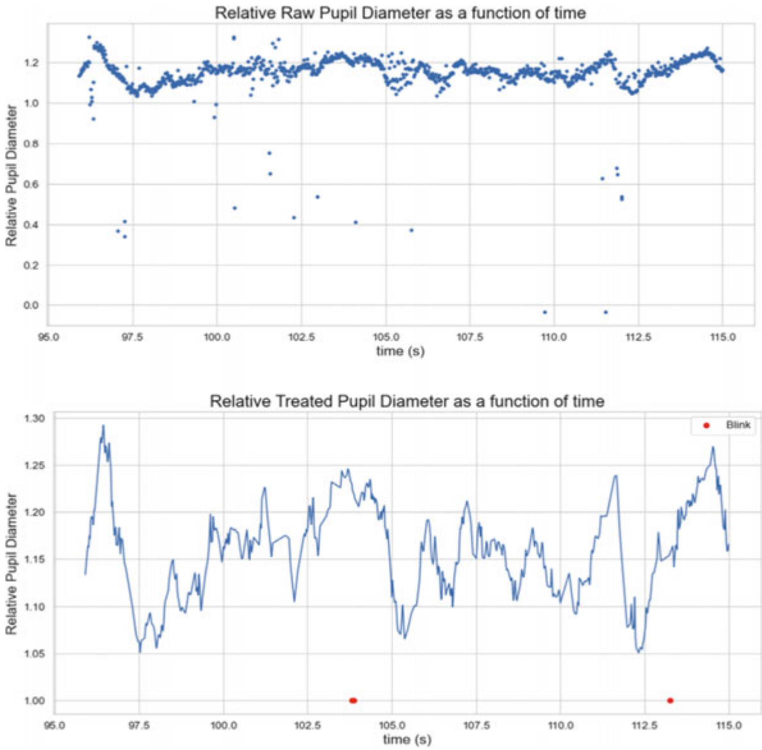
Fig. 5 Prototype Hololens 2 + Core Device

based on the work of Reiss, et al. [16]. The model was trained on the PPG-DaLiA dataset, the largest dataset focusing on electrocardiogram, acceleration, and blood volume pulse in various activities (see Fig. 5). The input was 4-time frequency spectra (1 for blood volume pulse, 1 per acceleration axis), and the label is the heart rate on the sequence.

6 Results

6.1 Signal Collection with System

The study uses the problem-solving tasks in the MX explain Sect. 3. The outcome are each feature collection and associated signal treatments: pupil diameter signal (see Fig. 6), eye-gaze velocity (see Figs. 7), electrodermal activity and body temperature signals (see Fig. 8), and blood volume pulse (BVP) and 3-axis acceleration signals (see Fig. 9). It also important to annotate that were collected and treated in the MX technology ecosystem in real-time in. Note that the pre-processing of the eye data permitted the removal of all the outliers due to errors in pupil detection. The framework provides a solution to collect data and proceed with inference in online mode and in real-time.



6.2 *Output of the Deep Learning Model for Heart Rate Prediction*

At the phase of development, the first deep learning model to predict heart rate was trained on the PPG-DaLia dataset with cross-validation training with early stopping. Figure 10 represents the mean absolute error in beat per minute of each best model for each fold on each validation set. The evaluation metrics of each fold's model on the validation set are given in Fig. 11.

The mean error of close to 18 beats per minute can be explained because subject 15 was part of the validation set of this fold, and subject 15 has a significantly higher heart rate than other subjects. This model was fully trained on the validation set to observe its performance on the testing set. However, the model has been performing on the testing set with a mean error of 10.9 bpm and a standard deviation of the error of 1.18 bpm. Yet with this low standard deviation, the heart rate variability should be computed with a result close to reality. Future work includes measuring the ground truth of the heart rate using a new sensor to be used as a comparative-based line for the model.

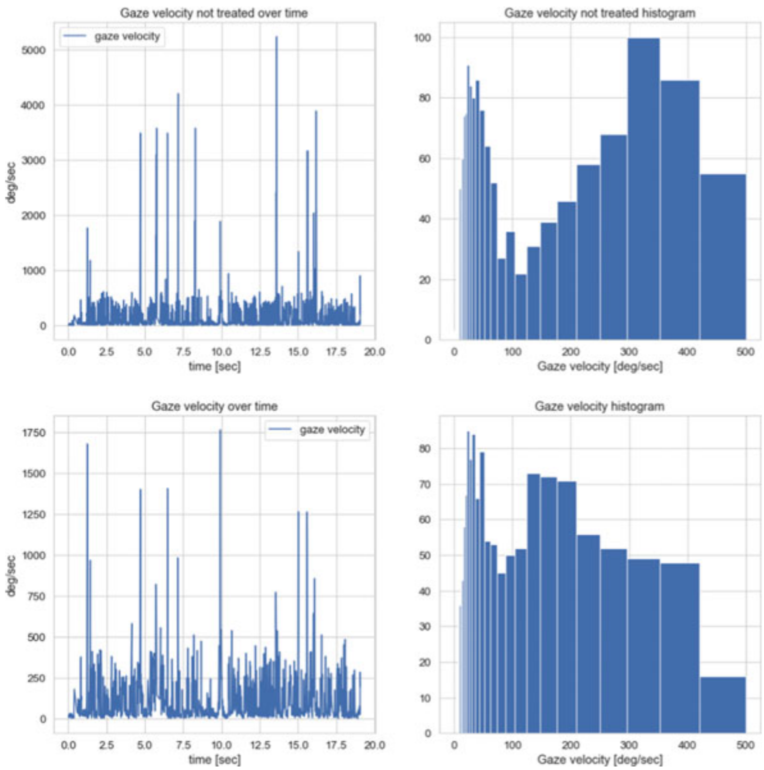


Fig. 6 Pupil diameter signal treatment

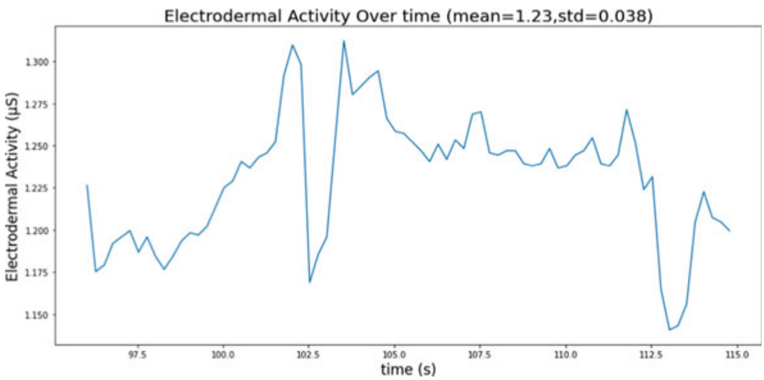


Fig. 7 Eye gaze velocity signal treatment

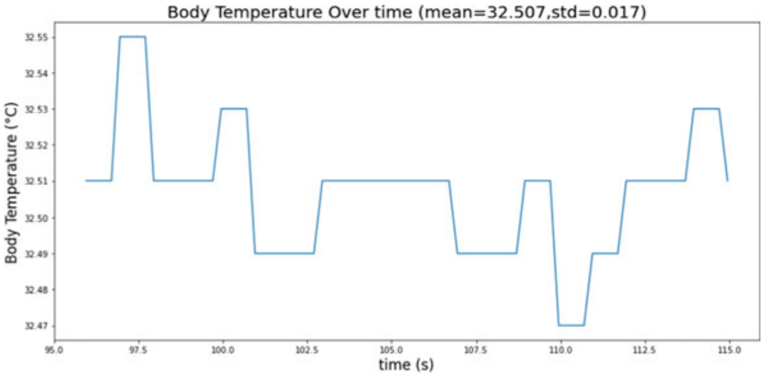


Fig. 8 Electrodermal activity and body temperature signals

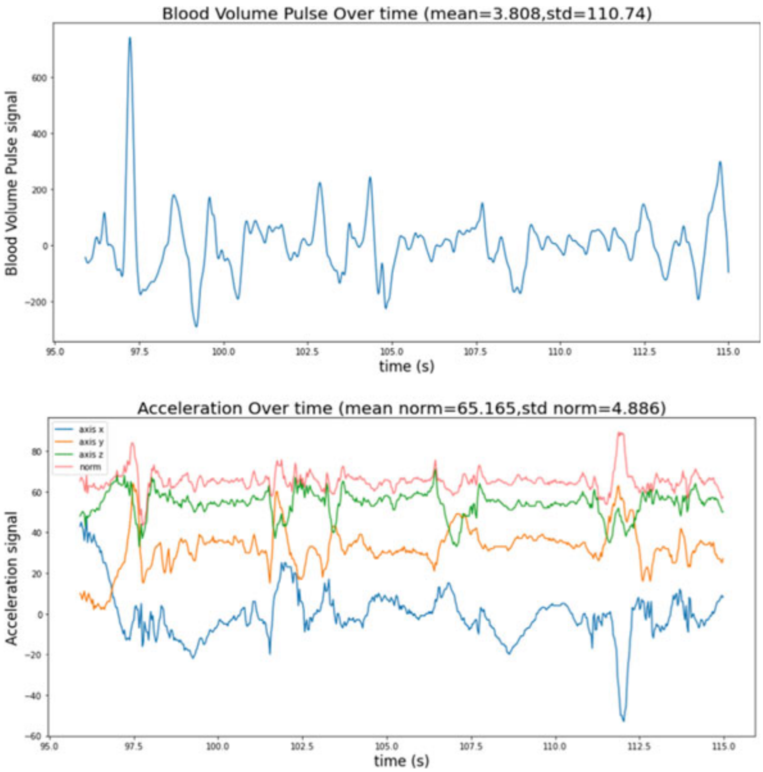


Fig. 9 Blood volume pulse and 3-axis acceleration signals

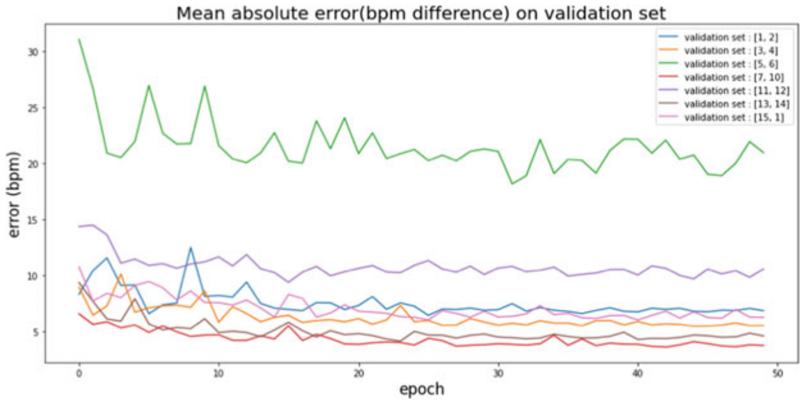


Fig. 10 Validation loss over epoch for each fold's training

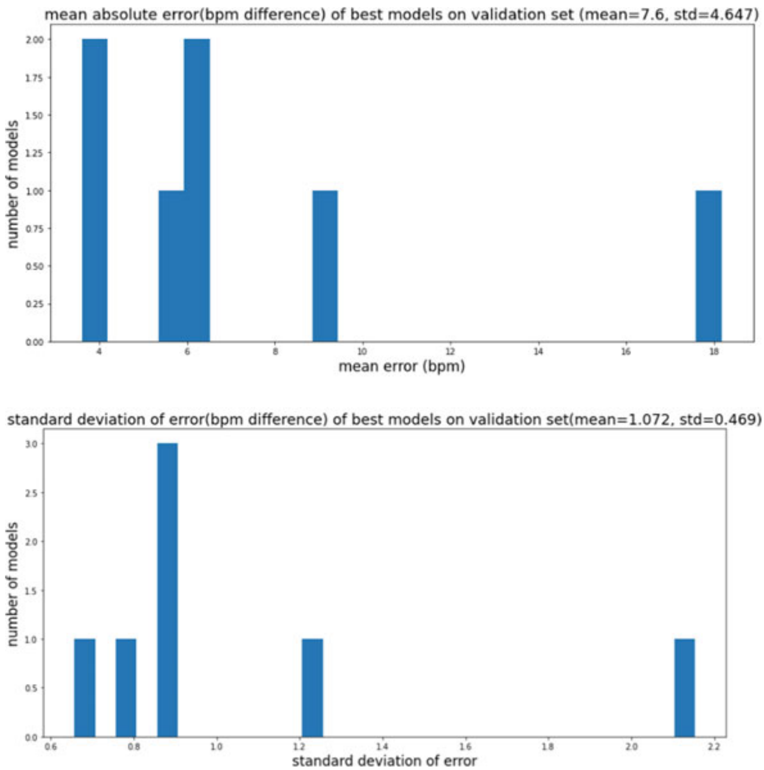


Fig. 11 Mean and standard deviation of the error for each fold's best model

7 Conclusion and Discussion

This study presented the first phase of developing the MX and ML system for the augmented technology-user interaction to allow inference of the data in real time. The approach is a construction of a technology platform that incorporates wearable sensing technologies and OST-HMD into a system. The ecosystem allows the collection of physiological and pupillometry signals in real-time using an online protocol. The developed system aims to gain a highly effective user interaction with the MX when problem-solving—by collecting users' data to feed the ML models, assessing the estate of the user, and getting feedback from the system to the user in real time.

The study also proposes a treatment of the data methodology on eye trackers, as the reduction of errors on data to build inferences using ML models is a major technology challenge. The method identifies and drops values due to errors in the eye tracker. Examples of this outcome are given in the data collection system. The system is ready to provide real-time data collection and inference for collected data.

The future work will be to improve the deep neural network(s), which predicts the heart rate, and use a device to measure the ground truth of heart rate to evaluate the efficiency of this neural network data collected by the ecosystem system. Secondly, data collection will be realized by creating a dataset to build and train a deep learning model for user's estate assessment. The researchers expect to improve the data processing layer, especially concerning the blood volume pulse data, as the heart rate prediction could be enhanced by improving the training and the architecture of the neural network. The researchers anticipate that the approach will be successful in assessing the cognitive process states in problem-solving in Construction Engineering and Management tasks by treating physiological and pupillometry signals collected with this system.

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Other

Blockchain-Enabled-Trust for Construction Project Governance: A Conceptual Framework

Seongha Hwang, Mingzhu Wang, Mohamed Osmani, and Karen Blay

Abstract Construction project governance (CPG) acts as a 'steering wheel' that keeps a construction project steady in a challenging external environment. CPG frameworks can be divided into two types: control-based hierarchical governance and trust-based relational governance. To increase cooperation and networking between the participants in a project, effective CPG depends on well-combined control and trust mechanisms. However, the current CPG framework, which is control-based, is biased toward hierarchical governance and can lead to a lack of trust in the construction project. These issues have resulted in several studies that have focused on blockchain technology (BT) as a potential enabler for addressing the low levels of trust in CPG. However, existing research in this area has failed to address the nature of the relationship between trust as a key CPG challenge and BT. Hence, this paper aims to identify trust as a major CPG challenge and potential BT capabilities to reveal the relationship, through a state-of-the-art review. The findings show that the effective use of three decentralized BT capabilities (decentralized data storage, validity, and access) can positively influence the three relational norms (mutuality, flexibility, and solidarity), which are the functional tools of relational governance. Thus, a more flexible trust-based CPG framework is proposed by establishing relational governance with blockchain technology. Ultimately, this study is expected to enhance the trust between the key stakeholders in construction projects and enable more efficient collaboration and networking between them.

Keywords Blockchain technology (BT) · Construction project governance (CPG) · Hierarchical governance (HG) · Relational governance (RG) · Trust

S. Hwang (✉) · M. Wang · M. Osmani · K. Blay
School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough LE11 3TU, UK
e-mail: S.Hwang3@lboro.ac.uk

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1 Introduction

The complexity of construction projects can increase due to external environmental factors (such as the technological development and fragmentation of the construction industry) and internal factors (such as stakeholder management issues, the complex scope of a project, and the range of project interfaces) [1, 2]. This increasing complexity can result in low project performances [3, 4]. Accordingly, the responsiveness and resilience characteristics of governance are emphasized for steering and decreasing construction project complexity [5]. Construction project governance (CPG) provides appropriate structures and processes with decision-making tools and systems [6, 7]. In particular, CPG aligns construction project objectives with the overall organizational strategies developed to benefit a diverse range of stakeholders [8]. However, the type of construction project governance (CPG) that is being currently practiced—hierarchical CPG—has failed to respond to these two characteristics (responsiveness and resilience) because of the low levels of trust across construction project networks [9, 10]. Indeed, many construction projects based on a hierarchical governance framework face low performance such as time delay and cost overrun due to governance failures that arise from a low level of trust [11, 12]. In response to this, various industries have begun to consider blockchain technology (BT) as an enabler for a more flexible trust-based CPG due to its transparency characteristic [13, 14]. BT as a distributed database or digital ledger provides more flexible access and validity by storing records of transactions and events in blocks [15, 16]. However, existing research in this area has failed to address the nature of the correlation between CPG and BT [13, 17–19]. Accordingly, this research aims to identify trust as a major CPG challenge and potential BT capabilities to reveal the relationship. To achieve this aim, this study conducted a state-of-the-art literature review on blockchain and trust in construction project governance. Based on the review, this paper proposes a new type of CPG framework: the BT-Enabled-Trust Framework for CPG.

2 Research Methodology

The state-of-the-art review is adopted in this research because it is to provide information on the level of scientific development in the field and offers new perspectives on the relationship between trust as a key CPG challenge and BT [20]. The Scopus and Web of Science academic databases were searched to obtain high-quality publications [21]. Details of the inclusion criteria and search terms are given in Table 1.

Figure 1 describes the procedure of the state-of-the-art review conducted in this study. Specifically, Step 1 performed scoping and identification of relevant literature by using keywords and inclusion criteria in the selected databases. In Step 2, the screening process was performed based on the abstract review. Finally, through the

Table 1 Details of a state-of-the-art review

Category	Descriptions
Databases	Scopus and Web of Science
Inclusion criteria	Academic journal papers including the following keywords: project governance, blockchain, trust, relational governance, contractual governance, hierarchical governance, relational norm, construction project
Search terms	Term 1: ("project governance" OR "governance" OR "relational governance" OR "contractual governance" OR "trust" OR "relational norm") AND "construction project" Term 2: ("distributed ledger" OR "smart contracts" OR "trust") AND "blockchain"

eligibility process based on the full-text review, a total of 60 papers were selected for the final analysis. Ultimately, the state-art-review revealed that existing research has failed to examine the relationship between BT and relational CPG.

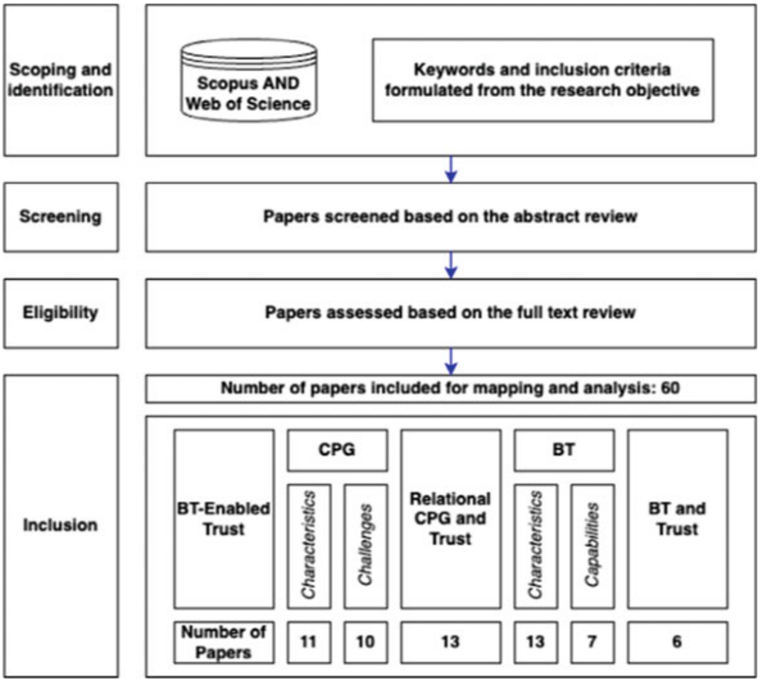

Fig. 1 The state-of-the-art review procedure in this study (devised by authors)

Table 2 CPG theories (devised by authors based on the literature) [23–25]

Governance theory	Assumption	Characteristic
Agency theory	Agent's opportunism	Transparency, Accountability, Responsibility
Transaction costs economics (TCE)	Transactional costs	Transparency, Accountability, Responsibility
Stakeholder theory	Stakeholders' benefit	Fairness
Contingency theory	Organizational effectiveness	Responsiveness
Network theory	Network efficiency	Resilience

3 Construction Project Governance

3.1 Characteristics of Construction Project Governance

Many governance theories are used in CPG research; these provide the foundation for conceptualizing and understanding CPG [22]. In general, governance theories can be divided into three major categories [23]: agency theory, transaction cost economics (TCE), and stakeholder theory. In addition to these general governance theories, contingency theory and network theory are both emphasized in CPG research and provide additional information about the characteristics of a construction project [24]. As can be seen from Table 2, CPG is characterized by six distinct factors—transparency, accountability, responsibility, fairness, responsiveness, and resilience—arising from five CPG theories [23–25]. Various assumptions based on CPG theories provide contextual information about the current practices and challenges of CPG [12].

3.2 Challenges of Construction Project Governance

Governance frameworks can be divided into two types: hierarchical governance (HG) and relational governance (RG), details of which are shown in Table 3 [26].

Table 3 Governance frameworks (devised by authors based on the literature) [27, 28]

Governance framework	Also known as:	Power relations	Binding	Mechanism
Hierarchical governance (HG)	Contractual or formal governance	Static	Legal	Control
Relational governance (RG)	Cooperative or network governance	Flexible	Psychological	Trust

In general, CPG adopts a HG framework to support a better response to the complexity of construction projects [22, 29]. Specifically, the decision-making process for the current CPG framework is the control mechanism (not the trust mechanism) in the governance context, whereby future outcomes are perceived as negative [30, 31]. Accordingly, the current CPG framework has a relatively high focus on HG through its utilization of many control-based project governance tools, such as procurement methods, construction contracts, and relevant laws and regulations [11].

However, the detailed contractual specifications and rigorous monitoring processes of the current hierarchical CPG framework lead to a lack of trust among the stakeholders within the construction project [32]. This lack of trust has been deemed a critical CPG challenge and results in reduced responsiveness to the internal and external construction project environments and less resilience in the network [33, 34]. In other words, the current hierarchical CPG framework is designed to only respond to the characteristics of transparency, accountability, responsibility, and fairness.

Effective CPG relies on well-combined control and trust mechanisms [35]. However, the current control-based CPG framework, with its lack of trust, is biased towards HG [30]. Consequently, several CPG studies have converted the hierarchical control-based CPG to a more flexible trust-based governance, which is founded on the principles of relational governance.

4 Trust in Relational Construction Project Governance

The current CPG framework can be converted into a more flexible trust-based CPG framework by establishing relational governance (RG) [11, 27]. RG is defined as governing inter-organizational relationships through informal structures and shared norms [36]. RG aims to avoid opportunistic behavior by exploiting participants' willingness to preserve their own and the organization's reputation and develop long-term relationships [37]. Specifically, RG leads to reliable transactional relationships, by using the concept of relational norm as a governance tool [38]. Relational norm theory describes a social process that regulates relationship behaviors [39], and there are three underlying dimensions (see Table 4) [40, 41]. Ultimately, relational norms are the core components of relational governance [39].

Table 4 Three relational norm dimensions (devised by authors based on the literature) [40, 41]

Dimension	Description
Mutuality	Willingness to mutually improve the current situation compared to a previous situation
Flexibility	Willingness to accept adjustments and contract modifications according to changed circumstances
Solidarity	Willingness to maintain and stabilize partnership relationships

Table 5 Three types of trust (devised by authors based on the literature) [42, 43]

Trust type	Description
System-based trust	Aims to strengthen the communication channels between the parties in a transaction by establishing a formalized and procedural system
Cognition-based trust	Refers to the knowledge-based trust between the parties in a transaction by establishing a formalized and procedural system
Affect-based trust	Establishes a sentimental framework to strengthen the emotional bonds between individuals and parties

There are three types of trust in a construction project, including system-based, cognition-based and affect-based trust, as shown in Table 5. Ultimately, RG can positively affect trust through the establishment of different relational norms at the project level [42–44].

However, RG requires a considerable amount of time and resources to develop, which often limits its implementation and development [37]. This has led to several studies [14, 19, 45] that have focused on blockchain as a potential enabler for establishing RG, which are discussed in the next section.

5 Blockchain Technology

5.1 Characteristics of Blockchain Technology

Blockchain Technology consists of four elements: peer-to-peer (P2P) networks, hashing algorithms, cryptography, and consensus algorithms (see Table 6) [46]. Specifically, BT's blocks are connected with cryptographic hashes with a timestamp to form a connected P2P network by using consensus algorithms [14].

Table 6 Blockchain elements (devised by authors based on the literature) [18]

Element	Description
Peer-to-peer (P2P) network	A P2P network is a type of distributed system that keeps copies of project files on each node, which eliminates the need for a server to act as a central administrator
Hashing algorithms	Hashing algorithms connect multiple blocks and the multiple transactions within a block by creating an encryption link between each block
Cryptography	Cryptography secures blockchain data, such as user privacy and transaction information, by using symmetric and asymmetric encryption and decryption
Consensus algorithm	The consensus algorithm aims to reach an agreement on a single piece of data

Table 7 Blockchain layers (devised by authors based on the literature) [18, 48]

Layer	Sub-layer	Description
Foundation layer	Infrastructure	Blockchain sets a decentralized database through P2P networks
	Data	The data layer processes the blockchain data through its hashing algorithms and cryptography
	Network	The network layer maintains an effective state through communication, propagation, and synchronization between blockchain nodes
	Consensus	The consensus layer draws consensus among all nodes within the blockchain network through various consensus algorithms
Application layer	Application	The application layer is based on user application programming interfaces (APIs) and frameworks

Blockchain Technology forms a layered architecture that consists of two main layers: (1) the foundation layer, which is the underlying architecture of the blockchain database, and (2) the application layer [47]. In particular, the foundation layer comprises four sub-layers: infrastructure, data, network, and consensus. Ultimately, the two main layers and five blockchain sub-layers represent BT. Each layer is described in Table 7.

Such a layered architecture leads to seven crucial characteristics of BT, including immutability, transparency, anonymity, security, decentralization, consensus and programmability [49–51]. Details of each characteristic are explained in Table 8. These characteristics indicate the capability of BT to improve trust in construction project governance.

5.2 Capabilities of Blockchain Technology

Based on the seven blockchain characteristics outlined in Table 8, there are three blockchain capabilities: decentralized data storage, decentralized data validity, and decentralized data access [54]. Specifically, the relationships between the blockchain capabilities and characteristics are illustrated in Table 9.

The three blockchain use cases – Blockchain 1.0, 2.0, and 3.0—are associated with the different blockchain architecture layers and capabilities (see Table 10). Specifically, Bitcoin is the world's first blockchain application (Blockchain 1.0) [19]. Blockchain 2.0 introduce various financial applications such as lending platforms, decentralized exchange and stable coins by using smart contracts [18]. Blockchain 3.0 describes the autonomous industrial services in numerous industries including banking, public sectors, healthcare, insurance, manufacturing and supply chains [59].

Table 8 Blockchain characteristics (devised by authors based on the literature) [50, 52, 53]

Layer	Characteristic	Description
Foundation layer	Immutability	Transactions stored in the BT cannot be cancelled once they have been added to the blockchain
	Transparency	The BT network participant can view and trace records within any node because all transactions are recorded and verified with a timestamp
	Anonymity	By using public and private keys within network transactions, blockchain can maintain anonymity for its users and protect personal information
	Security	Information stored in the BT is encrypted through asymmetric public-key cryptography to prevent fraud
	Decentralization	BT is a distributed ledger system that does not have a central data storage mechanism
	Consensus	All relevant parties agree to verify transactions within the blockchain network
Application layer	Programmability	BT provides computer programming capabilities that automate business algorithms

Table 9 Blockchain capabilities (devised by authors based on the literature) [55–58]

Capability	Description
Decentralized data storage	A blockchain-enabled decentralized database guarantees immutability, transparency, anonymity, security, decentralization, and consensus. Accordingly, a blockchain network leads to a reliable and standardized decentralized data storage system
Decentralized data validity	The decentralized data storage system provides the decentralized data validity function by using cryptography and consensus algorithms to prevent fraud and achieve decentralized trust in the blockchain
Decentralized data access	Programmability on the blockchain application layer optimizes decentralized data access within the blockchain network. In particular, smart contracts and DApps (decentralized applications) maximize the utilization of decentralized data accessibility on the blockchain by providing autonomous services based on predetermined business algorithms and user-friendly interfaces

Table 10 Blockchain use cases (devised by authors based on the literature) [15, 18]

Layer	Capability	Use Case	Application
Foundation layer	Decentralized Data Storage	Blockchain 1.0	Cryptocurrencies
	Decentralized Data Validity		
Application layer	Decentralized Data Access	Blockchain 2.0	Smart contracts and financial applications
		Blockchain 3.0	Industry applications

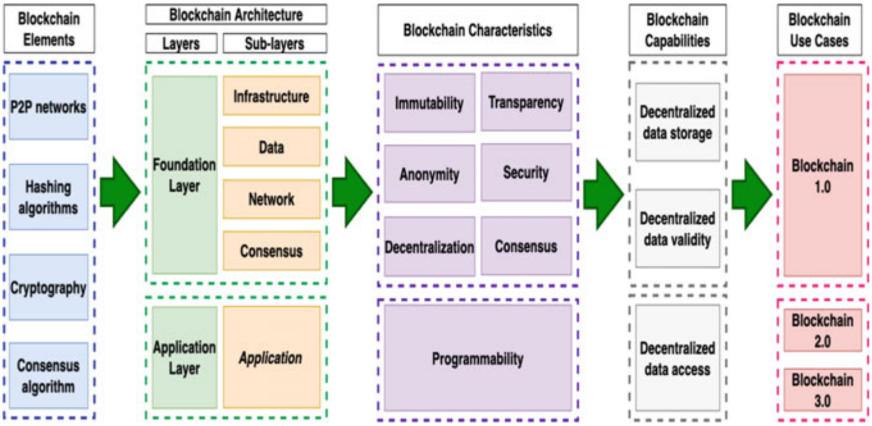

Fig. 2 The capabilities of blockchain technology (devised by authors)

Figure 2 shows the relationships between the BT elements, architecture, characteristics, use cases, and capabilities. Specifically, BT's four different elements including P2P networks, hashing algorithms, cryptography, and consensus algorithms form the layered architecture consisting of infrastructure, data, network, consensus and application layer [46]. The layered architecture of BT creates seven distinct characteristics including immutability, transparency, anonymity, security, decentralization, consensus and programmability [49–51]. Ultimately, three BT capabilities (decentralized data storage, decentralized data validity, and decentralized data access) based on the seven characteristics triggered Blockchain 1.0, 2.0 and 3.0 era [18, 54].

6 Blockchain as a Trust Enabler for Relational Construction Project Governance

The three decentralized blockchain capabilities (data access, data validity and data storage) support the three relational norm dimensions—mutuality, flexibility and solidarity, as explained in Table 11. This support indicates that blockchain capabilities have the potential to assist relational governance and increase trust at the project level [14].

Table 11 Blockchain capabilities and the relational norm dimensions (devised by authors based on the literature) [27, 41, 60–62]

Relational norm dimension	Blockchain capabilities
Mutuality	Two decentralized blockchain capabilities (data storage and data validity) improve mutuality. The decentralized database architecture is used for remote interaction and information-sharing between participants in the construction project network through the P2P network. Also, decentralized data validity enables collaboration between non-trustworthy parties through the decentralized network
Flexibility	All three decentralized blockchain capabilities (data storage, data validity and data access) are involved in improving flexibility. The decentralized storage system secures the flexibility of the system controls. In addition, decentralized data access determines the level of data access within the construction project network. It also enables real-time data sharing and rapid integration of data into the network to cope with the rapidly changing external environment through decentralized data access
Solidarity	All three decentralized blockchain capabilities (data storage, data validity and data access) enhance solidarity. Construction information-sharing in real-time leads to better collaboration between participants in an established partnership. Accordingly, information transparency (gained through decentralized data storage and decentralized data validity) and stable access to information (gained through decentralized access) can increase participants' solidarity

7 A Framework for Blockchain-Enabled-Trust in Construction Project Governance

From the literature review, it was found that the existing CPG system only focused on hierarchical CPG based on procurement methods, construction contracts and project assurance. Therefore, a BT-Enabled-Trust framework was proposed in this study to provide an integrated solution by establishing a practical relational CPG system and integrating it with the existing CPG system (see Fig. 3).

Specifically, effective CPG depends on well-combined control and trust mechanisms [35]. However, the current control-based CPG framework, with its lack of trust, is biased toward HG [30]. In other words, the current approach to CPG has very little balance between the control and trust governance mechanisms (i.e., between hierarchical and relational governance). Meanwhile, the control governance mechanism is an essential element of CPG [63, 64]. The current control mechanism cannot be ignored because it uses essential governance tools such as procurement methods, contracts, and project assurances to make construction projects more predictable [65]. Due to its characteristics, BT can be an enabler for a more trust-based construction project governance by establishing RG. Therefore, a BT-enabled trust framework is proposed for CPG. Specifically, three BT capabilities (decentralized data storage, validity and access) positively impact three relational norms (mutuality, flexibility and solidarity) of RG. Such BT-enabled relational norms can raise the levels of

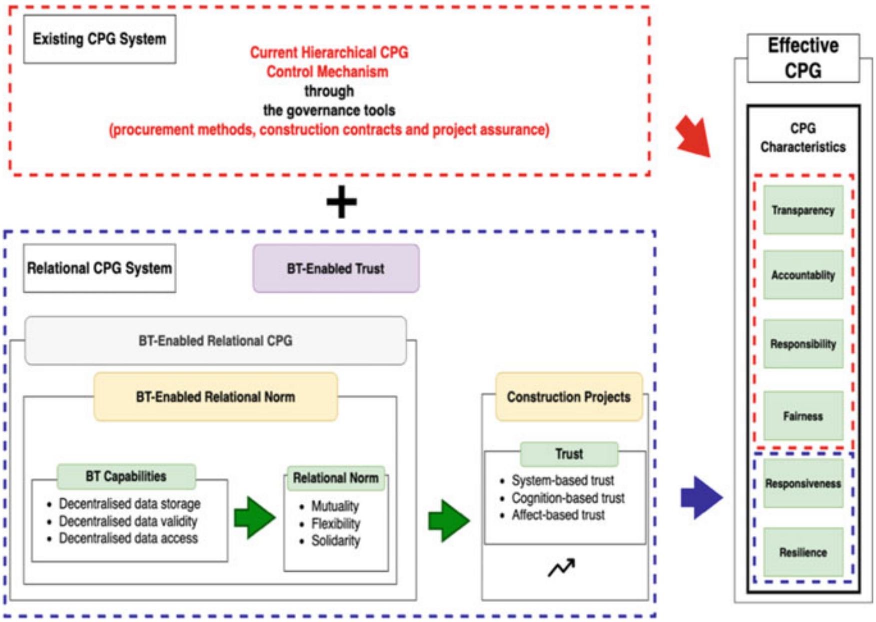

Fig. 3 A proposed BT-Enabled Trust Framework for CPG (devised by authors)

system-based, cognition-based and affect-based trust in construction projects. Consequently, this BT-enabled trust enables responsiveness to the internal and external construction project environment, and resilience for networking within the construction. Ultimately, BT-enabled trust, gained through RG equipped with blockchain, offers a cornerstone for building a more effective CPG framework.

8 Conclusions

This paper sets out to identify trust as a major CPG challenge and potential BT capabilities to reveal the relationship, through a state-of-the-art review. A balanced CPG of the control and trust mechanisms in a construction project is needed to cope with the complexity of the internal and external environments the project sits within. However, the current CPG framework is unbalanced because it is biased toward control-based hierarchical governance. Establishing and strengthening relational governance is essential for providing a more flexible trust-based CPG. The findings of this review suggest that BT could be a crucial enabler for establishing RG. It has the ability to strengthen the three relational norm dimensions, which are essential tools of relational governance, based on three crucial BT capabilities: decentralized data access, data validity and data storage. Ultimately, a BT-enabled trust framework is proposed based on BT-enabled relational governance, which operates

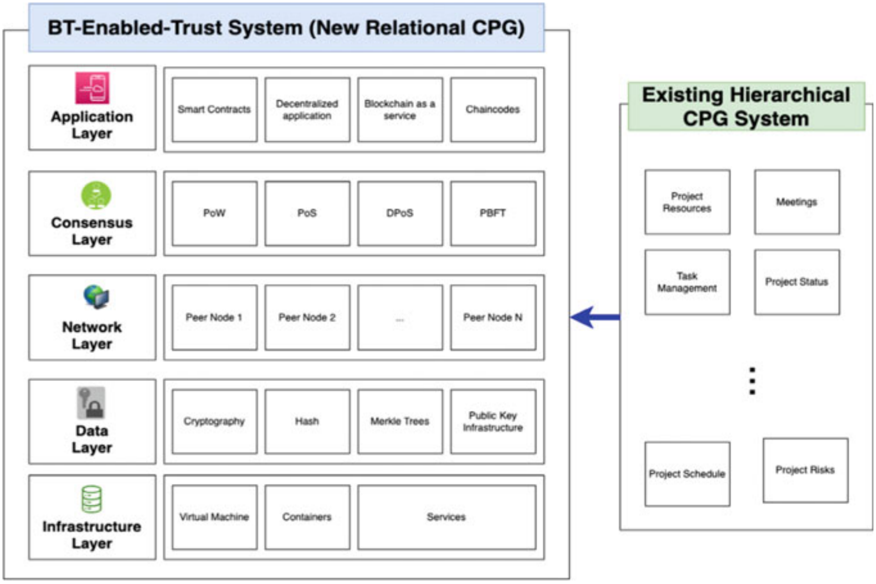

Fig. 4 A proposed BT-Enabled Trust System for future research (devised by authors)

within the current control-based hierarchical CPG framework, and can effectively control the complex construction project environment by satisfying the six distinct CPG factors.

To establish the practicalities of using this new framework, future research could further investigate how existing project governance systems function as governance and explore appropriate BT infrastructures, data, networks, consensus, and applications that meet the requirements of relational CPG (see Fig. 4).

Through the establishment of a BT-enabled trust system, the new proposed BT-Enabled Trust Framework for CPG provides the opportunity to allow for a rapid response to a complex project environment without changing the existing project governance system, which is likely to be based on construction contracts, procurement methods, and project assurances. Ultimately, BT-Enabled Trust Framework for CPG has the potential to act as a steering to develop the practical BT-Enabled Trust system that keeps a construction project steady through more efficient collaboration and networking between the key project stakeholders including clients, consultants, and contractors.

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Blockchain Technologies and Building/City Information Modelling

A Conceptual Framework to Facilitate Urban Asset Management Using Distributed Ledger Technology

Oluwatoyin O. Lawal and Nawari O. Nawari

Abstract The advent of smart technologies and their application in the Architectural, Engineering, and Construction (AEC) domain has been extensively documented; however, the development of Blockchain technologies (BCT) is a concept that is relatively new to many fields. In design and construction, there is a plethora of literature but very few practical use cases. Following an exploration of substantive scholarly contributions on relationships between Building Information Modelling (BIM) and blockchain technologies and between Building Information Modelling and City Information Modelling (CIM), this research investigates the potential of a tripartite interface between BCT, BIM, and CIM using Distributed Ledger Technology (DLT). The study proposes a conceptual framework to facilitate geo-specific value exchanges and asset management within the urban space akin to the exchange of cryptocurrency within the financial space. This framework is validated with simulated data. With the use of a permissioned blockchain, the suggested framework offers streamlined management of physical assets by leveraging the existence of digital models and representations of these assets. Moreover, the paper concludes with a discussion of the benefits and limitations of the research.

Keywords Blockchain technologies · Distributed ledger technologies · BIM · CIM · AEC · Asset management

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O. O. Lawal (✉) · N. O. Nawari
University of Florida, Gainesville, FL, USA
e-mail: o.lawal@ufl.edu

N. O. Nawari
e-mail: nnawari@ufl.edu

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1 Introduction

Cities are the largest, most complex, and most dynamic man-made systems [1]. Paradoxically, their large size and rapid growth testify to their superiority as a technique for exploiting the earth, yet they provide a poor local environment for man [2]. The automation of numerous industries, through the exploration of artificial intelligence, blockchain, robotics, Internet of Things is at the core of industry 4.0, but the use of blockchain in architectural design and construction has seen an abundance of research proposing a conceptual framework with very little use cases on the actual implementations [3].

The cybercity has been conceived as a speculative idea of immaterial electronic imagery of the city, which exists in parallel with reality and its potential to affect a material existence [4]. As with many urban networks of the previous era, such as cybernetics, ubiquitous computing, Internet of Things, blockchain technology (BCT) promises to be yet another disruptive innovation in urban studies. Since the success of bitcoin, there has been an increased focus on studying the application of blockchain in a broad range of contexts, leveraging its decentralized and distributive attributes to address pre-existing issues [5]. This distributed setup, the driving force behind Bitcoin and other cryptocurrencies, is now being piloted and implemented across many other domains [6].

This paper proposes a conceptual framework for improving urban management and governance. Ultimately, the trust mechanism is explored with respect to the acquisition, ownership, control, and management of urban features in a decentralized space. A consensus is developed through Building Information Modelling (BIM)—City Information Modelling (CIM)—blockchain integration in urban development and administration. The interoperability of BCT and BIM at the city scale is attained through Geographic Information System (GIS) by deploying decentralized, immutable distributed ledgers throughout the lifecycle of all urban assets within the blockchain. This guarantees holistic and auditable management of assets.

The paper begins with a systematic literature review around thematic areas such as blockchain data structure, BCT, BIM and CIM integration, value exchanges within the urban environment, and the future of blockchain technology in the AEC industry. This is followed by an illustration of the proposed framework and its mode of operation with respect to its participants. The study closes with a real-life use case in urban blockchain to derive conclusions.

The study investigates the efficacy of BCT in facilitating the management and exchange of value and valuable urban assets. The applications and potentials of blockchain as it pertains to the BIM workflow is evident [7]; however, the application of CIM and the Distributed Ledger Technology (DLT) of blockchain towards improved asset exchanges in cities is yet to be explored. Advancement in CIM as the integration of models of varying semantic details for urban components, yet having a semantically rich model already gravitates towards a more distributed system of urban information management. Thus, this paper proposes a framework for a blockchain-based CIM that leverages the immutability of historical data and the interaction data linking these components to facilitate effective urban asset management.

1.1 Research Methodology

Relevant literature was selected for review of scholarly work to address the following thematic areas; Blockchain Technology, Building Information Modelling, City Information Modelling, Urban Assets Management, and Value Exchanges. This paper begins by defining the underlying concepts of blockchain, such as DLT and its data structure, consensus mechanisms, BIM, and CIM. A system is proposed for effective value exchange within the urban space by first discussing the current challenges of the traditional approach to urban asset management. The framework development is in two parts; first, the study expatiates on the mode of integration of BIM data of building models with CityGML data of geographic information systems to create a City Information Model. Secondly, a suitable distributed ledger is introduced to record activities within the digital assets in the CIM.

2 Literature Review

2.1 Blockchain—Definition and Data Structure

Blockchain gained its current popularity after the creation of Bitcoin in January 2009; however, research into its application is relatively recent. Bibliometric studies by Darabseh & Martins (2020) showed the most recent scholarly work in blockchain research in construction dating back to 2017 [8]. Blockchain is a shared ledger containing records of transactions in a given network that is locked cryptographically. The decentralized nature of the network database and the interconnection of one block to another makes it immutable. Many scholars define blockchain as a decentralized ledger system; however, Zheng et al. (2019) classified blockchains based on three different degrees of decentralization, namely; private, consortium or permissioned and public blockchains. The difference in these types lies in the consensus approach. The degree of decentralization increases from private to consortium blockchains to public blockchains [9].

Decentralization in the blockchain is in data storage and recording of data. It is not a homogenous technology but a network of technology, thereby creating a new form of distributed record keeping within a network. As Sundararajan (2016) highlighted in *The Sharing Economy*, and in the context of this research, a distributed platform's first critical infrastructure element is the shared ledger. The second is the distributed hash table, to index what is available on the network, while the third is the contract which acts as the mediator between two parties [10].

The fundamental unit of the blockchain is the "block." The block refers to a record of a category of transactions or a sequence of transactions hash-chained with the previous one in a *blockchain* [11]. Nodes are outlets on the network connected to hardware which may be a computer or any electronic device. Specific hardware is required in order to connect to a node.

Consensus in a peer-to-peer network requires no centralized server or authority to validate incoming blocks. Communication between nodes is not controlled by a single node, and the data security is assured by various consensus mechanisms such as Proof of Authority, Proof of Space, Proof of Work or Proof of Stake [8]. The hash function maintains the security, integrity and immutability of the blockchain by linking blocks together in chronological order [12]. The hash function is a unique identifier of a data block and a mathematical function that converts text input into an encrypted code, connecting each block to its previous block [13].

2.2 Blockchain, BIM and CIM

Building Information Modelling is the process of generation and management of the physical representation of building components. It includes transactions at the *data, information, and knowledge* semantic levels [14]. The City Information Model is often simply referred to as a digital representation of urban components and information or the urban equivalent of a Building Information Model. This definition may suggest that CIM is an enlarged version of BIM against CIM as a digital proliferation of BIM models and other models that make up the city fabric.

One of the ways to derive a city information model with semantically rich information is the integration of BIM with GIS as a suitable method to organize city information [15], as a suggestive tool for integrating the numerous fragmentary urban definitions, discourses, and ideological positions [16]. Similarly, combining a digital platform with a spatial database to provide storage, interoperability of file formats, access to information, centralization of data, and an urban environment data model which provides the level of detail of the urban components can form a spatial data model. This spatial data model is described as the backbone of the CIM [17].

BIM and CIM have to be unified for geolocation. Yu & Liu (2016) proposed integrating BIM and GIS to analyze the 3DGIS valuation model in effectively computing property values [18]. The blocks and territories in cities are always referenced by relational geography, therefore CIM is conceived as an evolution of GIS, with emphasis on relationships between "blocks" and "territories" [16].

2.3 Value Exchange in the Urban Context

The land is a ubiquitous urban asset, therefore, administration and management of land and all above and within it is crucial towards achieving urban smartness. This follows the argument that future cities are only smart when investments in human and social capital coupled with urban infrastructure fuel innovative sustainable development [19].

Faniran & Olaniyan (2016) suggested that the adoption of GIS-based applications in land administration by sub-national governments across the country can ultimately reduce the number of slum dwellers [20]. The adoption of BCT by the public sector is no longer new, with land administration being one of the earliest adoptions of the BCT and DLT [21]. BCT was first used to solve the problem of irregularities and counterfeit land registration in Honduras between 2016 and 2017. Since then, other areas where blockchain-based solutions have been deployed in land registration include Brazil, Ukraine, Sweden, and India [22].

2.4 The Future of Blockchain Technology in the AEC Industry

As of 2019, research on blockchain applications in environment, construction, and smart cities was significantly lower than studies of its application in other subtopics such as ownership, security and privacy, and supply chain management [23]. This is in resonance with Sarah Underwood (2016) regarding blockchain's data privacy issue, as reported by Microsoft. [24]. Inter-blockchain communications need to be enabled and improved upon. A few industrial solutions to BCT interoperability exist within cryptocurrency, however, interoperability amongst other major blockchain platforms by connecting heterogenous blockchains will be a massive paradigm shift and is key to unlocking its diverse applications [25].

3 Proposed Frameworks

This framework streamlines increasingly complex blockchain concepts for specific applications in urban studies. Three interaction components across two distinct interaction levels are identified. The interaction components are the BIM, GIS, and DLT components. The interaction levels are the blockchain-BIM (bcBIM) building level framework and the BIM-GIS city level framework.

Two frameworks for the application of blockchain and CIM are presented and coupled, to ensure a geo-referenced solution at building level. The bcBIM building level framework focuses on design, construction and lifecycle management processes and workflow. As Sreckovic et al. (2021) proposed, this framework uses BC and

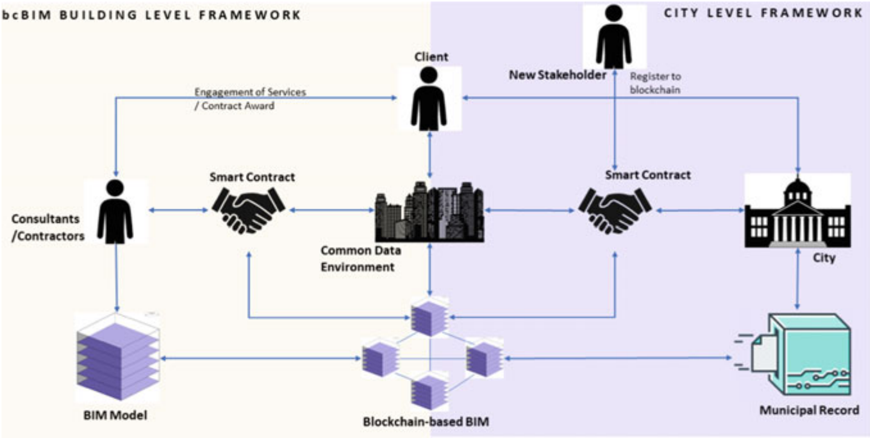

Fig. 1 bcBIM building level and BIM-GIS city level frameworks

SC for traceable documentation and transaction across the design and construction ecosystem [26]. Based on the hybridized bcBIM model, the city-level framework digitizes the relationship between buildings and their geographical context (Fig. 1).

Earlier studies have proposed a Common Data Environment (CDE) for secure data storage of digital assets, interdisciplinary coordination, management, and versioning of information containers [26–28]. This study proposes a double-layered CDE in the form of the Building Level Data Environment (BLDE), which is a subset of a larger City Level Data Environment (CLDE). BLDE is used in the building-level framework, while CLDE is used in the city-level framework.

The two frameworks use contrasting standards, yet they are not mutually exclusive. Hence, coupling both concepts is required to complete the urban blockchain loop. The building level and city level frameworks employ a private consortium blockchain; however, a public blockchain may be more suitable once the adoption of this framework becomes more widespread. In both concepts, smart contracts are service solutions deployed to automate agreements and payments when are where necessary.

3.1 The bcBIM Building Level Framework—The 'BIMCHAIN' Approach

As recently as 2021, despite the high volume of scholarly publications within the field of BIM and blockchain integration, perhaps the most common known commercial product that integrates BIM and blockchain is BIMchain [29]. The BIMchain software is developed by Lucetium SAS in Paris, France. For a holistic blockchain-based BIM solution, it is essential to understand how the various processes are designed

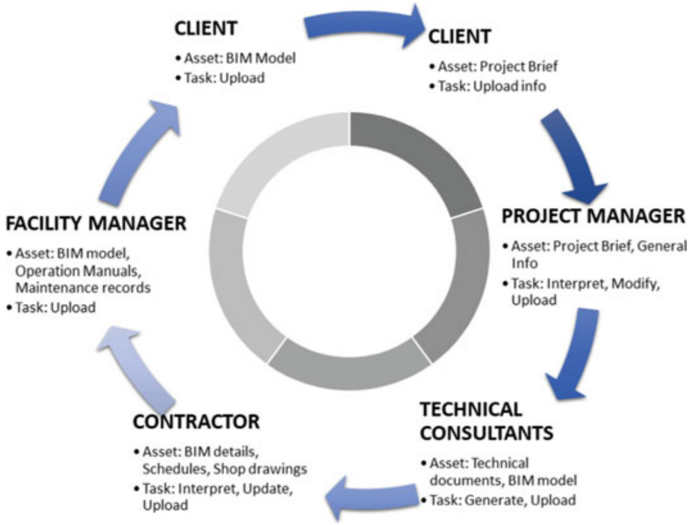

Fig. 2 Stakeholders workflow wheel

and configured for DLT and smart contracts (SC) and how they can be adapted for multiple workflows and procurement methods. The key participants in this framework are the project stakeholders in the form of the client or owner, Project Manager (PM), Technical Consultants (TC), General Contractor (GC), and Facility Managers (FM), and the activities include the exchange of digital assets in varying forms. Figure 2 shows the stakeholder workflow where the client or owner is at the start and end of the process.

In the Building Level framework, Blockchain and Smart Contracts (SC) are service-level solutions that ensure the interconnectivity of all activities within the workflow and allow for transparency and scalability. SC serves as a mechanism for retrieving details and provenance records of any information within the blockchain.

The workflow (Fig. 3) begins with the client commissioning project consultants. The paper-based consultancy engagement is stored in the BLDE. The client and PM further engage other domain-specific consultants. The PM role includes interpreting the client's brief, developing and coordinating the complete design package, and managing other technical consultants and an intermediary between the client and project team, depending on the conditions of engagement.

The client defines the project requirement and provides all relevant information, forming the basis of the design. For effective provenance audit of decisions and outcomes, the basis of design is stored as a paper-based document in the BLDE. All digital assets are evaluated by the client and PM based on the stored brief and basis of design. The client gives the approval to proceed to the next stage once the design is satisfactory. The architect develops the BIM model and uploads it to the BLDE. Other consultants synchronize with the BLDE-hosted BIM model and develop their domain-specific design information. The architect is however responsible for periodic

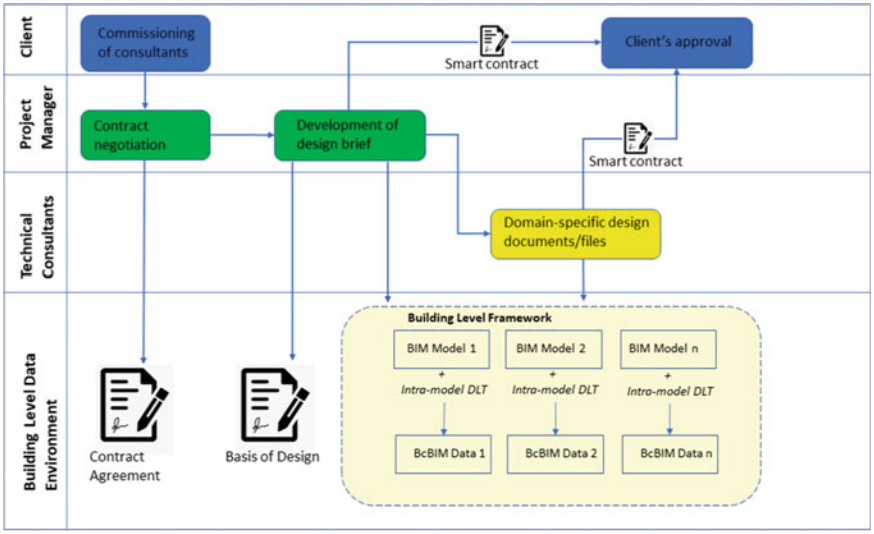

Fig. 3 The building level framework

review and audit of the BIM model to ensure data integrity. The architect's verdict on any audit or coordination of the BIM model is communicated to the PM, who then deploys SC to document all changes to the model.

The GC also falls under domain-specific professionals. The exact workflow between the PM and TC in the pre-construction stage is adopted between the GC and subcontractors in the construction stage. All professionals update the BIM model throughout the project lifecycle and all updated information is stored in the BLDE. The completion of the contract triggers an SC between the client and FM. The FM also continually updates the BIM model throughout the project lifecycle and stores all maintenance records in the BLDE. All revised versions of digital assets supersede previous ones but will always be in reference to the superseded versions. This ensures transparency, traceability, and immutability of building information.

3.2 The BIM-GIS City Level Framework

The framework proposes a solution that allows peer-to-peer interactions of asset owners. The city-level framework investigates the relationship between the asset and its locale. Owners of non-digital assets or digital assets that are not blockchain-based may also participate at City Level, but the total value of the solution is derived when digital assets incorporate BC and SC.

The key participants of this framework are the client or owner and the municipal authorities. The BLDE is now expanded into a City Level Data Environment (CLDE) by integrating the bcBIM model with GIS data by merging the Industry Foundation

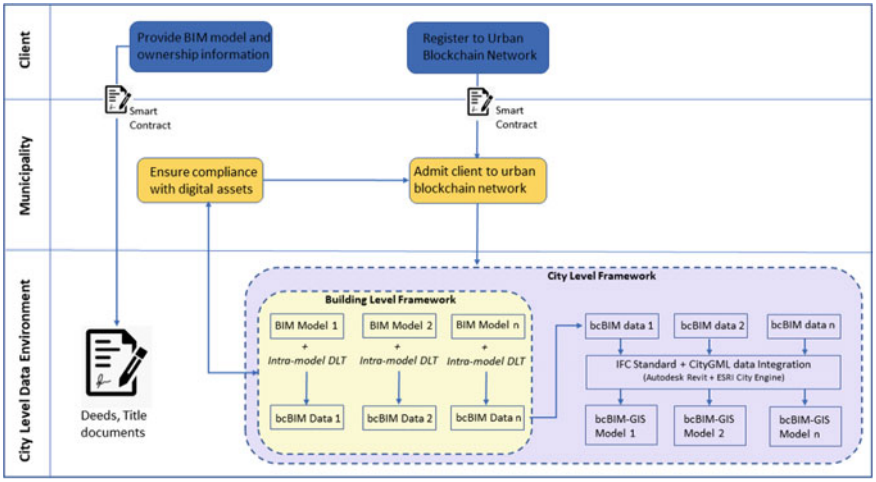

Fig. 4 The city level framework

Class (IFC) data structure of Revit with CityGML data structure of ArcGIS. First, the asset owner provides the traditional paper-based title documents, which is reviewed by the municipal authorities before uploading to the CLDE. This BIM model is then integrated into CityGML data and hosted with other ownership documents. The municipality is the administrator of a private consortium urban blockchain. They register asset owners to the network, using SC to record inputs of new registrants. The algorithmic workings of the urban blockchain are enumerated in the next chapter (Fig. 4).

4 Use Case

4.1 Project Overview

In previous sections, the integration of blockchain technology in various workflows and scenarios has been enumerated. A Build-Operate-Transfer (BOT) procurement model for a four-storey student apartment building in Orlando, Florida is used for demonstration. This concept is further expanded in order to deconstruct the workflow and illustrate the real-life application of BIM, BC, and SC.

The Build-Operate-Transfer type arrangement is a popular option amongst many procurement routes for its high efficiency considering the risks to be undertaken by a concessionaire whose responsibility is to design, finance, construct, operate and transfer infrastructure within stipulated terms of the agreement [30].

4.2 Application

Using the above-coupled framework, transferring the concession to a new stakeholder will trigger a multi-layered series of inquiries that will require data audit and provenance in a tamper-proof database. The design phase is as described under the building level framework wherein the client engages the PM and the rest of the project team, who develop a synchronized BIM model of the apartment building. After necessary reviews, coordination, and approvals, all activated by SC, the model is shared with the municipal authorities for planning permit. Upon approval from the authorities, a smart contract triggers the commencement of tendering process and the engagement of a GC.

GC signs a contract with the client. The contract clauses and obligations are codified and self-enforced by the SC, thereby protecting the interest of all parties involved by automating the next step once conditions are met and as a gatekeeper when conditions of the contract are breached. All contract information is stored in the CDLE. The GC's contractual relationship with the subcontractors is also maintained with SC. The BIM model will be updated by the contractor for the development of shop fitting drawings and an as-built model. The PM, however, ensures that the CLDE is constantly synchronized with the most recent domain-specific models.

Upon completion of the contract, an SC prompts the client to commence operations through the engagement of FM. The workflow between FM and other vendors is a replica of the workflow between GC and the subcontractors. Once FM is engaged, the PM cedes administrative authority over the BIM model to the FM, who now ensures that the as-built model is constantly synchronized with all maintenance records. Peer-to-peer, decentralized asset exchanges within this network are described in Sects. 3.1, 3.2

5 Conclusion

The research proposes two integrated frameworks, bcBIM building level framework and BIM-GIS city level framework, seeking to answer the question of how efficient urban administration and management will be using DLT.

In response to the research question, the suggested BCT has to be designed to be highly robust to accommodate changes in workflow. Furthermore, the study proposes reconfiguring traditional procurement workflows. The proposed cohesive integration of BCT and SC in BIM for asset management requires a highly digitized process and auditable digitization of the entire workflow in a project lifecycle. The contribution of the presented research is twofold; First, the paper demonstrates the feasibility of a BC, BIM, and GIS integration to develop an immutable CIM. Secondly, it proposes a system to facilitate the peer-to-peer exchange of value as a substitute for traditional paper-based processes with a high level of third-party involvement.

Future studies will focus on (1) Virtual Planning Permitting Process where a Common Data Environment, a blockchain repository, and municipality participation can allow for a completely automated permit application process. And (2) Automated Building Regulation and Control, whereby the deployment of Smart Contracts prevents unauthorized transition to a subsequent phase of work provided conditions for progress are yet to be fulfilled.

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Exploring Digitisation as a Solution to the Long-Term Insurance Sector Efficiency Quagmire

Linda Malifete, Samuel Adekunle, and Clinton Aigbavboa

Abstract The insurance industry is necessary for the global economy, the stability of the economic system, and its sustainability. However, the industry continues to face challenges related to customer service, market competition and re-engineering of processes. The insurance industry is no different to other industries, it is also affected by the forever changing customer requirements and demands and this fast growing digitalization. Almost every organization wants to be part of the new revolution because of its ability to bring company improvement in process efficiency, productivity and performance. Just like industrial revolution did more than a century ago, it continues to reshape the way humans live and perform their daily duties. As a result, organizational processes, customer expectations and the adoption of new channels, products, and services have all undergone significant change, forcing a reconsideration of business models. Digital technology has been embraced by many businesses because it has the potential to transform business operations, much as it did for other industries, and it has the potential to change the insurance industry as well. The sparse use of digital technology is the main hindrance to the South African insurance sector's success. The main goal of this paper was to examine the extent in which digitalization has been explored in the South African long-term insurance industry compared to other industries. This was accomplished by doing a thorough PRISMA-based critical analysis of the current literature. Sixty-two accredited journal articles were assessed to understand the contribution that has been made by digital models in the previous research and to identify gaps and be able to contribute to the body of knowledge by introducing effective techniques to close the identified gaps. The first finding was that digitalization has not been thoroughly explored in the insurance

L. Malifete (✉)
Department of Operations and Quality Management, University of Johannesburg, Johannesburg, South Africa
e-mail: linda.malifete@gmail.com

S. Adekunle · C. Aigbavboa
Cidb Centre of Excellence, University of Johannesburg, Johannesburg, South Africa
e-mail: sasamuel@uj.ac.za

C. Aigbavboa
e-mail: caigbavboa@uj.ac.za

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industry and there is dearth of research about digitalization in this industry, particularly in the African continent. Secondly, the reviewed literature revealed that the application of Internet of Things and big data has the potential to enhance customer database in insurance business, because these digital tools can help insurers obtain customer data in real-time. This has been highlighted as a solution to the problems the long-term insurance sector is currently experiencing.

Keywords Company performance · Digitalization · Insurance · Long-term insurance

1 Introduction

Companies are working on solutions to keep up to date with new technology to stay relevant in the business. The term digitalization is increasingly getting recognition in the current era. This is the latest strategy of manufacturing centered on scientific notions of Internet of Things (IoT), Internet of Services (IoS), automation, cyber-physical systems, and robotics [59]. German has a rich digitalization history and is known worldwide as an international leader in manufacturing equipment sector and for having the best competitive manufacturing businesses [59]. This is an exciting time for all industries and an opportunity to be smarter than the competitors, hence it cannot be overlooked. Digitalization can change the way in which people work, learn, and think about production or industrial manufacturing and expertise needed in the job market. It is difficult to overlook the notion of digitalization because young and older people are affected by this revolution. We live in a world whereby almost everything is digitalized, with the help of the latest technologies and automation of most occupations has become a neccesity. Digital revolution is an important word associated with the information revolution. The whole world is going through an immense transformation because of the digital revolution [49]. Schroeder [60] further adds that the digital revolution is often referred to as the ability to advance the technology from equivalent electronic expedients to digital machinery. It is therefore understood as the conversion from equivalent gesture to a numerical form and it allows the gesture to be processed by computers. Zhong et al. [61]; Brettel et al. [47] added that a lot of industries have adopted the digitalization, these include, healthcare, communication, administration, finance, customer service, entretainment, hospitality, manufacturing, training and education etc. The initial three revolutions were basically about mechanization, electrical energy, and IT. The Fourth wave came about because of the presentation of the IoT and IoS into the industrial environment [54]. This means that for the first time, we can network resources, data, items, and individuals to generate the IoT and Services.

2 Overview of the Insurance Industry

The insurance industry is one of the most fascinating and important sectors. The insurance business is vital to the security and sustainability of the economic structure and the worldwide economy [6]. It is known for its rich antiquity that dates back to the Middle Ages. The insurance sector matured in the nineteenth century, consequently, the life and non-life insurance products were established [57]. According to Willet [32], insurance is a social mechanism for building up resources to prevent capital loss due to unforeseen situations. It does this by transferring risks from individuals to a community of people. In accordance with NWAFOR [16], insurance is a contract whereby one person, known as the insurer, makes a commitment to compensate another person, known as the insured, for a set amount of money, known as the premium, which is paid to the insured in the event of a disaster/loss. The insured person passes the risk of a potential loss to the insurer in exchange for a monetary payment known as the premium as a risk management strategy (NWAFOR, 2018). Governments have indorsed the transaction of insurance products because they provide protection against financial loses and they promote long term savings. This is because of the insurance's ability to provide policyholders with the way of securing their future well-being and that of their loved ones (NWAFOR, 2018).

All South Africans will be capable of safeguarding themselves from unforeseen circumstances if they have access to insurance. This is crucial for households with low incomes, as job losses can lead them to sink further into poverty. They can avoid falling further and further into poverty by purchasing insurance, which compensates the loss. Increasing insurance availability can support the nation's growth strategy. One of the industries that contributes the most to GDP is financial services. The insurance sector has undergone gradual change, which is not consistent with South African reality. Building more teams with different backgrounds and skill sets is necessary because they stimulate business innovation. The insurance industry is searching for new markets, business strategies, and business models to expand, build customer relationships, and develop a functional infrastructure. The industry requires sophisticated organizational infrastructure and highly trained human capital. According to Kazancoglu and Ozkan-Ozen [55] digitalization doesn't just influence the industrial organisations, there is an extensive impact on the idea of work, which adjusts the desires from work personel in all sectors as well, including the insurance industry. Kazancoglu and Ozkan-Ozen [55] further added that we cannot run away from the fact that the digital technologies are anticipated to change the occupation profiles of workers in various ways and it is important to explore all the areas. This means that the need for labor in an old-fashioned manner that needed man power falls gradually as a result of latest technology machineries which are able to interconnect and communicate between one another to control themselves [55]. For many years, the insurance industry has been using old fashioned technologies such as web applications, mobile, online insurance portals, and call centers. However, there are various insurers that are already using innovative tools such as big data, IoT, advanced sensors with the aim to retain more customers, improve profitability of services and optimize

Fig. 1 Insurance Value Chain (Author's compilation)

pricing. The new technologies have a potential to help insurers to make better risk calculations using modern predictive techniques to project customers that are high risk. We now live in a digital era where people's data can be easily retrieved from various platforms. This means all activities done by customers can become data. This therefore brings new technology called Internet of Things (IoT), because of its ability to connect database from different types of objects that can all be connected to the internet. This type of database is valuable for any kind of business and if utilized correctly, can give a competitive advantage.

The current insurance value chain includes the below six stages moving from product development to asset management as shown on the below diagram labelled as Fig. 1.

The studies done by Gatteschi et al. [50] suggested incorporation of Blockchain technology in the above value chain with the aim to provide innovative user product based on a usage model, improved analysis of the customer activities pattern, usage of machine learning techniques like deep learning to evaluate information kept on Blockchain. Because customers want to oversee the management of the insurance policies, therefore insurers need to offer products that are more transparent. For this reason, it is thus vital for insurers to have an innovative value chain. Previously, customers would communicate more with brokers and sales advisors, but as the digitalization is gradually being adopted by companies, there has been a decrease in interaction between customers and insurance advisors [50]. However, the adoption of the new technology requires building of new ICT systems, making alterations to business model, changing the business culture (Gatteschi et al.).

By preventing losses for consumers and governments, insurance may play a crucial part in creating a sustainable economy. In South Africa's financial economy, the insurance industry is a crucial pillar. The largest insurance market in Africa is in South Africa. The insurance industry can be crucial in addressing some of the problems South Africa is currently experiencing, including the consequences of climate change, COVID-19, the current state of economic uncertainty, a prospective recession, a credit rating reduction that is rapidly approaching, and more. The insurance sector is a critical one in any economy. Its services are advantageous to individuals and business entities, thus it caters to a wide range of industries, including construction, health, retail, manufacturing, agriculture, and so forth. However, the industry in South Africa has faced numerous difficulties, including disputes, legal matters, revenue losses, and customer dissatisfaction, among others. This has been attributed to many causes, among which are perceived unfair premium calculation, and data management challenges, among others.

This study looked at how emerging technologies could be adopted in the long-term insurance industry to address these issues. The study also looked at how these emerging technologies have improved customer service, performance, and productivity in other sectors. Several technologies were investigated, and their potential for resolving issues in the insurance industry was carefully examined. This study is important because it has relevance to the current industrial revolution and assists stakeholders in the insurance business in being more productive, efficient, and digitally aligned. In addition, it provides an insight into ways to have a digital matured long term insurance sector in South Africa.

Assuming that an insurer is acting solely in his or her own self-interest when it comes to refusing to pay up on a disputed claim is not sufficient. The insurance industry is one of the industries that are strictly regulated, there aren't many other sectors that are this strictly regulated. According to Wang et al. [31] insurance companies still use statistical factors like age, gender, and profession to determine a customer's premium and the likelihood of unforeseen events like accidents, illnesses, deaths, and other situations, even though they have specialized departments like actuarial. Furthermore, Wang et al. [31] noted that it doesn't seem like this calculation is fair for all parties. This is because a client who lives a healthy lifestyle may be required to pay the same premium as a client who lives an unhealthy lifestyle just because they share the same age, gender, or profession. Insurance companies may experience financial hardship if medical issues are not disclosed. The study has looked more closely at customer complaints that were filed with the long-term insurance Ombudsman (OLTI), specifically cases where insurance companies rejected claims because the customers failed to disclose pre-existing medical conditions. The graph below shows the number of long-term insurance cases that the Ombudsman marked in the complainants' favor from 2017 to 2021 (Fig. 2).

The above graph shows that there is a significant disagreement between customers and insurers throughout the claim stage because of the policyholders' failure to provide significant data. This is because insurers solely rely on the information provided by customers during the insurance application stage, even when this information is sometimes misleading. The administration and engagement of the ombudsman in settling disputes between dissatisfied clients and insurers is very expensive, because the insurers are required to pay more than R4000 for each standard case submitted to the Ombudsman.

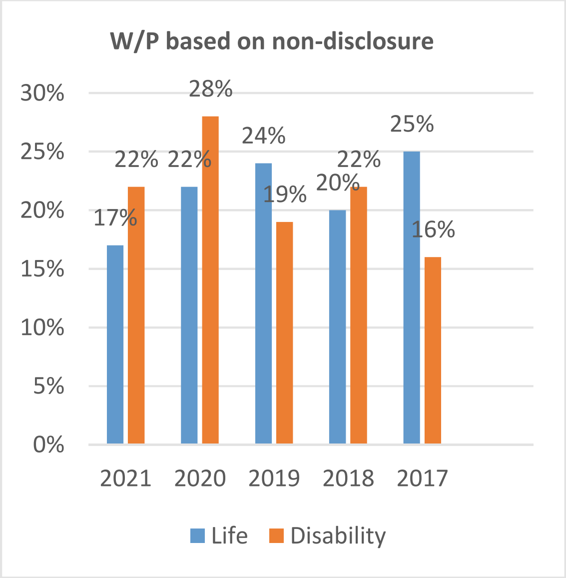


Fig. 2 Cases ruled in favor of complainants at the ombudsman (OLTI Annual Reports 2017–2021)

Table 1 Ombudsman costs (Ombudsman Annual Reports: 2017–2021)

Ombudsman costs				
Year	cost per standard case	Compensation awarded	Total expenses	Recovered value for complainants
2021	R4,406	R948 592	R33.634 m	R200.7 m
2020	R4,387	R817 970	R30.761 m	R177.9 m
2019	R 4,086	R874 286	R29.49 m	R200.4 m
2018	R 3,629	R632 737	26.04 m	R185.8 m
2017	R 3,707	R531 429	R24 406 m	R193.3 m

The costs of each case submitted to the Ombudsman, total client compensation paid, total insurer expenses paid, and total amounts recovered for complainants are all shown in the table below (Table 1):

3 General Overview Of Digitalization

Earlier studies have been conducted to help organizations realize and comprehend the entire potential of artificial intelligence, the findings showed that all examined industries could benefit significantly from artificial intelligence [22]. The value that artificial intelligence adds to industrial organizations has been previously measured and the results have revealed that most industrial organizations are undergoing a digital transformation with the goal of enhancing the usage of computers and automation through intelligent, autonomous systems that are driven by data and machine learning. This transformation has been broadly embraced in industries thanks to the introduction of digital machines, which have helped sectors like construction transition to a technology-driven industry and keep up with other sectors [46]. In the construction industry the potential for AI methods like neural networks to ensure accurate cost estimating is very high. AI technology has been used to estimate the expenses related to the construction sports fields and the earlier studies proposed a neural network-based approach for calculating construction expenses [53]. IoT-based algorithms have been developed by several authors to improve the rate of productivity and performance. IoT algorithms were found to play a huge role to detect when temperatures in work environments are too high and signal an emergency [26]. IoT was also explored by Raiyn [25] when he proposed a technique to compute trip time by first determining the fastest route based on previous data. The research showed that this strategy supports independence and proposed that it might be used in Internet of Things-compatible smart cities. According to research, IoT is crucial to future activity prediction. Previous research has provided IoT based models to assess IoT cyber risk and estimate IoT cyber risk in the future [24]. A trustworthy model that can identify and avoid cybersecurity threats and weaknesses has been previously recommended with the aim of predicting future activity occurrence times using an IoT-based sensor model [13] and [30]. Without any human involvement, this approach may computerize the procedures for sharing crucial real-time data across machines. Because this model gets rid of operational management tools while enhancing security on the Internet of Things environment. In the Agriculture environment, IoT based models have been developed track drought, monitor soil moisture, humidity, and temperature [9] and [10]. The models also provide a 10-day forecast to assist farmers in successfully planning their farming activities. This model was developed in the hope that it will help the government address the problems caused by climate change, which have long had an impact on the economy and society. The outcomes of the IoT-based system that was created showed excellent dependability and efficacy. Other industries are faced with difficulties of managing the database of a digital twin product properly and securely in terms of data storage, data sharing, and access because there are many competitors involved in the product lifecycle. A Blockchain-based platform to manage digital twins of products was created to address this challenge [51]. In the health sector, digitalization has been thoroughly investigated to enhance the performance of the health sector, as seen in studies by Tanwar et al. [28], and Murugan et al. [14]. In their studies, they suggested using the blockchain technology to share healthcare data as a solution to the issue with patient access to hospital and medical records. Technology has proven to the health sector that it would help by gathering data for further insurance claims and research purposes. Authors like Jamal et al. (2020) have employed artificial intelligence in the medical field to predict drug resistance in particular genes. AI approaches have been recommended to lessen the workload that is continually growing in the healthcare industry, they allow doctors to offer patients a wide range of personalized treatment and detect low blood sugar levels in healthy individuals [45, 52, 58]. Artificial Intelligence frameworks to predict the patients' overall survival time and the progression of a virus have been suggested in the medical unit [48]. In testing the efficiency of the suggested models, they provided the machine with data such as age, historical background, to produce the final prediction result [56]. The experimental results show that this AI framework beats standard methods, achieving a reliability of 90.66%. The modern technology tools have been extensively explored in the healthcare industry and it has been validated by several authors as a solution to many of their problems and a great way to improve their services.

3.1 The Status Quo of Digitalization in the Insurance Industry

The term digitalization is not new, and it has been broadly defined in a variety of ways by different scholars. In their study, Eling and Lehmann [6] defined digitalization as the integration of the analog and digital worlds with modern technologies that can enhance customer interaction, data accessibility, and operational processes. In the context of the insurance sector, Eling and Lehmann [6] analyzed various definitions of digitalization from various authors. Digitalization was described by Łyskawa et al. [44] as the adoption of Information and Communication Technologies (ICT) in the insurance sector to lower premium costs and increase profits. Digitization in the insurance sector will offer an opportunity for a meaningful innovation.

3.2 Method

The next section analyzes the digital technology models that were employed in the earlier journal papers through a systematic review of the literature. This review's objective was to compare the insurance business to other industries in terms of how the use of digital technology has been investigated. To understand how prior academics interpreted digitalization, existing studies were reviewed. Due to its capacity to reduce bias associated with the article selection process, systematic literature reviews are widely employed in all fields [21, 29]. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was used in this paper since it is an evidence-based collection of articles designed to help researchers report a wide variety of systematic reviews and meta-analyses [21] (Fig. 3).

Using Scopus database, the study first looked for journal articles using the following keywords: Insurance 4.0, digitalization, big data, industry 4.0, artificial intelligence, internet of things, and blockchain. Thousands of publications were produced by the search, which was limited to only complete peer-reviewed academic articles. The papers were then filtered based on subject, language, publication year,

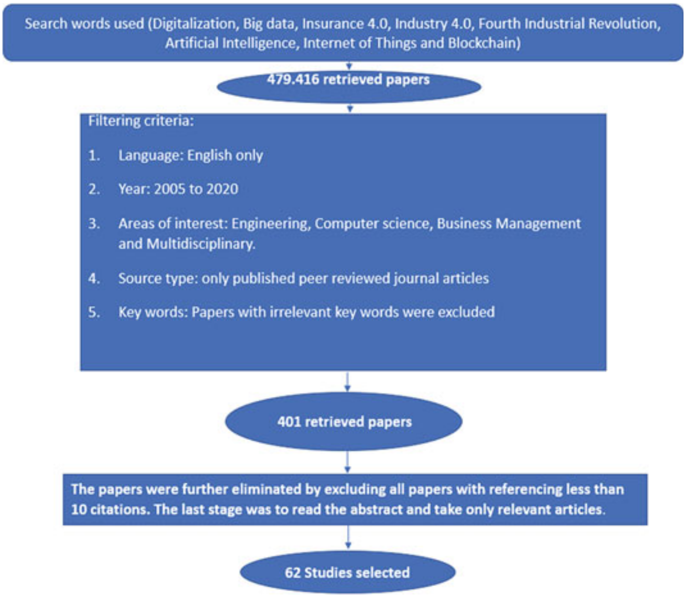
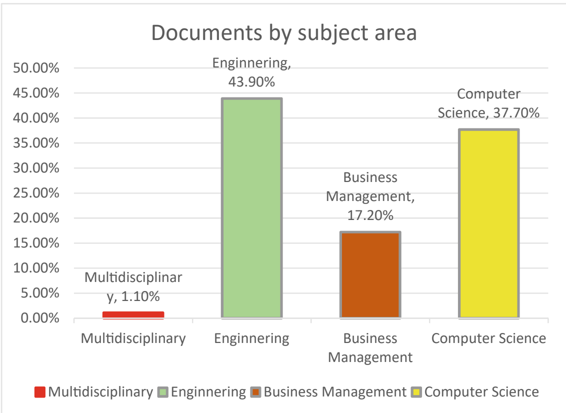


Fig. 3 Data retrieval process using a Prisma Approach (Author's compilation)

and abstract to select the most relevant studies. More elimination was done by checking the most cited papers. All authors' self-citations were not included in the study. According to the graph below, marked Fig. 4, the fields of engineering, computer science, business management, and transdisciplinary studies were those where the most relevant research was found.

The next chart shows how various nations have examined and embraced the evaluated literature on the adoption of digitalization (Fig. 5).

Fig. 4 Documents by subject area (Author's compilation)



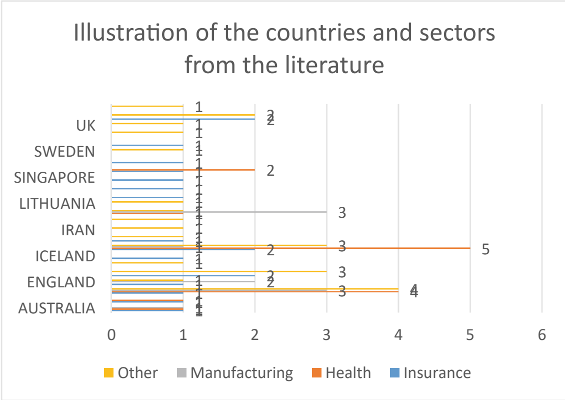


Fig. 5 Illustration of the countries and sectors from the literature (Author's compilation)

The illustration in the previous figure shows how digitalization has been investigated in various countries. India and China are the top two countries in the adoption of digital techniques, according to the 62 research produced from the Scopus database. Despite the fact that these two nations have published numerous articles on digitalization, their research focuses more on other sectors, such as the manufacturing, health, and other sectors. Only 21 percent of the 62 publications examined focused on the insurance industry, and none of these studies were from the continent of Africa. This demonstrates the need for scholars to investigate digitalization in Africa.

3.3 The Adoption of Digitalization

The selected papers are discussed in detail in the following section, highlighting the proposed technological models, the explored digitalization tools, and the impact they are making and will make in the insurance industry, the potential to improve productivity, performance, and customer service in the insurance industry.

4 Discussion

(a) *Fraud in the insurance industry*

Fraud is experienced by all types of insurance including the long-term insurance. The fight against fraud has been slowly getting popular to reduce insurance rates [34]. Insurance fraud is an issue that affects the entire world, not just the continent of Africa [8]. According to Viaene and Dedene [34], fraud in the insurance industry has existed since the establishment of the industry. The study further highlights that in addition to jeopardizing the insurer's ability to generate a profit, insurance fraud and, abuse of insurance may have a severe negative impact on economic frameworks as well as its value chain [34]. In the insurance industry, fraud is defined in the study done by Goleiji and Tarokh [35] as: setting up a false claim with the intent to intentionally mislead; reporting a loss or damage to be greater than it is, and/or using any other techniques to obtain funds above what the insured party is legally entitled to receive. Rawashdeh and Singlawi [36] defines it as any action taken with the purpose to mislead the insurance system to attain a misleading outcome. This could happen if a claimant tries to receive benefits to which they are not otherwise entitled. Insurance fraud is a significant issue for the insurance industry, a serious crime that weakens the entire system and affects insurers, customers, businesses, society, and the economy [36].

To reduce fraud in the insurance industry, studies have been conducted by different authors like Hargreaves and Singhania [2], Dhieb et al. [4], Bohnert et al. [8], and Łyskawa et al. [44]. These studies were conducted to develop a safe and digital insurance framework that would be able to reduce human contact, protect financial loss for the insurance processes, notify and inform about customers with high risk, and identify fraudulent claims. The findings show that digitalization can increase the accuracy of risk assessment [4]. The cost of manually managing fraud in the insurance sector is very high, data analytics can be used in the insurance industry to assist insurers in detecting fraud [8]. A powerful method for being more proactive in the battle against fraud is data analytics, which may be used to spot transactions that point to fraudulent activity or a higher risk of fraud. Studies have asserted that the insurance sector can detect fraudulent claims with accuracy and that this method has the potential to reduce costs for insurers and increase their profitability [4] and [8]. To understand the development of financial technology through big data, Liu et al. [12], conducted a study to enhance big data's usage in financial technology. By combining big data with space-time data, the industry can reduce costs, manage risks, and use both internal resources and those generated from a variety of products. Big data, according to Liu et al. [12] is crucial for the insurance industry's product development, advice, pricing, marketing, and fraud detection.

(b) *Real time data in the insurance industry*

According to Sagiroglu and Sinanc [42] Big Data refers to highly bigdata sets that may be analyzed to reveal patterns and trends. This indicates that there is a variety of information accessible to calculate risk, allowing for more accurate and detailed pricing as well as speedy and risk-specific underwriting. For insurance companies, it is a resource that, if used appropriately, can provide the company a competitive advantage [31]. However, Liu et al. [43] contend that the insurance business lacks sufficient sample data, real-time data, and internal data, which is a problem that must be addressed. The insurance sector is one of the many developing sectors that heavily rely on data to regulate some aspects in their business. The adoption of digital models by the insurance industry would have a significant positive impact on the economy of South Africa because the country is home to many of the largest international insurance companies, like Sanlam and Old Mutual. To address the issue that was raised by Liu et al. [43] about the lack of sufficient sample data, real-time data, and internal data in the insurance industry, Wang et al. [31] carried out research to improve the availability of client data in the insurance sector. Wang et al. [31] expanded on the claim made by Liu et al. [43], that the insurance sector depends more on historical customer data to decide key operational elements, including product design and pricing. According to Wang et al. [31], insurance businesses can collect accurate and reliable client data in real time with the help of advanced business tools. By using big data, the insurance companies can analyze the risk posed by their customers. The premiums can be priced fairly and accurately when an insurance provider is aware of the risk posed by the customer. After discovering this challenge, Wang et al. [31], recommended that the Internet of Things and Big Data will help the insurance industry to understand their customer's risk up front because these technological tools are able to gather information on the activities and health of the customer in real-time. This research will help improve the transparency and fairness of the insurance industry. This issue has also been a challenge in the short term-insurance industry. The inconsistent and unreasonable premium rates have been a long-standing complaint of customers. Machine learning and telematics have also been suggested to eliminate unfair premium pricing in the short-term insurance sector [27]. The models that are currently used to determine premiums in the field of auto insurance were mentioned as being unappealing to customers. Just like Wang et al. [31] proposed the use of Internet of Things and Big Data in the long-term insurance for accurate and fair pricing, Reddy and Premamayudu [27] suggested the combination of Blockchain technology with Deep learning, Bayesian network and fuzzy logic techniques to improve the calculations of the premiums, mostly based on the user's driving style. As the premiums would depend on the customer's driving style, Reddy and Premamayudu [27] evaluated the model's effectiveness and believed that it would offer fairness to all auto insurance customers.

(c) *Automated underwriting*

Insurance underwriting is ready for automation. It entails obtaining and analyzing data in organized, unstructured, or mixed formats from a diverse range of sources to assess the risks. It is an extremely drawn-out and lengthy process that, on average, takes 3 to 4 weeks to finish in the life insurance industry [37]. A health examination is required for applicants, and the insurance company requests any applicable documentation. It is time-consuming and error-prone to manually gather medical records [38]. The underwriter then carefully assesses the profile to establish the risk involved and evaluate if the application may move forward with additional processing. Then, premiums are determined [38]. The study also shows that approving wrong applicants for insurance coverage happens when clients do not provide complete and honest information, leading to insurers approving high-risk scenarios. According to Biddle et al. [39] all parties involved can benefit from automation of the underwriting process, which can help in a variety of ways. It is possible to speed up the underwriting process drastically, decrease instances of human error, and eliminate any confusion or knowledge gaps among the underwriters. Research on the importance of risk assessment in the long-term insurance industry were conducted by Biddle et al. [39] and Boodhun and Jayabalan [3] as the topic of risk prediction becomes more important and a center of attention. Biddle et al. [39] and Boodhun and Jayabalan [3] emphasized the importance of the underwriting process because underwriting is an essential stage in the insurance industry because it helps to make informed decisions about the acceptance of customers and pricing of insurance products. The development of data analytics has made it simple for insurers to automate the underwriting process. Their research sought to provide recommendations for using predictive analytics to enhance risk assessment in the insurance industry. To predict the individuals' level of risk, previous research used ML algorithms. Results showed that this method is far superior to the extensive, complicated actuarial formulas that were previously employed for risk assessment, and it will be able to benefit the insurance business. According to Liu et al. [12] with data analytical solutions, insurers will be able to calculate the risk assessment faster and get much better results.

(d) *Storage of confidential information*

Data is essential to the insurance industry because it enables the industry to assess risks, charge for them, and provide the necessary protection to their clients. Data is essential to remaining competitive because insurance businesses must gather huge amounts of information in our growing, data-rich world to maximize performance, mitigate risk, and satisfy consumers' increasing expectations [33]. Blockchain-based insurance storage system are needed in the insurance industry to give customers a high level of trust due to Blockchain's strong resilience to manipulation and its capacity to keep a virtual record of all data and transactions safe [40] and [33]. Zhou et al. [40] and Xia et al. [33] contended that because of the decentralized nature of the blockchain based solutions, users would be able to interact with one another without the intervention of a third party. According to Zhou et al. [40] and Xia et al. [33] to meet the insurer's requirements, the designated servers will be able to apply cryptography algorithms to the data and produce results. In case of hospital medical records, insurer will be able to retrieve the proper patient's spending data if they are able to gather a certain number of accurate answers [33]. Additionally, the blockchain-based solution would be able to carry out user functions more quickly and do public verification [40]. Consumer's willingness to pay for blockchain technology and smart contracts have been studied and the findings suggested that using the qualities of potential clients to build insurance products would be beneficial [15]. It has been highlighted that blockchain is incredibly safe by design and can handle a lot of data well. As a result, smart contracts created on the Blockchain can automate all processes and have a self-executing nature Nam [15]. The use of machine learning (ML) in the insurance sector, particularly has been evaluated because the ongoing global revolution is having an impact in the insurance sector. The adoption of the technological tools associated with the fourth industrial wave comes with significant changes to company culture, data-driven results, and increased competition, all of which may lead to higher levels of customer satisfaction [7]. The importance of creating an AI organization based on a theoretical framework for fusing artificial and human intelligence, was also explored. It was established that many organizations are dealing with difficulties brought on by the urge to replace human intelligence with artificial intelligence. Lichtenthaler [11] concluded that businesses require the three types of intelligence: meta, artificial, and human. He went on to say that the idea of a meta-intelligence, which benefits from the reintroduction and recombining of artificial and human intelligence, facilitates the reconciliation of numerous findings from previous research. Without meta-intelligence, most artificial intelligence programs will be difficult to sustain, which could have positive outcomes but also have a chance of falling short of expectations [11]. Therefore, organizations will require intelligence made up of meta-intelligence, artificial intelligence, and human intelligence.

5 The Gap in Literature Review

From the papers reviewed, 79% of the studies that were examined had a focus on different industries, such as health, agriculture, manufacturing. Studies pertaining to the insurance sector made up just 21% of all studies. It seems that many different industries have studied technology like blockchain, the internet of things, and artificial intelligence. The investigations' findings revealed significant advancements and a bright future for each of these models. It is evident that research must focus on examining how the insurance industry is becoming more digital. This is a result of the dearth of studies looking into modern technologies like the Internet of Things and Artificial Intelligence that have been done in the insurance sector. The authors have suggested using IoT and big data to improve client databases in the insurance industry. This is because IoT can assist insurers in gathering real-time client data. In turn, this will make it easier for insurers to assess client risks, consumer behavior, and health status. Authors like Albrecher et al. [1], Pousttchi and Gleiss [23] and Eckert and Osterrieder [5], have made important theoretical contributions to the body of knowledge in insurance while investigating how much digitalization is being implemented in the insurance business. All of them emphasize how the digital age is compelling traditional insurance companies to change their strategies, operational procedures, and organizational structures to incorporate AI tools into the insurance value chain. The commonality of these studies is that they offer a thorough evaluation and significance of digital tools in the workplace. The findings of these research indicate that all industries, including the financial services sectors, stand a considerably greater possibility of benefiting from the digitalization. But like many studies carried out in the insurance sector, they review the body of knowledge. To investigate these modern digital technologies that are part of digitalization, empirical studies in the insurance industry are required. Modern technologies enable communication between companies and their customers. These technologies enable companies to collect real-time customer data to identify customer patterns. Because the insurance sector uses previous customer data to inform business choices like accepting a customer, calculating premiums, and deciding whether to pay or reject a claim, this database is more beneficial to such an industry. As a result, big data and internet of things technologies can help insurers collect real-time client data and to make informed decisions. Due to the changes brought about by digitization, insurers must act in the form of opening their minds and choosing their own path to digital transformation, which would need a significant investment in skills and financial resources. It is necessary to restructure IT infrastructure, consider contracts with significant technology manufacturers, reconsider business processes in engineering labs, and create internal innovation and digitization teams. Think of partnering with FinTech or InsurTech startups as well as players from other sectors who can give client data. Adapting their human resource practices, such as creating or hiring a new class of tech-savvy and data-savvy employees, understanding what it means to act in a customer-centric way in the digital age, and making sure that the equitable insurance agenda is considered for underserved client categories are all crucial. The existing technologies contribute to the industry's transformation and present opportunities that could become increasingly significant in the face of competition. Claims costs and expenses can be reduced by using insurance use cases such as automated claims processing, effective underwriting with better data use, and more robust fraud detection. In addition, insurers could improve customer experience management while also strengthening client retention and satisfaction.

6 Conclusion

This paper presented a broad overview of the insurance industry, its purpose, and the contribution it plays to human lives. Not only it is good for individuals, but it is also essential to the economic system's sustainability, stability, and the worldwide economy. The insurance industry continues to face challenges such as fraudulent claims, brand reputation, disputes due to factors like non-disclosure of the existing health conditions and so on. The financial costs and administration efforts related to these issues are hindering the insurance industry. The study looked at how the insurance business may use the digitalization to address these problems. The idea of digitalization is not new; it has been broadly examined by various researchers in several ways, and it has already transformed business models in areas like healthcare, tourism, and other industries. To compare how digital technology models have been studied in the insurance business to those in other industries, the study conducted a systematic literature review adopting the PRISMA approach. The study also looked at prior research's findings to determine how academics in the past had perceived digitalization and majority of the studies focused on other industries, including health, manufacturing, agriculture, retail, food, etc. The findings of the studies indicated a substantial advancement and a promising future for all the evaluated digital models. The examination of the digitalization in the insurance industry must be the focus of research. This is due to the lack of research done in the insurance industry regarding the latest technology like the Internet of Things and artificial intelligence, particularly in South Africa. The study proposes enhancing client databases in the insurance sector with IoT and big data. This is because IoT can help insurers obtain client data in real-time. Insurance companies will then find it simpler to evaluate client risks, consumer behavior, and health status. Due to digitization, traditional insurance companies are being compelled to transform their organizational structures, techniques, and processes to integrate AI tools into the insurance value chain. The survival and success of the insurers merely depend on the integration and execution of the new technologies into the business strategies. This is because the main benefit of the use of the latest technology is the access to real-time policyholder database and consumer patterns.

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Space Partitions: An Alternative to Domain Assembly in Geometric Modeling

A Computational Robust Method for Spatial Decomposition - Test Case with Cadastral Data

Enrico Romanschek, Christian Clemen, and Wolgang Huhnt

Abstract This paper presents a case study of a novel spatial decomposition algorithm in the field of Geographic Information Systems (GIS). Real estate cadastral data of a district, consisting of parcels and buildings, are used as a test data set. A cadastral map is a set of parcels and buildings, or more generally GIS features. Each feature is geometrically represented as a polygon. The legally binding nature of the cadastral map (rights, restrictions and responsibilities on land) requires that the polygons do not overlap. There must also be no gaps between the parcels.

Based on the test cases, it is shown that the computationally robust space decomposition presented here with a complete, gapless and overlap-free two-dimensional topology can be used very well in this domain. With the added benefit that the results provided are completely error-free and reliable, and spatial queries can be easily formulated using set operations. The foundations of the algorithm were presented in previous research papers, and are summarized shortly in this paper.

While a previous paper provided a proof of concept using artificial datasets, this paper now uses real cadastral data. The fully automated procedure transforms OGC simple features in a space decomposition model. For validation purposes, all cases are additionally tested with a geospatial ETL-software, namely the Feature Manipulation Engine (*FME*).

Keywords Space decomposition · GIS · DE-9IM · robust geometry

E. Romanschek (✉) · C. Clemen
Faculty of Spatial Information, Hochschule für Technik und Wirtschaft Dresden University of Applied Sciences, 01069 Dresden, Germany
e-mail: enrico.romanschek@htw-dresden.de

C. Clemen
e-mail: christian.clemen@htw-dresden.de

W. Huhnt
Faculty VI Planning Building Environment, Institute of Civil Engineering, Chair in Bauinformatik, TU Berlin, Technische Universität Berlin, 13353 Berlin, Germany
e-mail: wolfgang.huhnt@tu-berlin.de

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1 Introduction

A feature is an abstraction of a real-world phenomena [6]. Geometrically and topologically consistent features are essential in the field of Geographical Information Systems (GIS) and especially in the real estate cadastre storing legal data. However, commonly used GIS data structures such as OGC-Simple features[1] are purely geometrical, e.g. polygons. The data structure does not have inherent logical set operations for checking the topological validity of the feature itself nor the relation between two features.

In practice OGC-Simple features are validated and used in a wide range of commercial and open-source GIS software products, libraries and spatial databases including GEOS library[2], GDAL library[3], PostGIS[4], QGIS[5], ArcGIS[6], Civil/Map 3D[7] as well as in the spatial *Extract Load and Transform* (ETL) software *FME*[8].

Since the coordinates of the Simple Features are represented by floating point numbers, the calculation of spatial relationships is not always unambiguous. Floating point numbers have a limited precision. Unavoidable rounding errors on floating point coordinates may lead to contradictions between topological and geometrical assertions.

An additional weakness of purely feature based approaches is that only known objects are represented. If there are gaps within a set of polygons, they are not conceptualized as objects in their own right. This means that gaps may only be detected indirectly, using workarounds to model the surrounding of a feature.

To tackle these problems with geospatial geometries, a novel approach to space decomposition was developed [8]. With this approach, it is guaranteed that the affected area is represented completely, without gaps and no overlaps. This is achieved by the following principles:

– Implementing a data structure that maps the topology as space decomposition.
– Modeling even empty spaces as objects.
– Exclusive use of integer coordinates for location tests and position calculations.
– Representing intersections only as positions on edges and not by coordinates.
– A special algorithm for reconstructing features in a mesh.

This approach allows unambiguous statements to be made about the spatial validity and adjacency of GIS features. In addition, once the space partition is created, the queries for spatial relations are fast and efficient, since they are based on set comparisons only and do not require any geometric calculations.

[1] https://www.ogc.org/standards/sfa.
[2] https://libgeos.org.
[3] https://gdal.org.
[4] https://postgis.net.
[5] https://qgis.org.
[6] https://www.esri.com.
[7] https://autodesk.com.
[8] https://www.safe.com.

The purpose of this paper is to show that this approach has advantages compared to established methods. Firstly, the results are absolutely reliable and secondly they can be obtained efficiently and flexibly.

To prove this, small test datasets as well as a German real estate cadastre dataset is examined with the presented method. The simple features are checked first for validity and then used for spatial queries. To validate the results of the test, the same input data were conducted with the well established ETL-software *FME*.

2 Related Research

The fundamental concepts of the approach used for the presented testbed are based on [5]. The relevance to GIS the general usability for space decomposition with geodata was discussed in [8]. Especially the importance of the DE-9IM matrices for the description of spatial relations was shown in the previous work of the authors.

The practical problem of inconsistencies in geometric computations using floating point numbers are well described in [7]. In general, floating point numbers have only a limited number of significant digits, so calculations, such as intersections, may deliver wrong results. An overview of the problem area on methods of exact geometric computation with geospatial data is provided in [12]. This research shows, that integer coordinates and space decomposition are good concepts for robust calculations also for geodata.

The Dimensionally Extended 9-Intersection Model (DE-9IM) is a well establish mathematical concept to describe topological relations and is founded on the research by Clementi and Eggenhofer [3, 4]. A diversity of topological data models has been published and found to be important for many use cases, e.g. [11, 13]. Current research extends theses concepts of topological queries [9, 10].

However, to the best knowledge of the authors, there is no extensive research literature on implementation details, for the particular use case "executing queries on spatial relations, using set operations" that focuses on robust calculations. A first description can be found in [2], but there the whole subject is considered in the context of database systems, mainly focusing on creating spatial indexes for fast queries on object-relational geo-databases.

3 Data Structure and Algorithm

The objective of the algorithm is to create a spatial decomposition for a given set of simple features. The resulting decomposition is complete, gap-less and does not contain any overlaps.

The algorithm reads simple features (`Point`, `Polygon`), creates a Delaunay triangulated mesh with integer numbers, reconstructs the features with `HalfEdges` in a space decomposition and eventually creates dimension-based feature sets

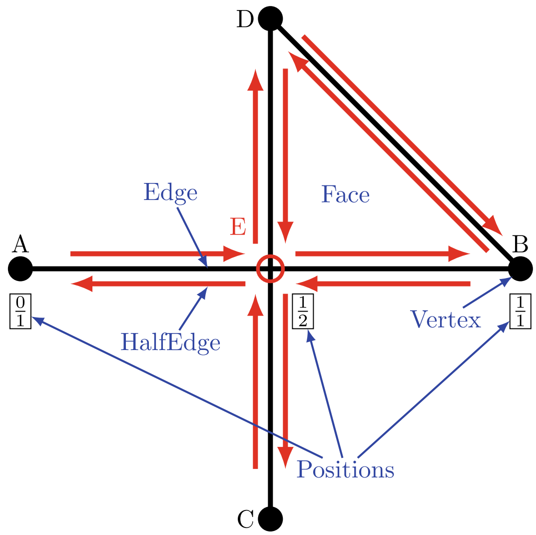


Fig. 1 Datastructure of the model

(`Dim0Set`, `Dim1Set`, `Dim2Set`), that allow robust DE-9IM set queries on the given simple features.

The topological data structure for the space decomposition is based on half-edges (Fig. 1) and consists of the following types:

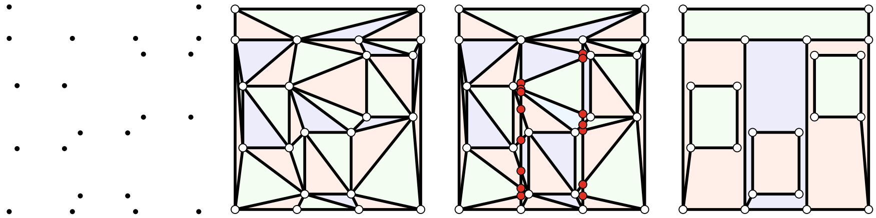
`HalfEdge`: Half-edges have a starting point (`Orig`), a following half-edge (`Next`), a previous half-edge (`Prev`), a twin (the adjacent opposite half-edge `Twin`) and the associated face (`RefFace`). As a special feature, each half-edge also has an associated edge (`RefEdge`). The starting point is not a `Vertex` object but a relative position on the associated edge. To specify the orientation of the half-edge, it also contains a flag (`InEdgeDirection`) which is `true` if the half-edge is in the direction of the reference edge.

`Edge`: Each `Edge` starts at a `Vertex A` and ends at `Vertex B`. To make these edges unique, the endpoints are sorted with respect to their coordinate values. Moreover, each edge contains a list of all intersecting edges (`Intersections`), sorted by their relative position on the edge. The intersection position is a proper fraction between $\frac{0}{1}$ (start point) and $\frac{1}{1}$ (end point). In addition, each edge contains another list with associated `HalfEdges` and a set with `Ids` of the associated features.

`Vertex`: The endpoints of the `Edges` are `Vertex` objects. These have an associated 2D coordinate represented by `Point`, a set of outgoing (`Edges`) and a set of associated features (`Ids`).

`Face`: The `Face` object contains a reference to a half-edge of the boundary (`RefHalfEdge`) and the set of associated feature `Ids`.

This data structure provides a representation of the simple features geometries, that is consistent with respect to geometry and topology. To generate this space decomposition, the following steps are necessary:



(a) Vertices (b) Triangulation (c) Reconstruction (d) Clean up

Fig. 2 Essential steps of the algorithm

1. A list of simple features of type `Point`, `LineString`, `MultiLineString` or `Polygon` with associated ids, are read from a given data set.
2. All points from the imported features are collected (Fig. 2a). From this, a bounding box is formed and the *scale* factor and the translation x_{min} and y_{min} for converting the coordinates into integers are determined.

$$\begin{pmatrix} x_{int} \\ y_{int} \end{pmatrix} = scale \left[\begin{pmatrix} x_{float} \\ y_{float} \end{pmatrix} - \begin{pmatrix} x_{min} \\ y_{min} \end{pmatrix} \right] \tag{1}$$

   The *scale* converts all given coordinates to integers without rounding. Since the given geospatial features the have millimeter precision, the resulting scaling factor(*scale*) is 1000.
3. With the scaled integer coordinates a Delaunay triangulation is computed (Fig. 2b). This mesh forms the basic data structure and guarantees that the model is gap-less and overlap-free. The outside half-edges along the boundary of the entire model are assigned to the `EXTERIOR` facet.
4. Reconstruction of the simple feature edges.
   (a) Intersection of the features-edges with the triangulation-edges.
   (b) Intersection of the inserted feature-edges, that are inside of triangles (Fig. 2c). This sub step avoids geometric calculations, by only using the order of intersecting edges within a mesh-triangle.
   (c) Once all edges inside a triangle are reconstructed, new faces can be created.
5. Assignment of the newly created faces to the original simple features.
6. Clean up of the finished model from unnecessary edges and intersections that come only from triangulation and do not belong to any feature (Fig. 2d).

After these steps, the space decomposition is complete and will not be changed in the following topological queries. Each `Vertex`, `Edge` or `Face` contains the corresponding ids and types (parcel, building, ...) from the original geospatial dataset and these can be grouped into dimension-based feature sets `Dim1Set`, `Dim2Set`

Table 1 The dimension-based feature sets Dim0Set, Dim1Set and Dim2Set are linked to the space decomposition Vertex, Halfedge and Face

	0-Dimension Vertex	1-Dimension HalfEdge	2-Dimension Face
Interior	Dim0Set Dim1Set Dim2Set	Dim1Set Dim2Set	Dim2Set
Boundary	Dim1Set[a] Dim2Set	Dim2Set	

[a] The Boundary 0-Dimension attribute of closed Dim1Set objects is an empty set.

and Dim3Set according to the ids. These new types form the basis for the analysis of spatial relationships using DE-9IM matrices.

Dim0Set: A Dim0Set corresponds to an original Point feature. And thus consists only of a Vertex, which forms the 0-dimensional interior of the Point feature. A Dim0Set has no boundary and everything except the Vertex itself is the exterior.

Dim1Set: A Dim1Set consists of vertices and half-edges. It is a 1-dimensional geometry object and is the equivalent of the LineString and MultiLineString features. The vertices between the half-edges form the interior of dimension 0, the half-edges form the interior of dimension 1.

Dim2Set: A Dim2Set is the equivalent of the original polygon features. Its interior consists of the faces, their common half-edges and common vertices. All half-edges and their vertices adjacent to unrelated faces form the boundary in the dimensions 0 and 1.

These three sets only use the indices of the respective elements (Vertex, HalfEdge, Face) of the space decomposition. Specifically, the attributes Interior and Boundary are used to link the space decomposition to given features as shown in Table 1. With this data structure, the spatial relationships of the original features can be mapped by simple set operations.

Only the Dim0Set, Dim1Set and Dim2Set are used to determine spatial relationships of features or to check the validity using DE-9IM matrices. Such matrices have the advantage to represent complex questions about spatial relations of features in a simple and expressive way. Two feature sets a,b can be queried, if they fulfill the topological relations, declared with a DE-9IM-Matrix.

$$DE9IM(a,b) = \begin{bmatrix} dim(I(a) \cup I(b)) & dim(I(a) \cup B(b)) & dim(I(a) \cup E(b)) \\ dim(B(a) \cup I(b)) & dim(B(a) \cup B(b)) & dim(B(a) \cup E(b)) \\ dim(E(a) \cup I(b)) & dim(E(a) \cup B(b)) & dim(E(a) \cup E(b)) \end{bmatrix} \tag{2}$$

The dimensions for the Interior I, Boundary B and Exterior E are 0, 1 or 2. All operations to calculate the query are set based and do not require any geometrical calculations.

Fig. 3 Map of a local subdistrict

4 Test Design

The purpose of the testbed is to demonstrate the functionality and robustness of the new approach. For this task, simple test files and a data set from the German real estate cadastre was used, which covers the parcel and building data of a subdistrict as shown in Fig. 3. These data were originally available in the gml-based NAS exchange format, which is common for German geo-data infrastructure (GDI). It was converted with *QGIS* into two simple CSV-files containing the geometry of the simple-features as well known text (WKT) and the corresponding ID of the feature[9].

All parcels and buildings are exported separately into a single file, so that an assignment to the categories can be made via the file name during import. In this way, each feature is assigned to a two-part Id, with category and object Id. The tests arise from the following fundamental questions:

1. Do the features meet the requirements for *OGC* simple features?
2. Are there overlapping parcels?
3. Are there gaps between parcels?
4. On which parcels is a building located?

Question 1 is related to geospatial data quality for a single feature, question 2 and 3 for a set of features. Question 4 exemplifies queries on heterogeneous data sources.

[9] https://github.com/dd-bim/cadastralTestData.git.

The testbed also ensures that the implementation can detect invalidities. Several possible defects are modeled as shown in Table 2. The CSV-files contain single simple feature geometries as WKT with invalid geometries. The test succeeds (true negative) if the simulated defect is detected.

4.1 Test 1: Do the Features Meet the Requirements for OGC Simple Features?

This test serves to exemplify the basic prerequisite for geospatial analysis in general. It checks whether the input geometry can be transformed to a valid space decomposition.

In [1] the types and their properties of the *OGC* simple features are described. In the testbed only the *OGC* types `Point` and `Polygon` are used.

Simple feature polygons are valid if they fulfill *OGC*/*ISO*-standardized topological conditions [1, sec. 6.1.11]. In addition, the assertions for `LinearRings` [1, sec. 6.1.7] have to be true.

Lines 1 to 13 in Table 2 shown which particular defects are simulated in the testbed. Column "Processing step" describes, whether these defects are detected during import of simple features, or while converting to the features to space decomposition, or at the final query level.

4.2 Test 2: Are There Overlapping Parcels?

This test stems from the legal requirement that parcels are disjunctive areas of land ownership, surrounded by well defined boundaries. This test is performed on the space decomposition, not on features.

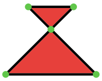
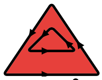
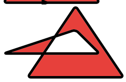
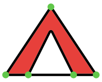
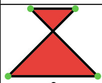
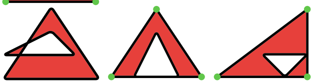
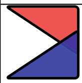
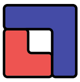
The basic functionality is checked by the simple test from Table 2, line 14, then the implementation is done on the real estate cadastre data. All dimension-based feature sets of the category "parcel" are mutually tested. If the following equation holds, then the two tested parcels (a, b) overlap.

$$relate(a, b) = \begin{pmatrix} 2 & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \tag{3}$$

With this DE-9IM matrix given, the presented algorithm checks, whether the `Interior2` attributes of the parcels are a non-empty intersection. This implies for any parcel (a) compared to any other (b), there is an overlap if the following equation holds:

$$2 = dim(Interior(a) \cap Interior(b)) \tag{4}$$

Table 2 Constructed defects for checking the test cases

#	Defect	Processing step	WKT or figure
1	consecutive identical points	feature / import	`POLYGON ((0 0,2 0,2 0,...))`
2	too few points		`POLYGON ((0 0))`
3	not closed		`POLYGON ((0 0,2 0,1 1,0 1))`
4	point used twice		
5	overlapping edges		`POLYGON ((0 0,0 1,0 0))`
6	empty polygon		`POLYGON ()`
7	wrong orientation		
8	inner polygon is outside		
9	more than one vertex connected to the inner polygon		
10	self intersection	decomposition / generation	
11,12,13	inner face shares outer edge		
14	Test 2 subsection 4.2 (overlap)	decomposition / query	
15	Test 3 subsection 4.3 (gap)		

4.3 *Test 3: Are There Gaps Between Parcels?*

An important condition in the real estate cadastre is that the concerned region is completely covered. This means that there must be no gaps between the parcels. First, the simple test from (Table 2, row 15) is performed to be sure that defects are determined correctly. With the completed space decomposition it is possible to check whether the entire set of `Dim2Set` objects contains objects that do not belong to the category "parcel".

This is where the advantage of space decomposition becomes particularly apparent, as the topology covers an area without gaps. With feature-based approaches, an empty area is not recognized as a separate object and can therefore only be determined indirectly via geometrical queries on "nearby" objects.

4.4 Test 4: On Which Parcels Is a Building Located?

This test serves to demonstrate the advantages of the space decomposition. It shows, that simple set queries can be used to reproduce complex use cases.

To determine on which parcels a building is located, one can proceed as in Subsect. 4.2. In this test however, only the objects of category "parcel" with those of the category "building" are compared. If the matrix results from Eq. 3, then the building and the parcel have a common area. Alternatively, it is again possible to compare the `interior2` attributes, as in Eq. 4.

Moreover, it tests if buildings edges cover edges of a parcel. For this purpose, when comparing the "parcel" (a) with the "building" (b) objects, the following equation based on a DE-9IM matrix must hold to show that both have a common edge:

$$relate(a, b) = \begin{pmatrix} * & * & * \\ * & 1 & * \\ * & * & * \end{pmatrix} \tag{5}$$

Expressed as a set operation, the following equation must be `true`:

$$1 = dim(Boundary(a) \cap Boundary(b)) \tag{6}$$

This means the two objects have a common edge if the intersection of the `Boundary1` attributes of both objects is not empty.

5 Test Results and Comparison

This section covers the results of the presented test cases. In addition, the same tests were performed with the software *FME*. Both software systems have identical results indicating that the developed approach is valid.

5.1 Results Test 1 (Valid Feature)

The analysis of this type of defects (lines 1 to 13 Table 2) is done during the import procedure when the model is created. When importing the artificial test data, as expected, the tests failed with the defective data set. Also the *FME* detected invalid features with the "GeometryValidator"-module.

The presented approach is especially useful for large datasets, one can identify the defective data from the error messages and possibly repair it afterwards, and still have a space decomposition from the remaining data (if any).

Nevertheless, no defects were found in the data from the real estate cadastre.

5.2 Results Test 2 (Overlap)

In this test, the artificial data set (Table 2, line 14) was imported first. The subsequent search for overlapping areas, according to the procedure in Subsect. 4.2 was successful. Thus, the overlapping area was found.

Subsequently, the data set from the real estate cadastre was imported and searched for overlapping parcels. This search was unsuccessful, meaning that the dataset does not contain any overlapping parcels.

The same results were obtained with *FME* with the modules "SpatialRelator" and "SpatialRelation" using the parameter "OGC_overlap".

5.3 Results Test 3 (Gap)

After the artificial test (Table 2, line 15) data was imported, it was possible to directly detect the gap.

As can be seen in the magenta polygons in Fig. 4, there are three gaps between the parcels. The gaps have been correctly found by the software as well as in *FME*. However *FME* required some advanced transformation modules like "Dissolver" to create a surface, that contains all parcels and then "DonutHoleExtractor" to conceptualize the holes.

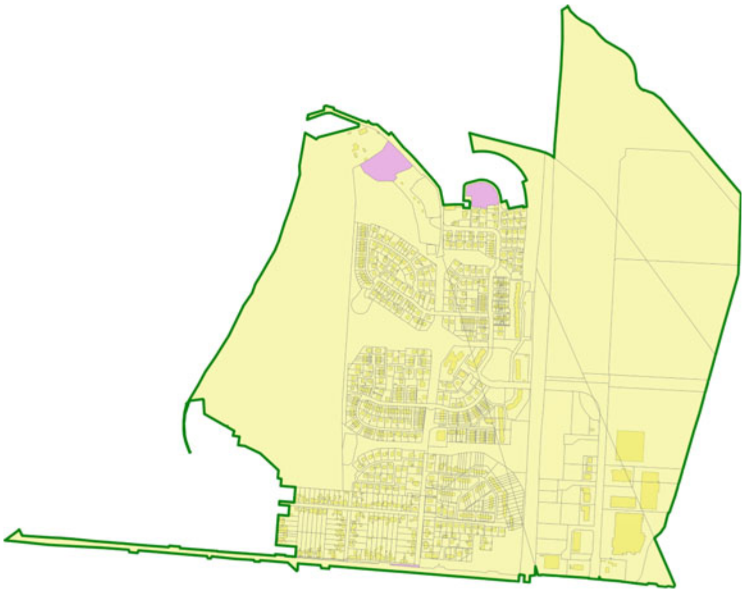
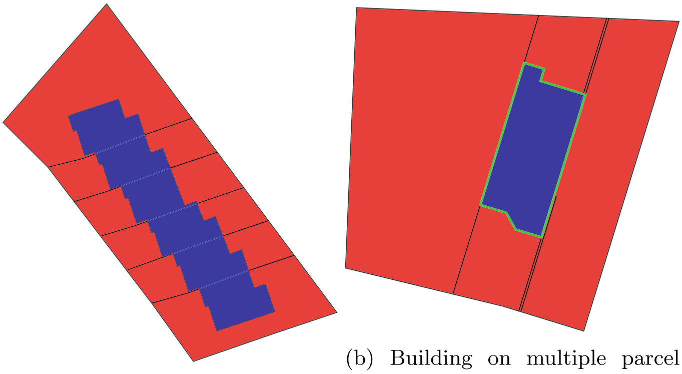


Fig. 4 Gaps (magenta) between parcels



(a) Building on multiple parcels. (b) Building on multiple parcel boundaries.

Fig. 5 Examples from the results of test 4

5.4 Results Test 4 (Parcels and Buildings)

This test is not made to detect invalid geometries, but serves as an example how to use the concept of space decomposition with heterogeneous geodata. The testbed determines on which parcels a building is located and which building has edges located on a parcel boundary.

A `Dim2Set-Dim2Set` result of the query "On which parcels is a building located?", is shown in Fig. 5a. Here, a connected block of small townhouses is located on several narrow parcels.

An example of a building with edges on a parcel boundary, is shown in Fig. 5b. There, the building is located with two sides on one parcel boundary each.

The algorithm presented in this paper and the *FME* gave the same results. However *FME* required some advanced transformation modules like "Topologybuilder" with some hidden parameters (e.g. "Maximum Coords Per Edge") and additional filter on the number of intersections.

6 Discussion and Outlook

In this paper it could be shown that an alternative approach, using a robust space decomposition with integer numbers only, can be successfully used to check data of the real estate cadastre. The results of the presented algorithm are more reliable, as there can be no ambiguities due to errors in the topology or due to floating point rounding errors. The tests were conducted with simulated and real data from German cadastre. By receiving equal results of basic topological queries with the ETL tool *FME* the implementation of the presented alternative approach has been verified.

With the presented implementation, topological queries on spatial features become more flexible, because proper DE-9IM matrices are supported, whereas *FME* only offers topological predicates. The conceptual key of the presented approach is, that topological queries are pure set operations. No computational expensive and error prone geometric calculations are necessary.

The parcel polygons data had been quality assured by the authorities before being published within the German geo-data infrastructure (GDI). Further research will be undertaken on more, possible inconsistent geodata like the open street map (*OSM*). The developed concepts are also applicable for two-dimensional CAD models. Therefore, the presented data structure and queries must be extended for additional semantic properties. These properties like color, line type, layer or block attributes might be extracted from CAD file.

The presented algorithm assumes purely deterministic input values. In the future, stochastic input data, such as measuring points from laser scanning, could also be included in the spatial analysis. The algorithm would then have to carry out significance tests on the nodes, edges and regions and thus check whether points are identical, edges have no significant length or regions have no significant area. The Statistical tests would then delete the non-significant elements and thus simplify the topological structure of the space decomposition.

Originally it was planned to carry out the spatial decomposition in geospatial and surveying applications in three-dimensional. This next step is non-trivial and can only be approached once the concepts, algorithms, data structures and use cases in the two-dimensional space are sufficiently understood and robustly implemented.

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Where is the End of the Wall: Decomposition of Air and Material into Spaces and Building Components

Felix Gabler and Wolfgang Huhnt

Abstract It is the state of the art to use point clouds in architecture and civil engineering. Lots of algorithms have been developed to create lines and polygons in 2D or patches and polyhedrons in 3D from point cloud data. The goal of this extensive research is an automatic generation of a building model. Specific subtasks in this field are supported sufficiently. Examples are object recognition or the identification of windows or doors. However, the internal decomposition into building components is still a challenge because only visible surfaces are detected and processed. This paper proposes a decomposition of the material into building components. The result is a decomposition into convex sub-objects. The algorithm supports the user by the finest decomposition but does not execute any unions. The algorithm identifies and computes the shape of each component. It does not classify. Furthermore, the algorithm can be used to decompose the space. The paper shows examples for both: the decomposition of material and air into building components and spaces. The paper focuses on a 2D approach. The outlook addresses the applicability to 3D. The algorithm presented in this paper is embedded in a sequence of algorithms which use space partitioning as the basic concept for all computations: the identification of material and space. The paper presents the actual state of research in this field. The concept has been worked out. Artificial examples give excellent results. The transfer to real point clouds as input is in progress.

Keywords Scan-to-BIM · Indoor environment reconstruction · Building components · Decomposition · Space partitioning

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F. Gabler (✉) · W. Huhnt
Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany
e-mail: f.gabler@tu-berlin.de

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1 Introduction

In architecture and civil engineering the scan-to-BIM approach is a rapidly growing field of research in the past years [5]. Various application possibilities during the design- and construction-process and the operation- and maintenance-phase are present [15]. However, current approaches in the industry still require labor-intensive manual work. It is therefore not surprising that multiple semi-automated and automated approaches have been presented in the recent years, comprehensive overviews of current approaches are given in [5, 11, 15]. Nevertheless, a complete automation of deriving as-built models from point cloud data remains an open challenge [4].

The research presented in this paper makes use of an approach developed by [13]. The location of the scanner plays a significant role. Triangles are the result of point cloud processing, describing a region of air that starts at the scanner and ends at the surface of material. This intermediate result is mapped onto a space partition. Furniture and circulating elements are removed. In addition, doors and windows are identified and removed as well so that the resulting model consists of regions of air, regions of material and unknowns.

The complete pipeline is addressed in the common research project ReconTOP which is executed with partners from TU Wien, Austria and TU Berlin, Germany. This paper addresses as a part of that project the decomposition of material and air. It is focused on geometry and topology. Semantic information are not addressed except the identification of spaces and material.

This present paper is structured in such a way it presents the concept using artificial examples. The transfer in using point clouds as an input is far driven and explained in parallel.

2 Related Research

A comprehensive overview of automated and semi-automated as-is BIM reconstruction techniques in the field of indoor environment reconstruction is given by [5]. Good results are computed if the geometry is parallel to the coordinate system (Manhattan assumption). Other geometries are still challenging. A summary of the present point cloud processing methods including registration, down-sampling and semantic segmentation methods are given by [12]. Lots of problems such as an automated registration are solved. The article points out that “a fully automated process for the extraction of semantics from the raw data in BIM remains a challenge”.

Multiple different approaches for the reconstruction of an indoor environment from point cloud data have been presented in the last years. [1] subdivides present approaches in “wall-based” and “room-based” approaches. At the end, these approaches address both, walls and rooms. However, they always start either with walls or rooms. There is no integrated approach identifying both, walls and rooms, in a single step. The approaches presented do not address the decomposition of material into components.

The identification of geometry can be structured in region-growing and random sample consensus (RANSAC)-based methods [5], applicable both in 2D and 3D. Presenting an approach for the automatic reconstruction of a floorplan, [3] makes use of a region-growing method for the detection of vertical planes, followed by a projection on the x-y plane. The result is a set of polygons, each of them representing the boundary of a room. A decomposition of material is not addressed. For an automatic extraction of structural elements, [14] makes use of a decomposition in 2D cells and region-growing for the determination of slabs and walls. Afterwards, a voxel-based region-growing method in 3D is used to derive columns and beams. The authors apply their method to structural components from concrete. They do not address any kind of rooms. In its present state the method can not be applied for an existing building (as-is BIM).

A known and often addressed challenge in indoor reconstruction is occlusion. Furniture may be a reason for occluded surfaces of building elements. An approach presented by [10] makes use of "pending" walls and an energy minimization problem for extracting a watertight 2D floorplan. The method is applicable for geometries which fulfill the Manhattan assumption.

Making use of region-growing combined with a conditional random field algorithm, [1] presents a method to derive wall elements from a 3D point cloud. In combination with the convex hull, room objects are generated. Not intersecting, best-fitting walls are calculated and topological connections of walls are generated afterwards. The approach is focused on walls as defined in IFC. The approach has several limitations. The authors write: "A manual operator should therefore still validate the model and some manual adjustments may be in order to complete the BIM walls."

Reconstructing structural elements, such as walls, floors and ceilings, including openings, is identified as a major field in indoor reconstruction. However, due to the fact, that only geometric information of visible surfaces of building components can be obtained by using a laser scanner [14], a lack of approaches addressing the decomposition of structural elements seems to be present. One approach taking non-visible contact faces into account and reconstruct wall intersections volumetrically is presented by [8]. In point cloud data detected surfaces are interpreted as infinite planes and intersected with each other. The result is 3D-space-segmentation into convex polyhedrons, followed by a determination of room, wall/slab and outside cells. With this approach building element intersections are modeled volumetrically. This approach seems to be far driven and seems to have the option to really result in a automated reconstruction of building models. The goal is not yet achieved. For instance, slanted walls can not be processed.

A basic assumption of our approach is the existence of exactly two conditions "known" and "unknown" or "air" and "material". The voxel-based growing method presented by [9] makes use of the same concept, the presence of "void" and "non-void" areas. Growing void-voxels results in cuboid 3D-cells, each of them known to be a room. The space between them, is identified as walls or more general as the building structure. However, the method is only applicable for geometries following the Manhattan assumption. In addition, a decomposition of material is not addressed.

In computational geometry, polygon decomposition is still a field of research with many applications including pattern recognition, collision detection and skeleton extraction. An extensive overview for planar polygons is given by [7]. Existing methods are classified by [6] in regards of the type of the input polygon, the allowance of Steiner-points during the decomposition and the desired sub-polygons. Many calculations, e.g. testing if a point is inside a polygon, are much easier to perform on convex polygons. An algorithm for the optimal convex decomposition is presented by [2], decomposing a polygon into a minimum number of convex parts. The algorithm presented in this present paper decomposes simple polygons into convex sub-polygons. Holes are allowed. This algorithm does not contribute to the research field of optimal or approximate convex decomposition.

3 Concept, Algorithm and Examples

3.1 Concept

Focus of this research is the decomposition of the building structure and of spaces. The concept is presented in this section. It is structured in several steps. In the 2-dimensional approach, triangles are generated from point clouds in a first step. These triangles are known to be from air. They have a line which separates air from material. The triangles are not ordered and form a triangle soup. In a second step, the triangles are mapped onto a space partitioning. This step identifies contiguous areas from air. All other areas of the space partitioning are potential candidates to be from material. The identification of the areas from material takes place in step three. The decomposition is step four. Results can be graphs and closed polygons in 2D.

In the 3-dimensional approach, all steps are equivalent. Tetrahedrons from air are generated from points clouds. They have a triangle which separates air from material. Results after the execution of all steps are closed polyhedrons. The following subchapters are focused on the 2-dimensional approach.

3.2 The Triangle Soup

Figure 1 shows two artificial examples of triangles from air. The first example has two locations of the laser scanner in the interior of a building, each in a separate room. The second example has four locations of the laser scanner, one in the interior and three outside the building.

The triangles shown in Fig. 1 describe the complete surface of the building without any gaps or overlaps. This is not true for real laser scans. Figure 2 shows an example

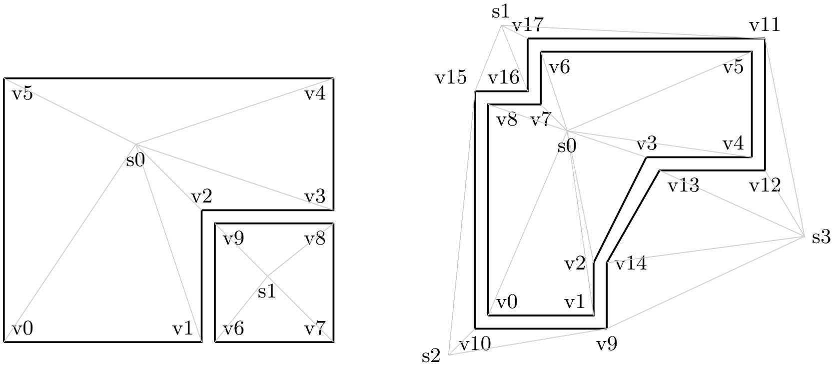

Fig. 1 Two artificial examples

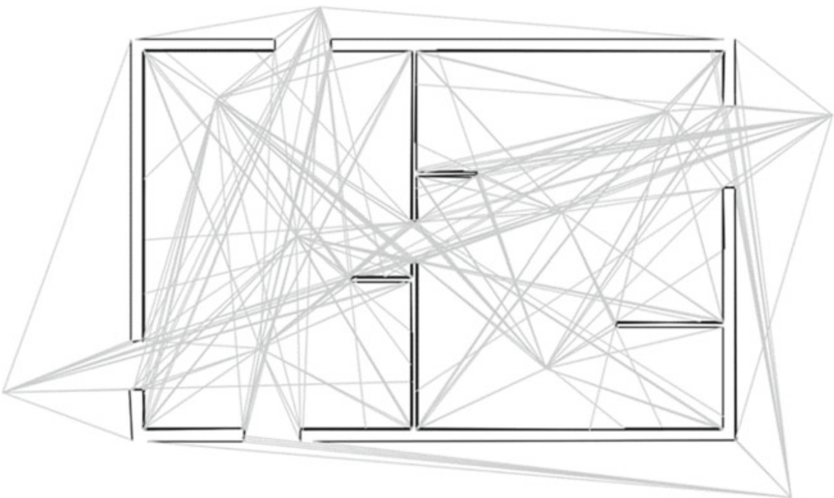

Fig. 2 Triangles from air detected from point clouds

of a simulated laser scan with several locations inside and outside. The triangles overlap; and not all points of the surface of building components are detected. The generation of these triangles is shown in [13].

3.3 Identification of Areas from Air

The triangle soup is mapped on a space partition. The result is a mesh of triangles. In this mesh, a breadth-first-search determines sets of connected triangles from air. Each breadth-first-search starts with a triangle behind an edge which is known to be a

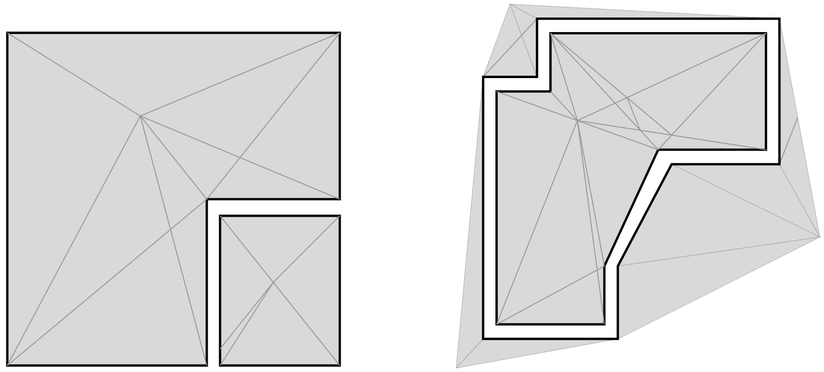

Fig. 3 Identification of Areas from Air of the two examples shown in Fig. 1

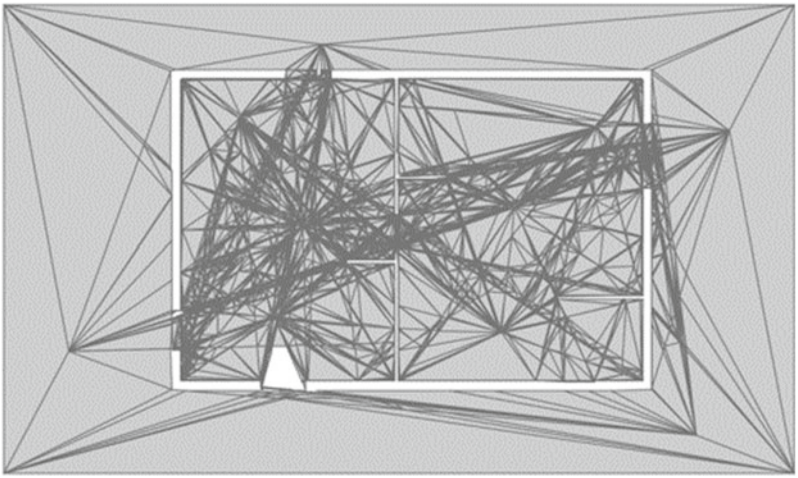

Fig. 4 Identification of Areas from Air of the Example shown in Fig. 2

boundary of an original triangle from air. The search ends at edges with the identical information.

Figure 3 shows the results for the two examples shown in Fig. 1. Figure 4 shows the result for the example shown in Fig. 2.

3.4 Identification of Areas from Material

All triangles which are not identified as triangles from air are the input of the identification of areas from material. The first artificial example shown in Fig. 1 has no laser scans of the exterior of the building. In this example, the triangles not from

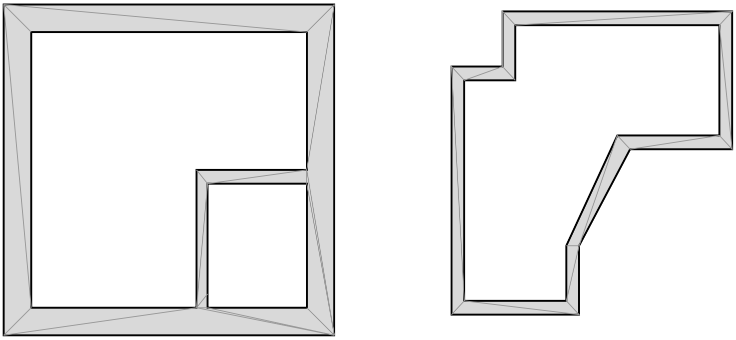

Fig. 5 Triangles not from Air of the Examples shown in Fig. 1

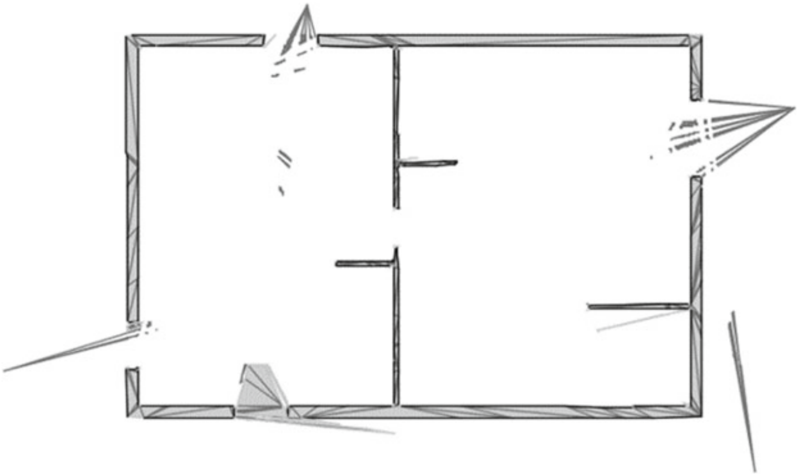

Fig. 6 Triangles not from Air of the Example shown in Fig. 2

air are potentially from material. The second artificial example shown in Fig. 1 is constructed in such a way that all triangles are from material which are not from air shown in Fig. 5.

Figure 5 shows examples which are special cases. In general, some boundaries of building components are not detected. This results in areas of unknowns. In addition, one boundary of a building component can be detected several times from different laser scanner positions at different locations due to imperfections of the scanning device and the scanning procedure. Figure 6 shows the areas which are identified to be not from air of Example 2 (see Fig. 2).

The areas not from air are investigated. Two topological conditions are applied:

– A triangle which starts at a laser scanner position must be from air.

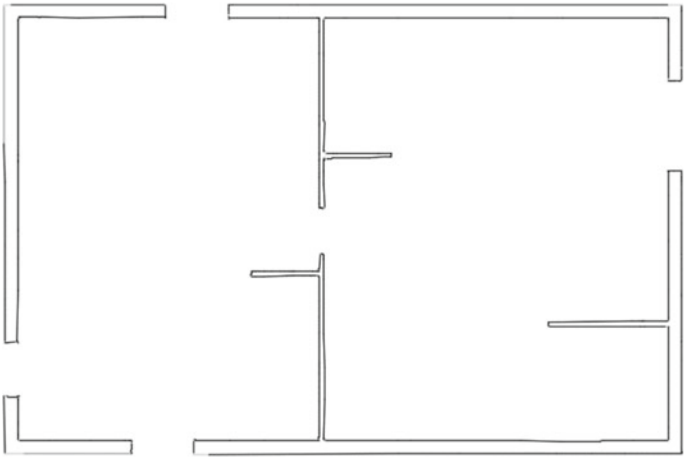

Fig. 7 Identified Areas of Material

– A set of triangles with no boundary between air and material which is surrounded by triangles from air must also be from air.

The result are sets of triangles in which material must be located. In a last step, a geometric condition is applied to the outer polygon of each connected set of triangles:

Consider two polygon edges e1 and e2 which are known to separate air from material. Consider only two edges e1 and e2 where between e1 and e2 are edges which do not separate air from material. p1 and p2 are start and end points of e1; p3 and p4 are start and end points of e2. Compute the intersection point p of the straight lines defined by e1 and e2. Substitute all edges between e1 and e2 by the edges p2 and p and p and p3 if p exists and if p lies behind p2 on e1 and in front of p3 on e2.

Figure 7 shows the result of the application of the three conditions on the example shown in Fig. 2.

3.5 Decomposition

The proposed decomposition algorithm focuses on splitting both, identified areas from material and identified areas from air into several convex sub-objects, leading to a convex decomposition of both, the building structure and the spaces.

Each connected set of triangles from either air or material is handled individually. First, the boundary polygon of a given set of connected triangles is determined, which may lead to polygons with holes. While an object can have multiple boundary loops, it is ensured that every boundary is a closed edge loop.

Starting from a random point, the boundary will be traversed counterclockwise, at every vertex the internal angle will be investigated. If the internal angle is greater than 180°, a vertex making the given object non-convex is found and stored for the next processing step.

In the first example given in Fig. 1, investigating the area known not to be air, v2 is a vertex fulfilling the previously mentioned criteria. Oriented counter-clockwise, the previous edge is from v1 to v2, the next edge from v2 to v3.

For all reflex vertices, the algorithm determines two direction vectors: one in the positive direction of the previous edge and a second in the negative direction of the next edge. For both vectors the closest intersection point with another boundary edge is calculated. To avoid round-off errors, the intersection point will be stored as a fraction as described in [13]. For the example in Fig. 1 this will lead to intersection points with the edges v4-v5 and v5-v0. Two new edges from v2 are created and stored as new interior boundary edges. For every edge the corresponding twin will be generated too.

After all edges have been created for vertices fulfilling the criteria, sub-objects will be found with a breadth-first search. The result is a set of multiple convex objects for every given initial object. The information about being "air" or "material" is consistent through the whole process.

```
input: n objects with m triangles each
forall objects do
    get boundary of object
    forall vertices v of boundary do
        calculate internal angle
        if concave vertex then
            calculate two direction vectors u,
            one in positive direction of previous edge,
            one in negative direction of next edge
            forall vectors u do
                forall edges e of boundary do
                    calculate intersection point p
                if amount of intersection points >1 then
                    choose closest intersection point
                create interior boundary edge from v to p
                create interior boundary edge from p to v
```

Algorithm 1: The Decomposition Algorithm

3.6 Results

Figure 8 and Fig. 9 show the results of the presented decomposition. Both, geometric and topological data are available. Geometric data results from the geometry of the triangles describing each identified object from air or material. For better display purposes, only the boundary of each identified object is shown. Edges of the triangles in the interior of each identified object have been removed.

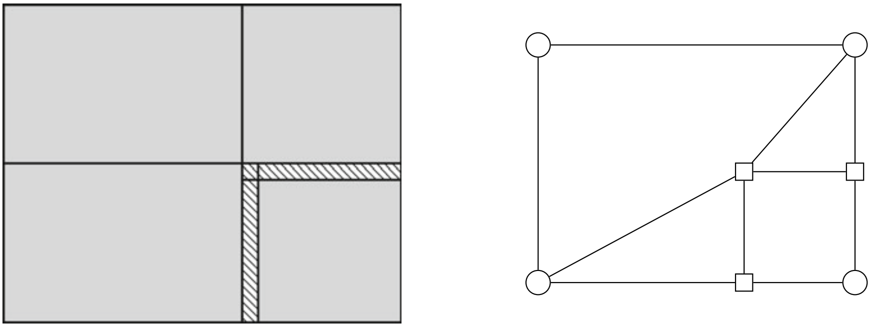

Fig. 8 Results of the Decomposition of the first Example from Fig. 1

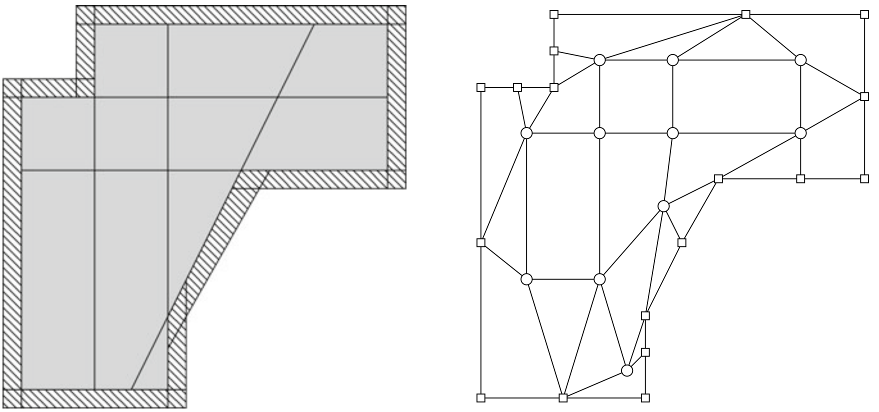

Fig. 9 Results of the Decomposition of the second Example from Fig. 1

Topological data results from the connected sets of triangles describing each object and the neighboring relation to other objects.

Topological data can be mapped onto each data structure describing the graph which now consists of objects from air which are spaces (circles) and objects from material which describe the internal structure of the building components (squares).

4 Summary, Discussion and Outlook

This paper presents research in progress. The overall goal is an automatic decomposition of a building into building components from point clouds. The presented results specifically focuses on the decomposition of areas into convex subareas. This is applied to both, spaces and material.

Artificial examples shown that the proposed concept results in acceptable results. The application to real scanned point clouds is still in progress. Two steps are still under development, the determination of points which are used to decompose an area and the determination of the two directions for the decomposition. The results of real scanned point clouds are boundary polygons with points with coordinates which of a stochastic nature. As a consequence, a point and the directions for a decomposition must be determined as best fitting points and best fitting directions. Algorithms from adjustment technique are at present time investigated.

The principle structure of all concepts and algorithms is set up in such a way that it can be transferred to the three dimensional space. In the three dimensional space, a mesh of tetrahedrons partitions the space. Input are tetrahedrons from air which start at the location of a laser scanner. Triangles separate air from material. The decomposition of air and material results in polyhedrons.

At present time, the research in the application to the three dimensional space is in progress. An algorithm for the partitioning of space into tetrahedrons has already been developed. Future results will show its runtime behavior for this field of application.

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Transforming Building Components into a Space Partition to Identify Indoor and Outdoor Spaces in Digital Building Models

Joanna Zarah Vetter and Wolfgang Huhnt

Abstract Modeling indoor and outdoor spaces is an important base in different application fields. In state-of-the-art modeling software products, spaces are often modeled as virtual solids. Nevertheless, these software tools suffer from unreliable identification algorithms for these virtual solids. This paper highlights different application fields and explains why current modeling techniques for indoor and outdoor spaces are not sufficient for those application fields. Examples of problematic cases and situations are given using two software products, Autodesk Revit and ArchiCAD by Graphisoft. Furthermore, the paper proposes the usage of space partition in digital building models as an alternative to overcome the illustrated problems. The boundary representations of building components are transformed into a space partition. Consequently, empty spaces in the interior and exterior of a building are an integral part of this partition and are identified automatically. It is shown that the resulting identified indoor and outdoor spaces of the partition are more reliable in problematic situations compared to the virtual solids created by conventional modeling software products. The advantages of using the concept of space partition to model indoor and outdoor spaces in digital building models are shown and discussed.

Keywords Room Generation · Space Partition · Empty Space · Topological Relations · 3-Dimensional Triangulation

1 Introduction

The developments of the last decades have enabled digital building models to become a centralized starting point for various fields of application. The functional scope of software tools has increased while the compatibility between software tools has

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J. Z. Vetter (✉) · W. Huhnt
Technische Universität Berlin, Berlin, Germany
e-mail: j.vetter@tu-berlin.de

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improved through standardized file formats such as the Industry Foundation Classes (IFC). Conventional modeling software tools for digital building models focus on modeling solids. Therefore, some parts are treated rather poorly during the modeling process, considering their significance in various use cases. By only modeling solids, modeling software tools insufficiently cover the empty indoor and outdoor spaces in building models. To compensate for missing information of the empty spaces, rooms or zones are often created as virtual solids in existing modeling software products. The generation of rooms based on such an approach tends to suffer from different problems. Additionally, modeling software products often do not consider outdoor spaces.

Nevertheless, different application fields rely on robust knowledge about empty spaces in digital building models. This paper suggests the alternative approach of using space partition to identify rooms and zones automatically. There are two different ways to construct a digital building model based on a space partition: developing a tool to model new building components based on a space partition or transforming a given model into a space partition. This paper uses the latter one. The input of the transformation process is a given boundary representation of solids. The output is a tetrahedral mesh in which a set of tetrahedrons describes each building object or each empty space. Identifying neighboring relations is possible without calculations of high effort by using resulting data structures that explicitly store topological relations.

The following paper presents relevant application fields that use indoor and outdoor spaces in digital building models in Sect. 2. Section 3 shows that the current modeling software products Revit and ArchiCAD cannot meet the requirements of different application fields. Section 4 presents the suggested transformation process of a given boundary representation into a space partition and an overview of previous research in this field. At the end of this paper, Sect. 5 describes relevant examples that show the difficulties of current modeling software tools. These examples also show the advantages of using a space partition to identify indoor and outdoor spaces.

2 Demand for Modeling Indoor and Outdoor Spaces

This section gives an overview of the current demand for modeling indoor and outdoor spaces in building models in different fields of application.

Indoor and outdoor spaces in building models play an essential role in different application fields. Digital building models play an increasing role in all processes in the AEC industry. Steps like quantity take-off calculation require detailed information about the geometry of objects and the empty spaces in building models. Current practices are often based on rooms in digital building models and may require high amounts of manual adjustments to ensure the correctness of volume or area computation. Recent discussions on social media platforms like LinkedIn showcase the demand for modeling indoor spaces and that workarounds are the constant companions of architects or civil engineers, as seen in Fig. 1.

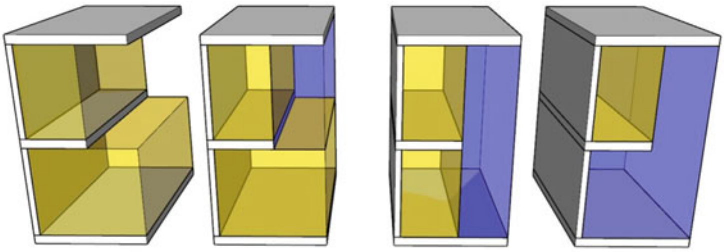

Fig. 1 Different options of placing spaces in a model. From left to right: automatic placement of rooms; addition of a separate room for the empty space; usage of separation lines to divide the lower space into two rooms; manual remodeling of the automatically created rooms [7].

Further application fields rely on information about indoor spaces in the AEC industry, e.g., indoor route planning and energy simulation processes. While indoor route planning requires information about topological relations between building objects, rooms and potential openings in building components, energy simulations often require second-level space boundaries. The Industry Foundation Classes (IFC) are a widely used standard to transfer building information models between software tools. They also provide necessary structures such as the entity *IFCRelSpaceBoundary* [4] to transfer information about topological relations and second-level space boundaries. Several papers cover the export of given indoor spatial information in IFC files to the OGC standard IndoorGML or other graph-based data structures for indoor route planning [19, 20, 22]. Additionally, an open-source tool to convert IFC files to the IndoorGML standard was developed by Diakité et al. [6]. Even though many papers depend on the space boundaries exported into IFC files, they are often incorrect or completely missing. Export functions of space boundaries in modeling software tools often require the accurate modeling of indoor spaces. Therefore, incorrectly modeled indoor spaces result in incorrectly exported space boundaries. Various approaches exist for computing spatial relations between indoor spaces directly from the geometry in IFC files, e.g. [14, 15], or to identify and fix errors in exported second-level space boundaries in IFC files [13, 23]. This paper follows another approach aiming to close the gap between digital building models and the automatic identification of indoor spaces in those models.

Next to indoor spaces in digital building models, outdoor spaces also need more focus. Outdoor spaces of building models could be the connector between BIM and GIS data. Lee and Zlatanova [10] developed a framework to map IFC files into the CityGML format, a commonly used standard for GIS data. They highlight that the outer surfaces of exterior walls are not explicitly saved in IFC files, even though a wall can be marked as an exterior building element in an IFC file. Therefore, the geometric computation of the outer surface is necessary for successfully mapping IFC files into the CityGML standard. Different approaches were developed to calculate this exterior surface from IFC files to overcome this issue [1, 5, 8, 11]. Donkers et al. [8] suggest improving the standardization and integration of exterior spaces

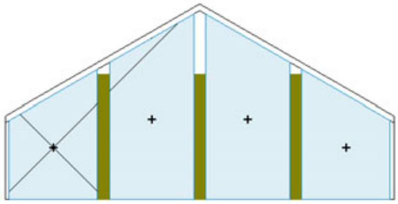

Fig. 2 Extruded rooms cannot be widened above walls that are not reaching up to the ceiling [3].

in the IFC standard. Arroyo Ohori et al. [1] listed guidelines for better conversion and integration of BIM and GIS data. One suggestion was to carefully and correctly model indoor spaces without gaps or intersections. However, this is not adequately supported by existing tools as described above.

3 State-of-the-Art Modeling Software Products

This paper investigates two state-of-the-art modeling software tools to identify which problems exist regarding the creation and export of indoor and outdoor spaces. For this paper, Autodesk Revit 2023 and ArchiCAD 25 by Graphisoft are used to showcase current problems. Revit and ArchiCAD are two of the most used modeling software tools in the AEC industry. It is assumed that investigating and comparing Revit and ArchiCAD covers the majority of users all around the world.

In Revit, spaces are called rooms. In ArchiCAD, spaces are referred to as zones. Indoor spaces are created the same way in both software products. A polygonal boundary can be created manually or automatically using the bounding building objects. This polygonal boundary is extruded until a vertically bounding element is reached. This general approach causes problems while creating rooms or zones for complex geometries. The extruded solid can be modified so that slanted roofs and slabs can be determined as bounded elements and crop the zone accordingly.

Nevertheless, it is impossible to widen a created zone horizontally after its extrusion in the upper part while preserving the lower boundary polygon. Figure 2 shows a simple example modeled in Revit suffering from this problem. The different workarounds created for a room with a gallery in Fig. 1 result from the same problem.

Revit additionally implemented a tolerance for creating rooms, making it difficult or even impossible to place rooms in tiny spaces. ArchiCAD does not have such a tolerance, making creating smaller rooms in ArchiCAD easier than in Revit. In Revit, the room creation algorithm uses an artificially increased wall width of 1.004 ft to detect spaces where it is possible to place a room and identify the room-bounding elements. This process is shown in Fig. 3. Once the bounding elements are identified, the actual room boundaries are calculated by reverting the artificially increased wall widths and using the actual wall measurements. A discussion [2] on the Autodesk Knowledge Network summarizes the impact and the issues caused by this implemen-

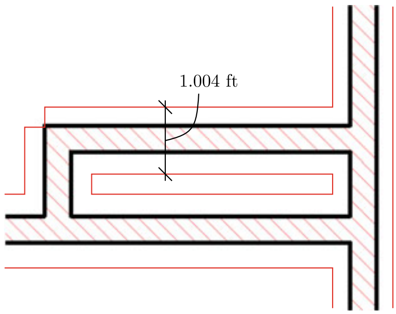

Fig. 3 Setting the wall widths artificially to 1.004 ft to determine all areas where it is possible to place a room [2].

tation. Another impact of this implementation is that spaces between building objects placed closer than 1.004 ft to each other will not be included in the surrounding room.

Issues regarding indoor spaces result in incorrectly calculated space boundaries in an IFC file because rooms and zones are the base for calculating first- and second-level space boundaries in Revit and ArchiCAD. Additionally, ArchiCAD cannot differentiate between first- and second-level space boundaries. It is only possible to export second-level space boundaries during an IFC export. In Revit, it is possible to select whether first- or second-level space boundaries are exported. However, it is not possible to export both.

4 Suggested Solution

The suggested approach in this paper is to transform a given building model into a tetrahedral space partition. Neighboring relations between the building components and the indoor spaces in the model are stored explicitly. Additionally, the outdoor spaces are an integral part of the space partition. Topological relations can be derived automatically without any geometric calculations once the space partition is created. This section summarizes the development of this approach from similar approaches in the literature and gives an overview of the transformation process.

4.1 Related Research

Using a tetrahedral space partition to represent digital building models is not a completely new concept. Penninga [16] used a tetrahedral mesh to model 3D topographic data. He uses a lightweight data structure in which tetrahedrons save topological relations. As an input, he uses piecewise linear complexes without any self-intersections. Kraft [12] used existing approaches and combined them to transform boundary representations of building models into a tetrahedral space partition. It is necessary to insert so-called Steiner points to generate a tetrahedral mesh from a given set of triangles describing the boundary. In some cases, uncontrollable refinement occurs and an unacceptable amount of points must be inserted to ensure robustness. The second problem results from the inaccuracy of floating point numbers which cannot store each real number. Huhnt [9] developed the first steps of an algorithm for creating a tetrahedral space partition of a given building model with integer values to overcome the problem of uncontrollable refinement. Romanschek et al. [17] implemented this algorithm in the two-dimensional space and used it for a scan-to-BIM approach. Romanschek et al. [18] also showed that this algorithm can robustly compute spatial relations between two geometric features. Exact computation based on rational numbers was used to ensure robustness. A previous research [21] showed that using this approach in the three-dimensional space is inefficient and suggested the usage of rounded integer coordinates. This previous paper introduced an implementation in three-dimensional space and investigated the accuracy of transforming a given model into a tetrahedral space partition. This implementation is also the suggested approach in this paper. The following section summarizes the presented algorithm.

4.2 Theoretical Aspects

A given building model is the input of the transformation process. Objects of this model need to be represented via triangulated boundary representations. All surface triangles are plane and must be oriented, each object forming a water-tight and orientable solid.

The overall process consists of three significant steps once a boundary representation is given, illustrated in Fig. 4. In the first step, an initial mesh is created with all the given points of the model and additional boundary points. The additional boundary points ensure that all newly inserted and rounded points during the refinement process lie inside the space partition. Everything outside of the initial mesh represents the unbounded space.

The initial mesh includes all given points after the first step but does not preserve the surfaces of the objects. Therefore, the next step is the refinement of the initial mesh. For a three-dimensional model, all intersection points between the given triangles of the input boundary representation and the edges of the tetrahedral mesh are computed and inserted into the mesh. The validity of the tetrahedral mesh in each step is ensured by a special treatment which is not the focus of this paper.

After the tetrahedral mesh refinement, the last step is assigning every tetrahedron to an object, multiple objects or no object at all. The result is a valid tetrahedral partition in which a set of mesh tetrahedrons represents each object. Indoor spaces can be identified automatically by collecting all tetrahedrons which are not part of building objects. Every disconnected component forms a different indoor space. The outdoor space is identified automatically as well. All neighboring relations or touching faces of this outdoor space to any building objects can be computed without further geometric computations. Contact faces of the outdoor space with the unbounded space are also saved.

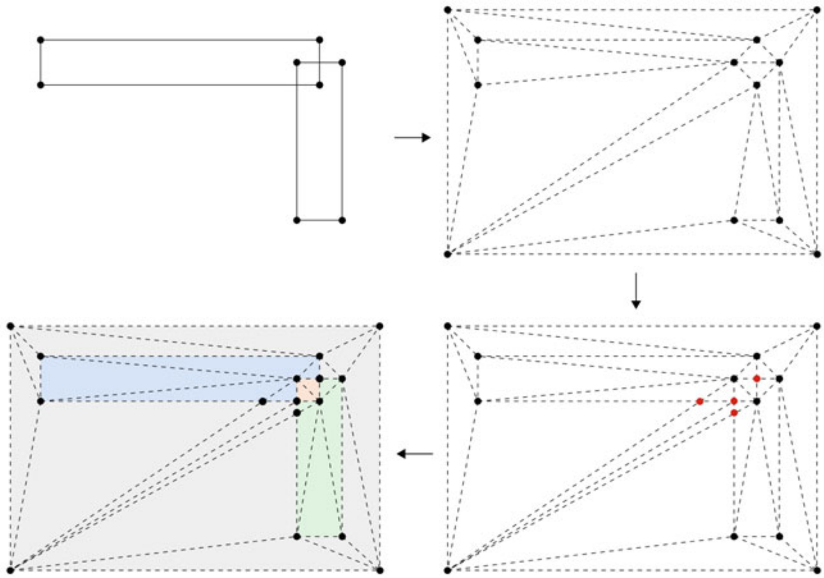

Fig. 4 Transformation process of a given boundary representation in 2D (upper left) into an initial mesh (upper right) in which all intersections are computed (lower right) and all objects are represented by a set of triangles (lower left) [21].

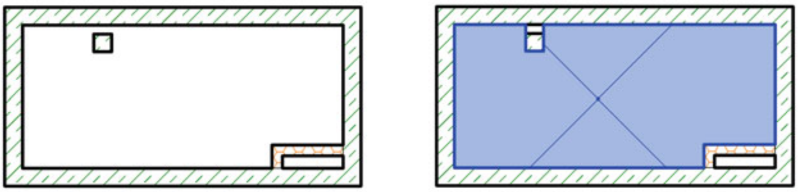

Fig. 5 Left: floor plan of the first example of a small room in Revit. Right: The room that is recognized by Revit. The space behind the column along with the smaller room is not recognized.

5 Validating Examples

In this section, two given models are transformed into tetrahedral space partitions. The purpose of the examples is to show the basic concepts of the suggested approach. Therefore, they are simple and small. The first example in Fig. 5 shows the problematic situations in Revit, which were described in Sect. 3. Revit cannot recognize the small room bounded by the inner walls in this example. The part of the room behind the column is not recognized either.

The boundary representation of this example was exported by using the Revit API. The triangulated input for the transformation process is shown on the left side of Fig. 6. After the transformation, sets of tetrahedrons representing the building

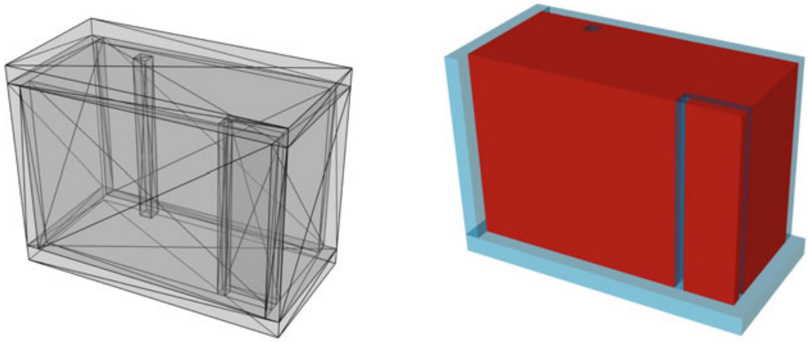

Fig. 6 Left: the triangulated input for the transformation process. Right: the resulting surfaces of the computed sets of tetrahedrons which represent the building components and the indoor spaces.

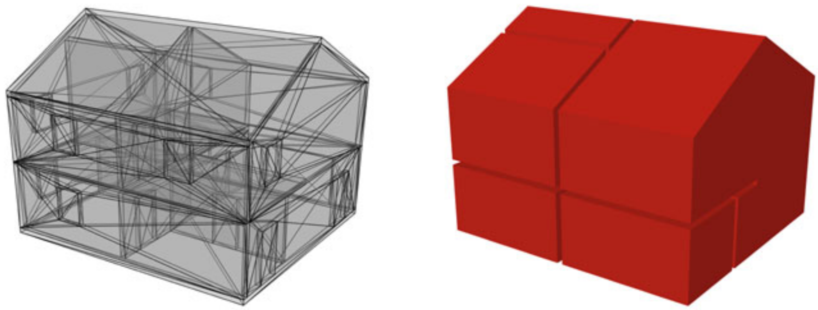

Fig. 7 Left: boundary representation of a small house and its openings. Right: the automatically extracted indoor spaces of the space partition.

objects can be collected. Only the surfaces of these resulting sets are displayed in the following pictures. Even though the underlying mesh is used to collect the sets of tetrahedrons, the mesh is not displayed to guarantee an optimal visualization.

The second example is a small house with complex indoor space geometry, windows and doors. Figure 7 shows the example's triangulated and exported boundary representation. The input is then transformed into the tetrahedral space partition. All indoor spaces can be extracted automatically using the resulting mesh, as shown in Fig. 7. Even indoor spaces with complex geometry can be extracted shown in Fig. 8. It would not have been possible to create all room geometries of the shown example with Revit or ArchiCAD.

The outdoor space of this example can be also extracted but is not visualized in the following pictures. Nevertheless, from the automatically extracted outdoor space, all touching faces with the actual building can be extracted without further geometric computations resulting in the outer shell of the building. All different types of touching faces can be determined. Therefore, the parts of the outer shell resulting

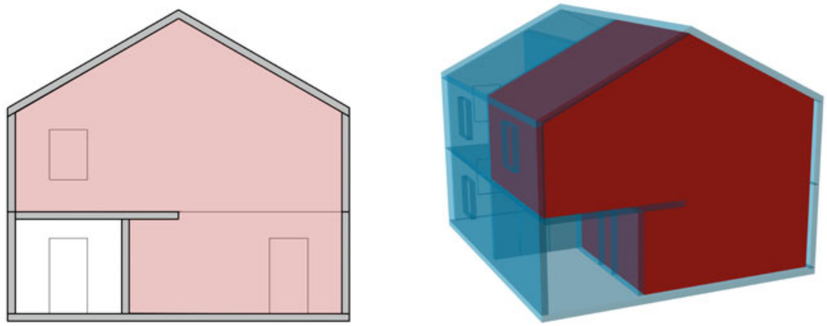

Fig. 8 Left: cut through the example shown in Fig. 7. The red highlighted space cannot be created as a single room or zone in ArchiCAD or Revit. Right: the automatically extracted indoor space of the space partition.

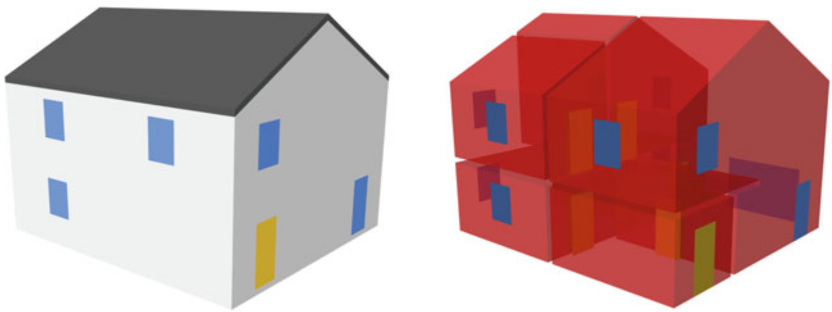

Fig. 9 Left: The outer shell of the building extracted from the space partition. Right: Topological relations between the extracted indoor spaces and all opening elements.

from an opening can be distinguished from parts resulting from walls or the roof. The underlying tetrahedral mesh can be used to extract topological relations between indoor and outdoor spaces. In Fig. 9, all resulting topological relations between indoor spaces and openings are visualized as an example. These topological relations can be used to create a connectivity graph of the building and its indoor and outdoor spaces.

6 Discussion, Conclusion and Outlook

This paper suggested transforming a given boundary representation of a model into a tetrahedral space partition to model indoor and outdoor spaces in building models. The resulting tetrahedral mesh stores topological relations explicitly. These topological relations can be a basis for extracting valuable information for various use cases.

This paper also showed current problems in state-of-the-art modeling software tools considering the representation of indoor and outdoor spaces. It is shown that these issues do not exist while using the suggested transformation approach and a tetrahedral space partition.

The suggested approach is a holistic way to detect indoor and outdoor spaces for input models. However, correctly detecting these spaces relies on correctly modeling the input boundary representations. Once transformed, the spaces are detected by collecting a set of connected tetrahedrons that are not assigned to any building objects for each indoor space. Therefore, the approach requires the indoor spaces to be separated (e.g., by boundary representations of opening elements). If the indoor spaces are not properly separated in the input model, they cannot be detected correctly. Additionally, only one set of connected tetrahedrons represents each indoor space. The partition of these indoor spaces into smaller subsets is possible but requires the addition of separation planes as input constraints.

Although this paper suggested an approach to model indoor and outdoor spaces in building models, usable output format exports are missing. The main focus of this paper was to validate the use of the suggested approach by identifying problems in software tools and showing how to overcome these problems. This research lays a foundation for the following research to export the collected information stored in the tetrahedral mesh to connect the suggested approach with the presented use cases.

As stated in Sect. 5, the presented examples only show why the presented approach overcomes the problems of the state-of-the-art modeling software tools. As a next step in validating the suggested approach, more extensive examples must be transformed to show the approach's applicability for realistic building models.

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Space Partitioning as a Holistic Alternative to Traditional Geometric Modeling Workflows in the AEC Industry

Wolfgang Huhnt, Joanna Zarah Vetter, and Maximilian Sternal

Abstract The need for data is indisputable in all fields of architecture and engineering. It is also state-of-the-art to differentiate kinds of data, e.g. geometric data and semantics. Modern engineering workflows are characterized by their high interoperability between different fields of application. Almost all architecture and civil engineering tasks have in common that they need geometric data. Task-specific data formats are defined proprietorially in each software tool and standardized for different fields of application such as Industry Foundation Classes, CityGML or gbXML. Thus, model transformation is a frequently performed activity. State-of-the-art modeling tools focus on representing object shapes and their transformation in space. Neighboring relations, which are treated in topology, are relevant in many engineering applications but neglected in many modeling tools and data formats. Another approach in geometric modeling, named space partitioning, focuses on the complete space. Space partitioning itself is not a new approach. However, its application to architecture and civil engineering geometry and shape representations has not been investigated in detail. This paper discusses fundamental aspects of space partitioning as an alternative approach to model geometry in architecture and civil engineering. The goal is to overcome existing challenges and to provide the basics for the streamlined alignment of domain models using space partitioning as central geometry.

Keywords Geometric Modeling · Geometric Models · Space Partitioning · Topology

1 Introduction

The geometric representation of building objects is a central task in the AEC industry. Building Information Modelling (BIM), Computer-Aided Design (CAD) and Engineering (CAE) workflows and software tools focus on modeling building objects.

W. Huhnt (✉) · J. Z. Vetter · M. Sternal
Technische Universität Berlin, Berlin, Germany
e-mail: wolfgang.huhnt@tu-berlin.de

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A common way to describe volumetric elements and their shapes is the definition of their boundary. This boundary constitutes separating the interior and exterior points of the represented object. It can consist of planar or curved faces, edges and points in the 3-dimensional space. While all boundary representations have an inner topology in common, topological neighborhood relations between objects are conventionally not considered. Shapes are created using local coordinate systems and transformed to a specific position in space. Manual issue management and heavy geometric algorithms are the consequence to overcome this problem.

The concept of space partition is a way to represent the overall topology of a model. Space partition is used to describe and divide the complete space by using different subspaces of various dimensions. These domains are conventionally called vertices, edges, faces and volumes in 3-dimensional applications. From a mathematical point of view, a topology classifies the space: (1) Each domain is not empty, (2) each pair of different domains do not intersect and (3) the union of all domains is the complete space. Typical data structures often used in computer graphics for partitioning space are the Octree or the Binary Space Partition. Different examples of applications of these data structures exist in the civil engineering field, Solihin et al. [13] using Octree decomposition of space for fast spatial queries in building models and Sacks et al. [12] propose R-tree space indexing as preprocessing for rule inference procedure.

While space partition can be used for indexing and fast search in space, its characteristics can also be combined with the boundary description of objects. A connection of both concepts, the representation of the geometry of objects and the integration of topology in the complete space, has the potential to function as a holistic way to represent building models. Fundamental research in this field has been conducted, for instance, by Walter Nef [8], who described the theory for polyhedron shapes and provided a first data structure considering Boolean operations of set intersection and set complement. Different research exists that combines the use of space partition and geometric representation of objects in civil engineering and architecture applications. Weiler introduced the Radial Edge data structure [17], which addressed the topology of the complete space and can be considered the groundwork for many Half-Edge data structures such as Partial Edge [7] or Dual-Half-Edge [2]. While these concepts are based on polyhedrons, Penninga [10] used tetrahedrons as topological manifolds to reach a space partition to represent city models in combination with Triangulated Irregular Networks (TIN). While this work thoroughly investigates the application of this concept for city models, the integration of building models is not covered sufficiently.

Creating a valid space partition for digital building models can be differentiated into two different approaches. The first approach is transforming a given boundary representation into a space partition. Examples of this approach are given in the field of computer graphics, such as by Hu et al. [4]. This example creates a tetrahedral space partition by transforming a given triangle soup. While this approach has been proven to be robust for single objects, the application of this concept to building models is not yet evaluated. Alongside transforming geometry into a space partitioning, the need to model and modify a valid partition arises. Therefore, the second approach for creating a space partition for digital building models is to develop operators for the step-by-step modeling process of building objects embedded in a partition of the complete space. A similar concept is implemented by Jabi [5] in the "topologic.app" kernel. While this tool can represent dimensionally reduced geometries for room topologies with a wide application for architects, modeling building objects has not been investigated in-depth. Furthermore, the unbounded space and multiply-connected subspaces are not explicitly defined. Thus, it does not constitute a complete space partition.

The different mode of looking at geometry has huge consequences. A lot of research addresses model transformation. Different application fields and problems of the transformation of geometric models are discussed in Sect. 2. Section 3 presents characteristics of space partition models to explain the presented approaches. In Sect. 4, examples illustrate the power of space partitions and it is shown how the application fields introduced in Sect. 2 could benefit by using space partition instead of a transformation approach. The paper ends with a discussion, conclusions and an outlook in Sect. 5 and 6.

2 Transformation as the Approach to Reuse Data

Creating and passing geometric descriptions of a specific design is a key factor in engineering communication and essential in every planning process. While a physical object only has one geometry, a modeled geometry of an object might have an abstracted, simplified geometric form constructed for the unique purpose of the specific domain model. While the level of detail is a general factor for all kinds of geometric models, domain models often use different domain-specific data structures that fulfill the intrinsic requirements of the intended engineering application, such as energy calculation, structural analysis or indoor and outdoor navigation and city modeling.

To pass on geometric data to other designers and applications, geometric descriptions must be transformed during export and import processes, leading to expensive algorithms, robustness issues and information loss. Standardized data formats such as the "Industry Foundation Classes" (IFC), which are based on the general "Standard for the Exchange of Product model data" (STEP) offer a vast number of possible geometric data structures, both implicit, e.g. Constructive Solid Geometry (CSG), and explicit, e.g. triangulation or Boundary Representation (BRep), but consistency or transformation functionality heavily lies with the domain software implementations of this huge standard that additionally features rich semantic data. Therefore, bidirectional interfaces are common practice in many workflows. On the other hand, vendor-specific and open source cloud platforms for exchanging geometry are on the rise recently, such as Nemetschek "BIMPlus", Autodesk "FORGE" [1, 9] or open source alternatives such as "SPECKLE" or the "Buildings and Habitats object Model" (BHoM) [14, 16]. While these systems provide great features for interoperability and outsource some of the geometric transformation needed in workflows, their geometric kernels and data structures use the same principles as provided with standards such as IFC and STEP and do not provide capabilities to reduce transformations and increase robustness significantly.

Future requirements for circular economy and data management in the operational phase of a building or infrastructure asset ("digital twin") demand a holistic view of building data in general and geometric data in particular. Therefore, a vast number of projects in recent years discussed aligning building and urban models as well as indoor and outdoor models [18] and cadastral data [6, 15]. A common and reliable geometric description is essential for interoperability in these application fields. A high number of transformations is detrimental to the robustness and the consistency of geometric project information. The utilization of space partitioning can provide a general and comprehensive platform for a vast number of geometric applications, thereby reducing error-prone transformation processes and making topological relations available, which are key factors for many engineering tasks.

3 Space Partitioning as an Alternative Approach

In order to understand the advantages and particularities of the space partitioning approach for representing geometric models, this section describes fundamental basics of space partitioning in general and the characteristics of the proposed approach in particular. Well-known concepts are compared to the presented approach and important properties are highlighted and explained.

3.1 Basics

The term space partition is sometimes used for specific data structures such as Octree, Quadtree, Binary Space Partition or kd-tree. These data structures allow efficient access to geometric objects so that, for instance, neighbors can be identified with a small number of operations. Nevertheless, the representation of geometric shapes is not of interest in the typical applications of these data structures.

Space partitioning, as treated in the context of this paper, requires a different mode of thinking. It addresses the complete space. Internally, data structures such as the Half-Edge and Half-Face data structures can store neighboring relations explicitly. The consequence is that the topology is stored by pointers. Topology is explicitly available and can be processed efficiently.

Figure 1 shows a rectangle in the 2-dimensional space. A boundary representation of the rectangle stores four vertices and four edges. The face of the rectangle is determined by the sequence of the points on the boundary and a rule that the interior of the represented element is on the left side. Looking to the same figure from a space partitioning point of view results in ten domains due to the fact that the unbounded exterior of the rectangle and the face of the rectangle are the 2-dimensional domains.

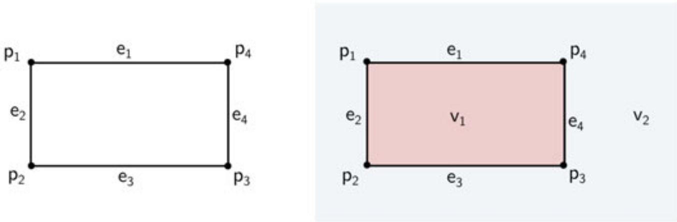


Fig. 1 Left: boundary representation of a rectangle. Right: space partition of the complete space including a rectangle

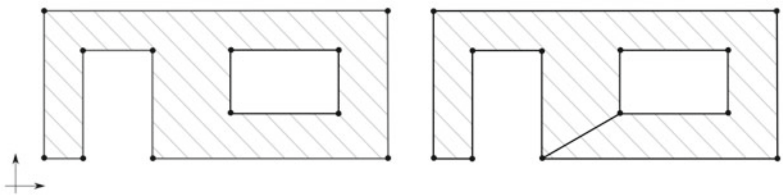


Fig. 2 Example of a manifold face **left figure** and a non-manifold face **right figure** in the 2-dimensional space

As a prerequisite, all domains of dimension n must have a manifold boundary of dimension $n - 1$. Figure 2 shows two geometric models of a face. The right model is not manifold. The connection to the opening violates manifoldness. Manifoldness ensures that the partition is a topology and fulfills the mathematical conditions of a classification. The left face is 1-manifold.

Tetrahedral meshes and triangular meshes always fulfill the condition of manifoldness. A tetrahedron is a convex 3-dimensional simplex; a triangle is a convex 2-dimensional simplex. Meshes are widely used in architecture and civil engineering for visualization purposes and as a basis for numerical methods. However, a mesh of an object typically does not include the exterior. Meshes that include the exterior fulfill the conditions of space partitioning. While using polyhedrons in meshes, the manifoldness must be ensured.

3.2 Characteristics

Topology: The prerequisite concerning manifoldness, introduced in Sect. 3.1, ensures that the partition classifies the space:

– Each domain is a subset of the space and not empty
– Each pair of different domains do not intersect

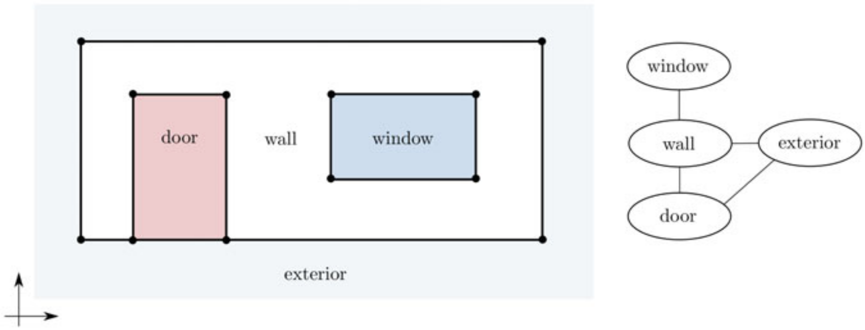


Fig. 3 A 2-dimensional example represented by a space partition with its connectivity graph

– The union of all domains is the complete space

The topology is the fundamental part of the introduced concept of using space partition. This topology can be used to extract information from the space partition and the represented shapes. Each partition can be mapped onto a graph. In the 3-dimensional space, volume elements can be regarded as vertices and their neighboring relations where two volume elements share a common face as edges of the graph. In 2-dimensional spaces, faces are vertices of the graph. Their neighboring relation, where two faces share a common edge, are the edges of the graph. An example is shown in Fig. 3.

Bounded and Unbounded Domains: It is necessary to introduce bounded and unbounded edges, faces and volume elements. Unbounded domains are required to consider the complete space.

In the literature, modeling concepts sometimes use bounding boxes for modeling the exterior. The term axis aligned bounding box (AABB) describes a bounding box that is parallel to the faces of the coordinate system. The disadvantage of such concepts is that they must be treated in special ways. For instance, a special treatment of the boundaries of such artificial objects is necessary to avoid reflections in the computation of wave propagation in soil mechanics.

In addition, the unbounded exterior of buildings is of interest. During the constructions of infrastructure like railways, there are often restrictions regarding the space above these railways. For instance, in Germany it is not allowed to work above railways on which trains operate. Additionally, the unbounded space above landmarks is of interest in geodesy.

Convex and Non-convex Domains: The geometry of buildings is not always convex. Faces are often triangulated, and volumes are often modeled as sets of tetrahedrons. These meshes consist of convex domains to describe the geometry of non-convex objects. The algorithms for triangles and tetrahedrons are simple compared to non-convex domains. On the other hand, a set of triangles and/or tetrahedrons is necessary instead of a single polygon or polyhedron for the description of a single object.

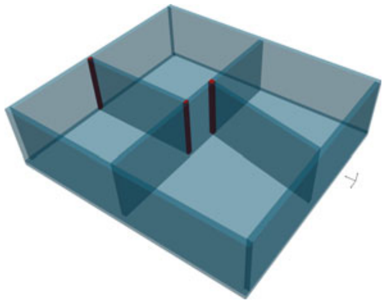


Fig. 4 Geometries of clashes in the given input model of Fig. 6 identified by using space partition

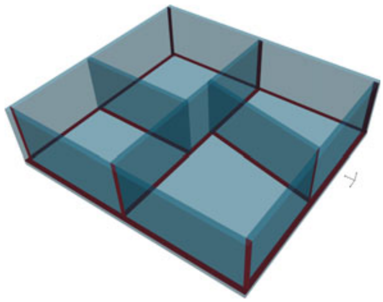


Fig. 5 Geometries of touches between the building objects in the given input model of Fig. 6 identified by using space partition

Singly- and Multiply-Connected Domains: The geometry of buildings requires the possibility to model multiply connected domains. The wall in Fig. 3 is an example of a multiply-connected face. The window in Fig. 3 is an example of a singly-connected face.

4 Fields of Application

This section describes fields of application. All applications are based on the fundamental property of the space partition that it classifies the space and that all neighboring relations are explicitly available, as described in Sect. 3.

Clashes and Touch Detection: Conventional clash detection is reached by testing surface triangles of boundary representations against each other geometrically. In contrast, clashes and touches can be easily identified once the model is transformed into a space partition. Additionally, information about the geometry of a clash or a touch can be derived from the space partition as well.

Figures 4 and 5 show examples, calculated in an ongoing research project called *ROF* that is funded by the German Research Foundation (Project-No.: 424641234) about transforming given boundary representations into tetrahedral space partitions. These figures show identified contacts and clashes of the given input, which was transformed into a space partition.

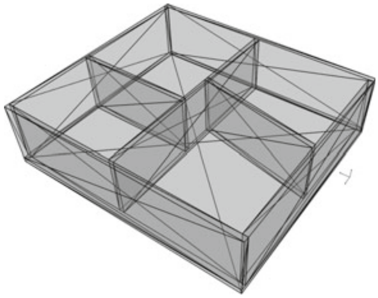


Fig. 6 Input boundary representations of a storey in an example model

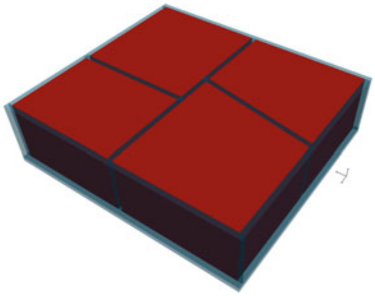


Fig. 7 Automatically identified indoor spaces in the given input of Fig. 6 of a space partition

Empty Space: Another advantage of representing digital building models with a space partition data structure is the integration of the empty spaces in the model. While only building objects are part of traditional geometric representations, empty spaces are an integral part of a space partition. Empty spaces can be rooms that are not represented by a geometric object in the interior of a building, unintended gaps or the exterior. This advantage can be used for the automatic recognition of indoor and outdoor spaces in building models. Two different ways of dealing with indoor spaces in models can be identified. Figures 6 and 7 show an example which also results from the ROF project. On the one hand, it is possible to automatically detect indoor spaces in space partitions from scratch. On the other hand, it is possible to validate existing modeled spaces by finding any leftover gaps in a given model by transforming this model and all modeled spaces into a space partition.

Once correctly identified, different application fields can benefit from the knowledge of indoor and outdoor spaces in building models. The explicit storage of topological information in the space partition enables the extraction of space boundaries. Energy modeling data structures like gbXML require these first- and second-level space boundaries. These different types of boundaries are shown in Fig. 8.

Detection of Air and Solids from Laser Scans: Point cloud processing can be improved by the information that there is air between the scanning device and a point, which reflects the laser [11]. This information can be processed so that in 2-dimensional space, a set of triangles describes identified areas from air. One vertex of each triangle is the location of the scanning device. The opposite edge

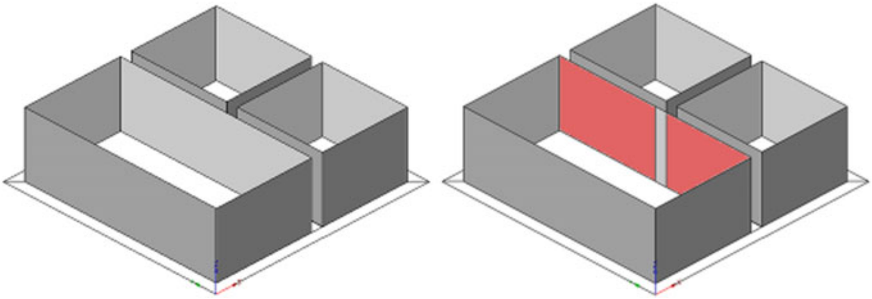


Fig. 8 First- **left** and second-level space boundaries **right** as defined in IFC [3]

separates air from material. In 3-dimensional space, a set of tetrahedrons describes identified air.

Connectivity and Navigation: Topology can be interpreted in different spaces. One typical example for different topologies is the theory of duality, where e.g. rooms in a building are reduced to 1-dimensional vertices, building a connectivity graph with edges, connecting different rooms. While such graph data structures must be additionally modeled with classical geometric descriptions, graph data is easily inferable from a space partitioning model. An inferred graph generated from a space partitioning prototype implementation of a building complex is shown in Fig. 9. Typical examples of connectivity graphs in architecture and engineering are found in energy modeling and indoor and outdoor navigation. Data structures such as IndoorGML explicitly store topological graph data, while primal geometries of objects and spaces are optional.

Furthermore, semantic web graphs of connectivity can be represented using the Building Topology Ontology (BOT), offering a minimal data structure to represent rooms and elements in regard to their neighborhood relations. An exported and visualized BOT graph, showing room and wall connectivity, is shown in Fig. 10.

Because unbounded space is explicitly modeled in the space partitioning approach, it can easily deal as a link model for inside and outside information and feature cadastral and city models. Parcels in cadastral models can be modeled unbounded

Fig. 9 Generated dual connectivity graph from a space partitioning model

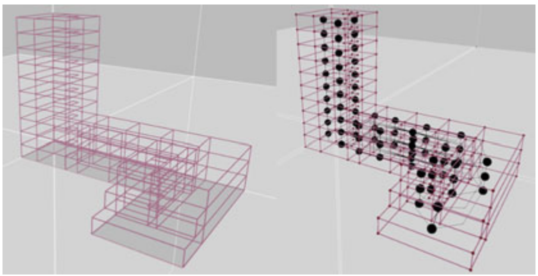
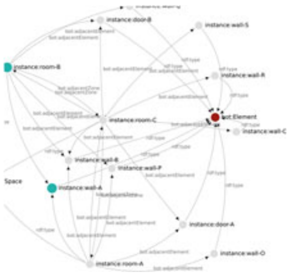


Fig. 10 Exported topology as semantic web graph in sparql-visualizer



to include air space above a building or infrastructure to fit the needs of modern integrated 3D cadaster.

5 Discussion

There are several advantages in describing buildings in space partitioning models with explicit neighboring relations. First of all, each geometrical and topological request can be answered in an efficient way. Navigation is simple and free from any inaccuracy. Each volume element can be extracted by extracting its boundary. Its selection is simple and does not require time-consuming calculations. Clashes and voids are avoided by the nature of the space partitioning approach. Each contact between domains is modeled once. There is no gap and no overlap in such a model.

Unbounded objects are necessary to fulfill specific requirements as described above. In addition, dimensionally reduced models such as skeletons are possible using this approach. The building components can be modeled by 1-dimensional and 2-dimensional domains. Spaces are modeled as cells. Such models are used, for instance, in energy calculations.

It is possible to model parts of a space partition in different level of details. This can be achieved in a simple way if the interior of a domain is detailed keeping its boundary unmodified. Such a model can be regarded as hierarchical graph where the hierarchies describe different levels of detail.

A challenge facing the acceptance of this approach is that space partition models require another mode of thinking and modeling. Architects and civil engineers are not trained in modeling faces which separate their objects of interest. However, this disadvantage can be avoided by suitable user interfaces.

Another mode of modeling always requires the implementation of new modeling functionalities. This is true for space partitioning as well. An ongoing research project called *PPSpace*, funded by the German Research Foundation (Project No. 429900376), tries to close this gap and develops specific modeling operators and spatial queries for navigation. The goal is the implementation of the core functionality required for a robust modeling of a polyhedral space partition.

6 Conclusion and Outlook

This paper presented basic principles of space partitioning as a holistic way of modeling geometries relevant in the architecture and civil engineering industry. Because many fields of application demand specific characteristics of geometrical models, geometric transformation has been highlighted as a central task in modern workflows. A crucial feature missing is the topology, describing spatial and neighborhood relations within a model. Furthermore, empty spaces are often ignored or even produced by transformation. These disadvantages can be overcome by a space partitioning approach.

Digitization of authorities and many workflows in planning and operating building and infrastructure assets increase the requirements for geometric models. In the future, data must be linked and consistent. Data silos in the form of legacy data formats such as IFC will prevent seamless cooperation, especially when it comes to geometrical information. Explicitly modeled topology will enhance any query to a building model substantially. Furthermore, the growing trend of separating geometric and semantic information using more generic data formats such as semantic web technologies strengthens the need for connected, complete and correct geometric data models.

Space partitioning models can support this necessity and can be applied when transforming, modeling or scanning geometries is needed. 3-dimensional cadaster to manage land use and the alignment of geo and building information modeling can benefit from the use of geometric representation in the form of space partitioning.

However, extensive research is still necessary to benefit from the advantages of space partitioning models. Suitable user interfaces are necessary for modeling geometries based on this approach. Existing models need to be transformed. A simple standard is necessary to access space partitioning models. A link to semantic data is necessary so that geometric domains can be enriched by semantics. In the end, products such as windows, doors, etc. must be available in a space partitioning model so that users can easily model their buildings using data from built-in component vendors at any required level of geometry. This list of required research is not complete. We are in front of fascinating tasks to apply space partitioning as a holistic approach for the architecture and civil engineering industry.

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Robust Modeling of Polyhedral Space Partitions

Maximilian Sternal and Wolfgang Huhnt

Abstract This paper introduces polyhedral space partition as a representation of geometric objects in digital building models. Operators to modify such a partition model are presented and strategies to guaranty robustness are explained. The topology of a polyhedral space partition can be stored explicitly by pointers in a digital environment. However, coordinates are mapped to numbers which are unavoidably imprecise in a digital environment. The partition model is called consistent, if its imprecise geometric attributes do not contradict its exact topological attributes. The platform is called robust if the imprecision in typical applications does not make the model inconsistent. This paper presents two novel concepts that enhance robust modeling: focused model construction and topologically controlled work steps. Conventionally, each object is constructed individually and added to the existing set of objects. Geometric imprecision leads to collisions of and gaps between objects. The algorithms that detect collisions or gaps are not focused on a subset; and they are expensive because they must consider all existing objects. Focused transformations affect only a small number of domains. A work step is topologically controlled, if modifications on boundary elements of the domain must be performed in preceding work steps. Errors are reported and corrected before the construction proceeds. Topological checks are performed on the manifolds based on a rank concept. It is tested geometrically that all domains that are added to a domain lie inside the existing domain using the novel concept of anchors and their clients for robustness. Truncation and round-off errors are treated with a single value subjected to the machine epsilon.

Keywords Geometric Modeling · Robustness · Topology · Space Partitioning · Building Information Modeling

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M. Sternal (✉) · W. Huhnt
Technische Universität Berlin, Berlin, Germany
e-mail: maximilian.sternal@tu-berlin.de

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1 Introduction

Digital geometric models constitute a basis for many tasks and analyses in architecture, engineering and construction. Therefore, a vast number of different modeling techniques and data models have emerged to create and store digital geometry since the invention of the first computer-aided drafting and design tools. Traditionally, many of these systems focus predominantly on the description of single objects such as building components, which are specified by parameters, transformed and placed in space. The description of their topology is often neglected or restricted to the intrinsic topology of one component. Space partitioning, on the other hand, focuses on the description of the complete space. Unbounded Euclidean space is chosen as the complete space that contains all objects. The operators are designed in such a way that each work step transforms a valid space partition into another valid space partition. If errors are detected, they are reported and the work step is aborted.

This paper presents robust modeling operators for a polyhedral partition of Euclidean space. The extrinsic topological relations between objects are described explicitly in the digital model with exact object names. The geometry of the partition is specified with the necessarily imprecise coordinates of its nodes and the direction vectors of its unbounded edges. Because the topological model is exact and the geometric model is imprecise, the two models are necessarily inconsistent. The modelling approach is called robust if the imprecision that occurs in typical applications does not make the topology and the geometry of the digital model inconsistent.

The model construction is called focused, if each work step modifies only a small number of the model domains. In order to achieve focus, a rank equal to its dimension is assigned to each domain. The two basic operations for model construction are split and merge. In a split, a single domain of the partition is replaced by exactly two domains of the same rank. In a merge, two domains of equal rank are replaced by a single domain of the same rank. The conditions that are imposed on rank lead to topological control of the modelling. The atomic topological and geometric operations on the model in a work step are restricted to the attributes of the single domain that is split, or the two domains that are merged. All higher modeling procedures are implemented with a topologically controlled sequence of split and merge operations.

In the space partitioning approach, the input commands are performed on domains of a user model, which consists of nodes as well as edges, faces and cells. The domains can be bounded or unbounded. The operations that are performed on the user model are arranged in work steps. The domains in the user model are not oriented. Internally, a core model automatically constructs and stores oriented arrows, facets and voxels (volume elements). The user does not come into contact with the core model, but indirectly makes use of its functionality for model construction and for navigation in the model. The partition concept includes efficient checks of the location of neighboring domains. Topological checks are performed on the manifolds. It is tested geometrically that the domains, which are added to split a domain, lie inside the existing domain. In order to reduce the effects of numerical inaccuracy, conventional methods that require solutions of sets of equations are replaced by the computation of distances and the novel concept of anchors and their clients.

The theory and the algorithms for polyhedral partitions are designed to treat non-convex, multiply-connected and unbounded domains without user assistance. Topological errors are detected, allowing only closed and connected manifolds. Geometric errors, such as intersections and gaps, are recognized and reported. The implementation makes use of floating-point variables to store coordinates. Thus, numerical imprecision occurs. The concept introduces a single value dependent on the machine epsilon and on the overall model size in order to describe the geometric surrounding of domains. All input domains, which are intended to be inside another domain, must lie in the surrounding of that domain, while no other domain is allowed to lie in the surrounding. The geometric checks make use of the concepts of anchors and client zones to guarantee robustness in all dimensions.

Section 2 introduces basic components of the polyhedral space partitioning approach that is the platform for the robust operators. The approach is compared with existing edge-based data structures and important features are highlighted. Subsequently, the operators for split and merge operations on domains are introduced in Sect. 3, before the concept of robust modeling in the context of topologically controlled work steps is introduced. The concepts for robust geometric modeling are evaluated in Sect. 4 by comparing their theories and their implementations. Checking procedures are presented separately for topological and geometrical checking in Sect. 5.

The paper contains some examples that illustrate the functioning of the operators. It ends with a discussion of the benefits of the proposed approach compared to other approaches in robust geometric modeling and an outlook to fields of application for operators that model space partition.

2 Polyhedral Partition of Space

2.1 Existing Space Partition Concepts

Space partitioning divides a space into subspaces. Intersection tests and other geometry queries on large models are performed faster by preprocessing with tree-based methods and data structures such as binary space partitioning and octrees. Every point in space can be uniquely allocated to one leaf in the tree. These features have been utilized in various projects for point cloud processing [9] or efficient database access [14] and rule-based geometric queries [2].

In general, the partition of a metric space is called a classification of space, if no subset is empty, none of the subsets intersect and the union of all subsets is the entire space. Paul [10] describes in detail, how the mathematical foundation of topology and continuous functions can enhance the description of geometric shapes using space partitioning.

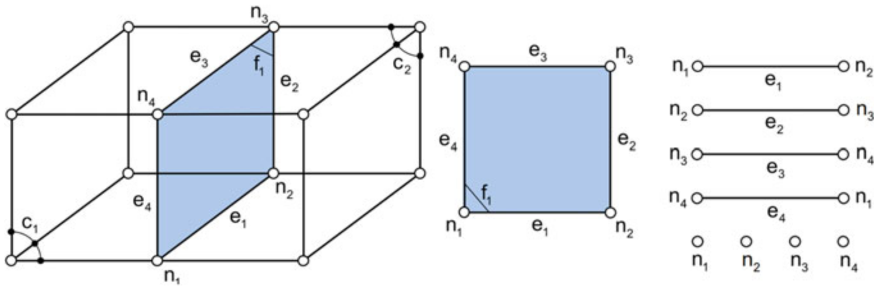

Fig. 1 Domains in a polyhedral space partition. Two cells share one common face (blue). The face itself is bordered by edges that share common nodes

2.2 Existing Topological Data Structures

Most data structures designed for boundary representation store topological information about the boundary of a single object only. In addition, data structures have been developed to describe neighborhood relations between objects placed in space. In the past, many data structures for the topological properties of planar, polygonal geometries have been proposed, spanning from radial-edge [16] and partial-edge [7] data structures up to the more recently proposed dual half-edge [1] and compact abstract cell complexes (CACC). Commonly, such edge-based data formats use topological pointers to traverse along the (co)edges of a boundary. Common examples for such pointers are “next”, “previous” in a loop and “mate” or “twin” to walk along the surface of a cell or switch to the opposite side of one (twin) faces. In addition, “radial” pointers are used to reference different cells around an edge. While some of these structures have been proposed many years ago, traversal in space is still not a common feature for exporters of modern modeling systems and exchange formats. The approach presented in this paper builds upon topological pointers and offers enhancements of modeling capabilities regarding features of a complete partition of space. In particular, the treatment of multiply-connected and unbounded domains is similar to that of simply-connected bounded domains.

Separating model entities for geometry and topology is a convenient way to structure a shape model. The approach is often encountered in data structures. Weiler [16] describes the connectivity among faces, edges, and vertices introducing the “-use” concept for the oriented objects. Lee and Lee [7] use “partial” entities equivalent to the radial edge. Separating geometry and topology has already led to enhancements in the usability and clarity, but the concept can be extended even further [4]. The extended aim is to keep the two models consistent at any work step as achieved with the user and core model structure in this paper. Figure 2 shows the oriented arrow bundles stored in the core model and used in the polyhedral space partition approach. The oriented arrows and twin-facets in this approach are based on existing half-edge concepts.

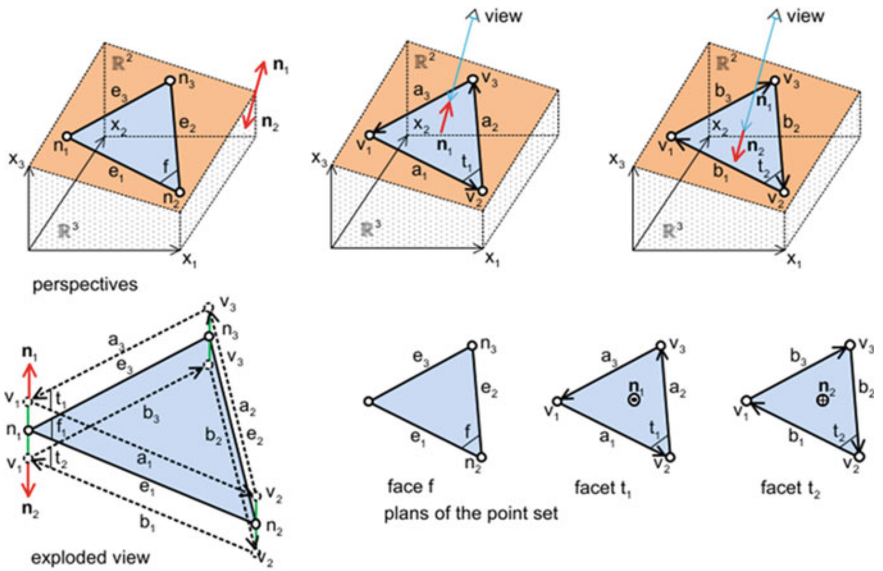

Fig. 2 A 2-dimensional face is embedded in the 3-dimensional space. Each edge is complemented by a oriented arrow bundle, describing polygons. Each face f has to sides (facets) with normal vectors pointing outside

2.3 Properties of a Linear Partition of Space

A linear partition of space is an alternative to the conventional approach of accumulating objects in space. In the novel approach, the point set of the unbounded Euclidean space is the initial model. During the model construction, subsets of the point set of the space are defined as user model domains of type node, edge, face and cell, as shown in Fig. 1. The domain types have rank 0 to 3 respectively. Because the defined geometric domains are linear, the partition is called a linear partition of space. The work steps of the partitioning are chosen such that the resulting model is a mapping of the original and of the space in which it is contained.

While the domains of the user model have some of the characteristics of a topology, navigation must be supported by orientation of the domains and explicit pointers for efficient spatial querying. Therefore, the described specified user model domains of the point set topology are complemented by a core model, where oriented boundary polygons are defined, surfaces are oriented by their normal vectors and the relationships between the faces at edges is described with dihedral cycles, as demonstrated in Fig. 2. Additionally, pointers for inner polygons in facets and inner surfaces in volume elements explicitly store information for multiply-connected domains without the use of supporting edges or faces as found in established data structures.

Modelling of the entire space requires a data structure that contains both bounded and unbounded domains. The boundary of a bounded domain consists of the point sets

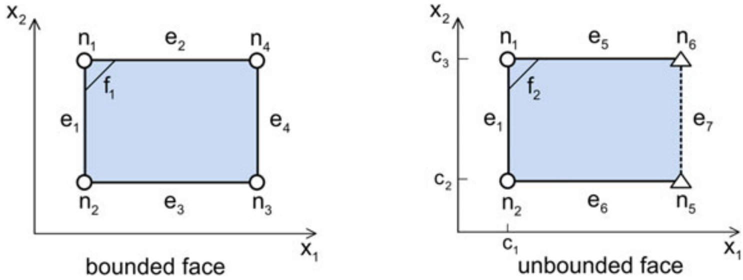

Fig. 3 Imaginary nodes are marked as triangle **right**. Edge e7 does not have a point-set, but the topological properties to enable navigation

of bounded domains of lower rank. The boundary of an unbounded domain contains the point sets of bounded and unbounded domains of lower rank. The unbounded domains are related by topological elements called imaginary domains, which do not have a point set. Figure 3 shows a bounded and unbounded face. Edge *e7* and nodes *n5* and *n6* are imaginary domains without point-sets.

3 Modeling Operators

3.1 Atomic Operators

Geometric kernels include core functionality to create and modify geometric models. Usually, models are created component-wise, with a focus on the boundary geometry of each object. Modeling operators are provided to the user. These are commonly based on parametric primitives and higher-level operators such as extrude, sweep or slice. While modern modeling kernels are able to calculate and represent a large number of different shapes with boundary representations, connectivity between objects is often not considered. Furthermore, partitions of space such as octrees are mostly calculated from existing boundary representations rather than created from scratch using operators.

This paper describes a step-wise construction process for a polyhedral space partition. Starting with a simple initial partition of the complete space, the partition is modified by repeated application of a small set of operator types. [18] gives a detailed overview of manipulation operators for both, manifold and non-manifold cell complexes. An important group amongst these operators are Euler-operators [3], which are commonly used in edge-based data structures [1, 16]. While the combination of parametric modeling and Euler operators are state-of-the-art in various modeling systems, a model constructed by partition of the complete space requires a different set of atomic operators, as described in this chapter.

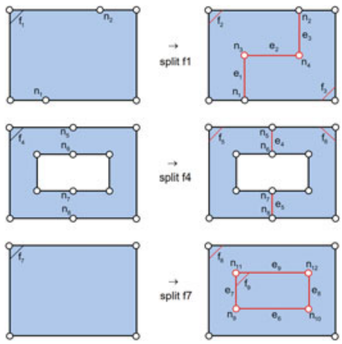

Fig. 4 Different splits showing single and multiply-connected faces before and after split

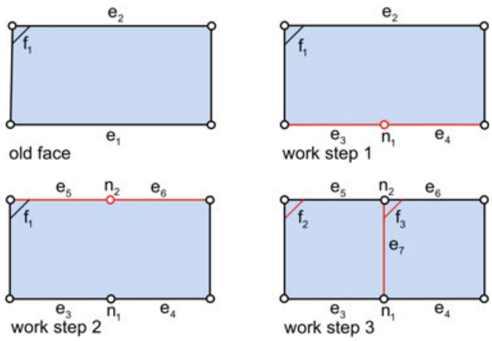

Fig. 5 Following the rank concepts, boundary edges *e1* and *e2* are split first before the face can be split

Various categories of operators can be distinguished according to Comic and de Floriani [18]: initialization, topology preserving and topology modifying operators. This paper introduces an initialization with a base decomposition of the entire space, complemented by only two types of topology modifying operators: "split" of a domain or "merge" of connected domains of equal rank. These two types of atomic operators are related to the frequently described operators "glue" and "splice" for manifold cell complexes [18]. The topology modifying operators "split" and "merge" are implemented for domains with rank 1 to 3. Any higher-level operator is a sequence of split and merge operations. Like the basic Euler operators such as "MAKE", domains are created only by a split operation and deleted only by a merge operation. Figure 4 shows various split operations for faces. New domains are marked red. It is shown that multiply-connected domains can be created or modified in this approach without the need of supporting edges. A valid operation always leads to a valid partition of the complete space.

3.2 Sequences of Work Steps

A sequence of work steps is always sorted according to the rank of the affected domains. Figure 5 shows an additional split of a face. Before the interior of the face can be subdivided in work step 3, all boundary domains must be prepared. Therefore, step 1 and 2 splits the interior of edges *e1* and *e2* to introduce new nodes, before edge *e7* is added to the partition in a split of the interior of the face.

User interfaces for geometric modeling in engineering practice require higher order operators, build from sequences of atomic operators. An example is a *move* operation of a box from cell A to cell B. Several work steps have to be performed to create a new box in cell B and remove the old one box from cell A. Following the rank concept, cells must be merged first, before edges and nodes in their boundaries can be deleted by subsequent merge operations. Boundary domains may only be deleted if they do not bound other domains in addition to A and B. Nodes and edges are introduced in the boundary of cell B by splits of edges and faces, before the new box is created by a cell split. This completes the sequence of work steps for the *move* operation.

During the execution of sequences of work steps, a number of checks must be performed to guarantee the consistency of the model after the step sequence. Various errors due to incorrect topology or geometry and due to numerical imprecision can occur. The concepts of robustness and of checking are outlined in the following chapters. If any kind of error is found during the checking of a work step or a sequence of work steps, the construction is aborted and the preceding work steps in the sequence are reversed. This operation is straightforward, because pairs of split and merge operations are counterparts that are readily derived from each other.

4 Robustness

4.1 Definition

A variety of definitions and interpretations of robustness exists in the field of computational geometry. Keyser [6] describes different implementation characteristics, where robustness is one characteristic besides "efficiency" and "accuracy" and increased robustness would be often a trade-off regarding run-time or storage efficiency. Traditionally, "robustness problems" are often discussed due to precision problems and specific "degeneracies", which can occur during computations [12]. Due to this lack of a clear definition, some developments claim to "improve robustness", while others claim that their approach is "robust". Different degeneracies in polyhedral computations are outlined by [15], who outlines two general strategies: multiple precision arithmetic or high priority for topological consistency. Hoffmann [5] gives an overview of robustness in solid modeling and justifiably calls it a "catastrophic event", if inconsistency occurs between highly structured topological data and the geometry of the model. Generally speaking, logical facts, or predicates, such as incidence, are deduced in algorithms based on numerical calculations, but imprecision of floating-point arithmetic makes the conclusions, inferred from such predicates, unreliable.

4.2 Inexact Computation

In the past, several approaches for exact geometric computations have been proposed addressing the robustness problem [17]. An implementation of an algorithm in which the arithmetic calculations are carried out exactly is guaranteed to avoid problems of consistency, since it will always construct a result with exactly the correct topology. In fact, correct topology is guaranteed if the predicates are evaluated exactly, irrespective of how the real values concerned are represented. Libraries such as LEDA and CGAL provide implementations of "exact" predicates using arbitrary-precision integers based on the arithmetic of Shewchuk [11]. While this solution seems straightforward, it can slow down computation substantially. Graphic-processing units (GPUs) are tested to accelerate the calculations [8], but this concept is very hardware dependent. To tackle this problem, floating-point filters can be used, providing an adaptive evaluation and calculating a strict bound on the extent of any numerical error, based on the known precision of individual arithmetic operations. Dynamic filters can compute a closer error bound than static filters, but also come with higher computation cost. Another specific form of filter is the use of interval arithmetic, in which upper and lower bounds are maintained by a switch of rounding up and down for each bound respectively compared to standard "round to nearest" in floating-point operations. This approach is inefficient.

While these implementations of exact computation may lead to a solution in every case, high computational costs may come with this certainty. Therefore, different approaches for "inexact computation" have been proposed recently, especially in the field of Boolean intersections. Smith [13] extensively describes different approaches for handling degeneracies, which guarantee consistency between the geometrical and the topological description. One of these strategies is the topologically-oriented approach and an extension of this approach, topologically controlled work steps, is used in the operators for polyhedral space partitioning presented in this paper.

4.3 Robust Modeling by Topologically Controlled Work Steps

A work step in the construction of a linear complex is called topologically controlled if a single domain is replaced by exactly two domains of the same rank in the work step, or if exactly two domains of equal rank are merged to form a single domain of the same rank. The intended topological change in the work step is known explicitly. In the beginning of a topologically controlled work step, it is checked whether the input data do in fact lead to the intended topological change. If they do not, the error is reported and must be corrected before the construction proceeds. Uncontrolled topological changes cannot occur if this procedure is adopted.

Because of the atomic operators, the topology-oriented approach is robust. Geometric degeneracies are detected. Because each operation is focused on the neighborhood of the modified domains, the number of geometric checks required when introducing new domains is significantly reduced from the number required for established procedures. The method does not require tree-based decomposition such as binary space partitioning or octrees.

5 Checking of Specified Input Data

5.1 Affected Domains

The input data are checked for every atomic work step. Work steps are ordered by rank. Interior point-sets can only be split after their boundaries have been split. If an error is detected, the work step is aborted and the error is reported. Errors can occur due to improper topological configuration of the input, or due to deviations from the real coordinates of the nodes. Each operation is focused, because the domain, in which a subdomain will be created, is explicitly specified in the commands. Because of the explicit topology in the core model, location test must only be performed on a minimal subset of geometric domains in the direct neighborhood of the modified domain.

The novel approach is structured so that the tools for topological and geometrical tests on domains are largely independent of the rank of the affected domains. The geometric tests are similar for bounded or unbounded domains. Because topological tests are performed by traversing the graph structure of the core model, they are faster than geometric tests that calculate floating point coordinates, distances and predicates to determine whether a point is in the interior of a domain. Topology is tested before geometry in the approach of topologically controlled work steps.

5.2 Topological Checking

There are four categories of topological errors that can occur when merging domains or splitting a domain and introducing new subdomains:

- Unbounded domains that intersect bounded domains
- Domains that are not closed
- Non-manifold domains
- Unconnected domains

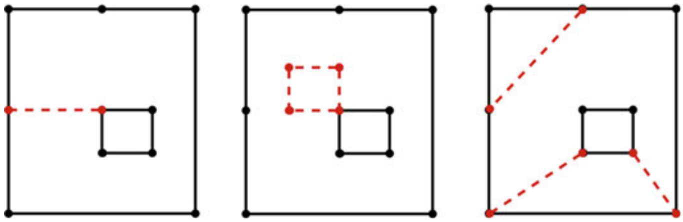

Fig. 6 Topological errors that are checked in the split of a face, not closed boundary **left**, non-manifold boundary **middle** and multiple not connected boundaries **right**

Because of the decomposition of the complete space, outer domains are bordered by imaginary nodes, edges and faces, which describe the topological relations of the unbounded edges, faces and cells. To ensure a correct partition of the unbounded space, unbounded edges and faces are not permitted to intersect with each other and are improper in the interior of a bounded domain. The configuration of the domain is checked at the beginning of a work step.

All domains of a model must be closed topological manifolds, homeomorphic to a Euclidean space. An example of a 2-manifold is a face with a 1-dimensional closed boundary as shown in Fig. 6. While each face can have multiple inner boundaries, each boundary by itself must be homeomorphic to a circle. This can easily be checked based on the topological graph structure of the input. The affected domain is evaluated independent of its surrounding. Lastly, each merge operation must be performed on exactly two connected domains of the same rank, resulting in one manifold output domain. Equally, a split operation must result in exactly two connected topological manifolds. If a decomposition into more domains is intended such as seen in Fig. 6 (right), several splits must be performed in a sequence of work steps.

5.3 Geometrical Checking

If the topological relations of the input data are valid, geometric checks based on the coordinate values are the next step in the check algorithm before any modification of the space partition takes place in the atomic work step. Geometric imprecision must be considered. Base geometries such as planes and lines can be analyzed to evaluate the distance of a point in space to the domain and to decide, whether a specific point in space lies inside a geometric domain. Figure 7 shows a simple face with four nodes in a plane. Due to imprecise coordinates, the nodes may not lie exactly in a plane. Therefore, a global accuracy parameter ε is introduced to limit the maximum distance of a node from the plane that approximates the exact plane that topologically contains all four nodes. This accuracy parameter ε is derived as a static filter from the model dimensions $size = 10^s$ and upper bound on the relative approximation error due to rounding in floating point arithmetic $eps = b * 10^m$:

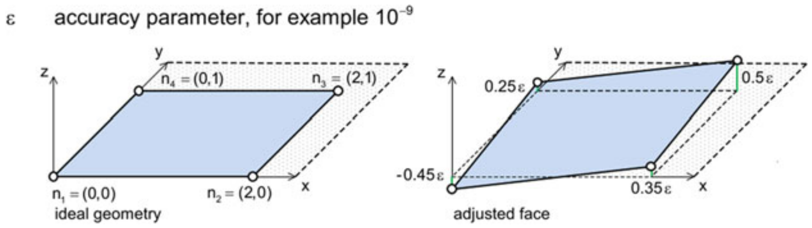

Fig. 7 Base geometry of a plane is shown. A face (blue) with 4 nodes is demonstrated. The point is inside the domain, if the distance is smaller than a accuracy parameter

$$\varepsilon = 10^{m+s+1} \tag{1}$$

For instance, the machine epsilon for double-precision is $eps = 2.22 \times 10^{-16}$. In case of a model size of $size = 10^6\, units$, a suitable accuracy parameter would be chosen as $\varepsilon = 10^{-9}$. While planes and lines in space are unbounded, the boundary of an unbounded geometric domain in a space partition contains at least one bounded domain. Predicates, to determine whether a point lies in the interior of a domain, must be calculated for geometric checks. To reduce number of geometric test types to a minimum, bounded and unbounded domains are treated in a similar manner. Because model size s and the accuracy ε are directly correlated, temporary coordinates for imaginary nodes can be chosen at the border of the model. These coordinates are used like coordinates of real nodes to calculate distances and predicates for unbounded domains in the same manner as for bounded domains.

As described in Sect. 4, computational strategies for imprecise values are often implemented for robust geometric computations. In space partitioning, the computation is reduced to three general procedures: (1) calculating the distance of a domain to another domain, (2) projecting a domain of lower rank, e.g. a node, into another domain such as a straight line or a plane and (3) computing the predicate of a point in relation to a specific domain using the orientation of arrows in polygons and facets in surfaces. Ray casting or segmentation algorithms, which are used to determine the point-in-polyhedron predicate in established procedures, are not required in the space partitioning approach. For a 3-dimensional cell in the polyhedral space partition, all boundary domains can be sorted according to the distance of their base geometry to a point in space. By projecting the point into the lower dimensional base geometries, the anchor on the boundary of a cell can be determined effectively.

Anchor and Client Zones. In the methods that determine the point on a boundary of a domain that is nearest to a given point in space and calculate location predicates for domains of different dimensions, the conventional concept of localization with simultaneous inequalities is replaced by the concept of localization with anchor zones and associated client zones. In order to localize a point relative to a domain A, the boundary of the domain is decomposed into open subdomains called anchor zones. Each anchor zone is associated with a client zone. The client zone contains the points

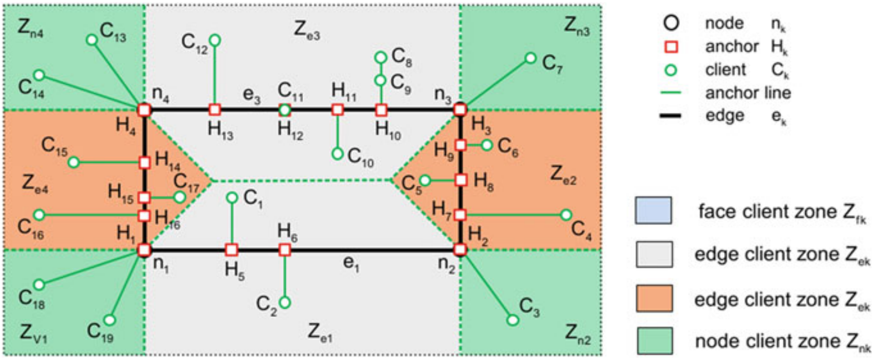

Fig. 8 Anchor and Client Zones in the 2-dimensional space. Client zones of nodes are green. Inside predicates for grey and orange zones are determined using orientation of the core model

in space, which are as near or nearer to the anchor zone than to any other anchor zone. The client zones are a decomposition of space.

Different types of condition are formulated for client zones of different rank. A point of a client zone is an inner, outer or boundary point of a domain, depending on which of the conditions for the client zone the location vector of the point satisfies. Figure 8 shows different client zones and anchors for clients (points) on a plane surrounding a face. Red anchors H have the projected coordinates of the closest boundary domains, in this case edges and nodes. Using the orientation of the core model, predicates for all domains of rank larger than 0 can be determined by calculating the scalar product or the vector product of two vectors in space. This principle is independent of the tested domain or the client zone. Normal vectors of faces are stored explicitly. Normal vectors of edges and nodes are calculated from the normal vectors of all adjacent faces. If the angle a between the normal and the vector from an anchor to its client (Fig. 8) is smaller than pi/2 the point is determined to be outside, and inside if it is bigger than pi/2. This principle is applied for all predicates needed in the geometric tests regardless of its dimension, thus leading to a systematic and convenient minimal set of calculations based on explicitly available topology and the theory of client zones.

Contact and Intersection. While the concept of anchors and clients in combination with oriented domains is a consistent way to determine distances and predicates if the affected domains are inputs, geometric errors can also occur due to unintentional contacts or intersections of domains. Therefore, a structured method of testing for intersection of existing domains and input domains is needed.

Figure 9 shows various types of intersections between domains. Because space partitioning provides all neighboring domains, no further calculation is needed to determine which geometries must be checked for intersections. Intersections of base geometries are calculated and the same theory of anchors and client zones is utilized in order to determine erroneous geometric input. The model topology and geometry

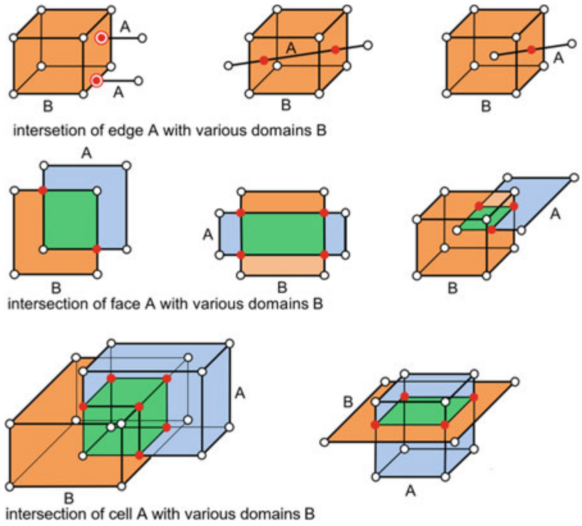

Fig. 9 Different types of intersections, checked during every atomic work step

are modified only if the checking does not reveal any errors. In this manner, it is guaranteed that the polyhedral partition is proper at the end of every atomic work step.

6 Conclusion

6.1 Summary

Various methods to treat topology in digital building models and to ensure robustness in computational geometry have been reviewed and compared to a novel approach of modeling a polyhedral space partitioning. Bounded and unbounded domains have been introduced and investigated for a complete partition of space. Imaginary domains have been introduced to topologically represent relations between unbounded domains. While the imaginary entities do not have a geometric point-set, they permit navigation in the complete space in the same manner as in a bounded space. Many applications such as energy simulations require information about the exterior surfaces of building components and opening. This information can be deduced using the presented unbounded domains.

For the construction of polyhedral space partitions, a minimal set of operators that split and merge domains of equal rank have been presented. Sequences of atomic operators are structured with a rank concept, ensuring that only the interior of a point-set is modified during an operation. Boundary domains of lower rank must be modified in preceding work steps split in the case of a split or removed in succeeding work steps merge in the case of a merge. Sequences of work steps for higher level operators such as *move*, which combine a sequence of split and merge operations, are described in Sect. 3.2 by an example.

The concept of space partition requires all domains to be manifolds. To ensure robustness in every work step, topologically controlled work steps are introduced and compared to existing approaches for exact and imprecise robust modeling. By checking topology and geometry in every atomic work step and using the characteristics of focused operators, efficient and robust work steps are implemented. The operators are called focused because the subset of domains to be tested is explicitly known due to the inherent properties of the space partitioning concept.

The presented concept of anchor and client zones provides a consistent theory for all geometric checks that are required. Distances and predicates are applied to base geometries to determine the location of points relative to domains of any rank. A global accuracy parameter is introduced to handle numerical imprecision, analogical to static floating-point filters used in imprecise computations. Because the topology is mapped exactly to the digital model, the system is robust if no discrepancy is detected between its topology and its geometry. Otherwise, the operation is aborted and the partition is not modified and related preceding work steps in a sequence of work steps are reversed using the complementary operators.

6.2 Outlook

The presented operators are key components for a future space partitioning modeling platform for geometric models in architecture and civil engineering. The robustness of the atomic operators is a prerequisite for modeling functionality of higher order, such as *extrude* or *sweep*. Robustness is treated independent of the source of the geometric data, and is ensured by the operators themselves. Future user interfaces will calculate coordinates and generate input for split and merge operations, whose consistency in the model is automatically checked and guaranteed by the basic operators.

Further performance tests have to be conducted to evaluate the usability of the topologically controlled work step approach for modeling polyhedral space partitions. First verification results show the general applicability of the robustness theory. In order to generate acceptance for this approach, interfaces for existing parametric modeling interfaces should be provided when implementing higher order operators.

Many fields of application can benefit from consistent and topologically enriched geometric data models. Transformation and issue management are two main tasks in engineering workflows today, especially in the coordination of architectural models, structural design and energy modeling. The alignment of indoor and outdoor modeling calls for robust operators that handle bounded and unbounded domains and provide means to create graph models for connectivity and navigation. First results in generating graph data structures such as semantic web graphs highlight the ability to model geometry and topology consistently. The novel approach provides a general basis for modeling that aligns different fields of application around one common geometrical model. Polyhedral partitions fulfil the requirements of most engineering applications and map the complete space.

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Feature-Based Decomposition of Architectural Spaces: Outline of a Procedure and Research Challenges

Georg Suter

Abstract Space modeling is a key activity in building design that is supported by BIM authoring systems. However, decomposing spaces with specific properties, such as spaces with non-convex volumes, into disjoint partial spaces, or sub-spaces, is a manual and non-trivial task. This study identifies the need for automated 3d space decomposition methods. Informed by a review of related space and shape decomposition methods, the problem scope for feature-based space decomposition is defined. A procedure is outlined that addresses this problem. The procedure recursively decomposes a space into sub-spaces using cutting operations derived from recognized features. The decomposition of a (sub-)space ends if it meets decomposition goals or if no features are recognized. The procedure is divided into space evaluation, feature recognition, and space cutting phases. The recursive decomposition of a space may be represented as a tree where nodes correspond to iterations of the procedure and edges to sub-spaces. Research challenges related to architectural feature taxonomies, feature recognition, and cutting operations are identified.

Keywords Building information modeling · Space modeling · Feature recognition · Volume decomposition

1 Introduction

Building information modeling (BIM) authoring systems support the modeling of architectural spaces. For several space modeling tasks, such as visualization, classification, and geometry simplification, there is a need to decompose spaces with specific properties into disjoint partial spaces or sub-spaces. Examples are spaces with non-convex volumes, multi-functional spaces, large spaces, and spaces with partitions or built-in furnishing elements. Currently, space decomposition is a manual

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G. Suter (✉)
Design Computing Group, TU Wien, Vienna, Austria
e-mail: georg.suter@tuwien.ac.at

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task that is time-consuming and error-prone. It is non-trivial because the boundaries between adjacent sub-spaces are usually virtual rather than physical. Boundaries may be defined in multiple ways. Automated space decomposition could improve user productivity as well as the consistency and data quality of space models.

The scope of most known space decomposition methods in BIM is limited to 2d geometries and specific application domains, such as indoor navigation and evacuation modeling [22]. By contrast, more general 3d geometry decomposition methods exist in the areas of computational geometry and computer-aided engineering [7, 29, 32, 35]. These methods may be reused and adapted for space decomposition.

This study aims to *i)* identify the need for 3d space decomposition methods; *ii)* review related methods; *iii)* define the problem scope for space decomposition based on features; *iv)* outline a decomposition procedure that addresses the problem; and *v)* identify research challenges. The novelties of the proposed decomposition procedure include coverage of 3d space geometries and the use of goals and feature types to guide the search for decomposition solutions that meet the diverse needs of space modeling applications.

2 Motivation

Space decomposition needs are identified for space visualization, space classification, and space geometry simplification. These tasks are relevant to multiple applications, such as floor area measurement or energy analysis. A space layout of an apartment unit is used to illustrate these needs (Fig. 1). Two alternative decompositions of a large space s (Fig. 1a) into partial spaces, or sub-spaces $s_1, s_2, \ldots, s_n$, are shown in Fig. 1b and 1c.

2.1 Space Visualization

Besides the large, multi-functional space s, the apartment unit consists of five small service spaces (Fig. 1a). Space volumes are convex except for s and the bathroom. A volume is convex if all interior angles between adjacent, planar face pairs are less than 180°. A property of a convex volume is that its geometric center, or centroid, is always located in its interior. For example, this property is useful for placing space labels in visualizations. There is at least one concave edge on the boundary of a non-convex volume. An edge is concave if the interior angle between its incident face pair is greater than 180°. The centroid of a non-convex volume is located on its interior or exterior. Thus, a label placed at the centroid may be incorrectly associated with an adjacent space, or it may be placed near the space boundary. One way to achieve an improved visualization would be to decompose a non-convex space into a small number of convex sub-spaces, and to place the label at the centroid of the volume of the largest sub-space. All spaces in the second decomposition example have convex

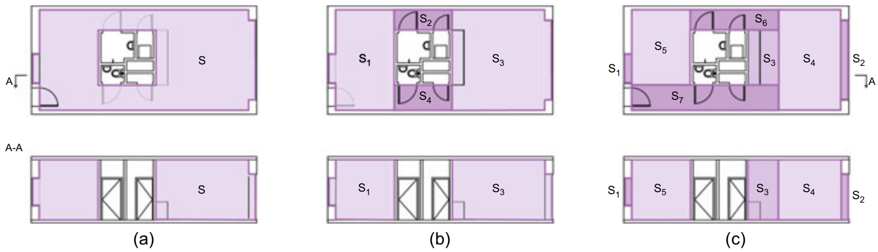

Fig. 1 Space decomposition examples. **a** Space layout of an apartment unit with space s, **b** Example for a non-convex decomposition of s into sub-spaces s_1, s_2, s_3 and s_4, **c** Example for a convex decomposition of s into sub-spaces $s_1, s_2, \ldots, s_7$.

volumes (Fig. 1c). Accordingly, the label for space s (Fig. 1a) would be placed at the centroid of the volume of sub-space s_4. The first decomposition is non-convex because the volumes of sub-spaces s_1 and s_3 are non-convex (Fig. 1b). Both would need to be further decomposed until all sub-space volumes in the decomposition meet the convexity condition for label placement.

2.2 *Space Classification*

Space s in Fig. 1a supports multiple activities or functions, including living, cooking, sleeping, and circulation. The function and shape of each sub-space must be determined for accurate floor area measurement or energy analysis. This could be done in two steps. First, s could be decomposed into functional sub-spaces based on its features. The latter include a vertical hole, two window niches, and a kitchen element. A functional sub-space is a space that can accommodate people or equipment. In a second step, sub-space functions could be classified based on their features, other geometric properties and connectivity to other sub-spaces or space elements [3, 33].

The first decomposition consists of four sub-spaces (Fig. 1b). All space volumes are large enough to be classified as functional spaces. While the two circulation spaces s_2 and s_4 have convex volumes, the sleeping and living space volumes s_1 and s_3 are non-convex because of window niches. A decomposition goal could be defined such that spaces in a decomposition do not need to be convex. Similarly, the bathroom includes a shallow niche that extends from ceiling to floor. It could be considered as being nearly convex. The decomposition procedure may end when only minor concave features remain. Again, near-convexity could be defined as a goal.

Cooking and living spaces s_3 and s_4 are modeled as separate spaces in the second decomposition (Fig. 1c), as are two window niches s_1 and s_2. The latter are shallow extensions of adjacent spaces s_4 and s_5 and may be considered non-functional spaces because they do not accommodate people or equipment. Allowing for non-functional spaces may be defined as a goal. The cooking space s_3 is derived relative to the kitchen element contained in space s. More generally, decomposition may be based not only on space volumes but also on the shapes of related space elements.

In both decompositions, the two narrowest functional spaces are located on opposite sides of the vertical hole. Based on their size and dimensions, these may be classified as circulation spaces. This illustrates how space geometry may correlate with function, and thus the former may be inferred from the latter. Both decompositions differ regarding the number of spaces, space volumes, related space elements, and accessibility. This may affect space classification. In the first decomposition, the circulation space s_4 only connects sleeping and living spaces s_1 and s_3. The corresponding circulation space s_7 is additionally accessible from the unit entrance door in the second decomposition. It may thus be classified as an entrance space.

2.3 Space Geometry Simplification

Space geometry simplification is relevant for visualization, planning, or simulation environments that support models with multiple levels of detail [34]. It involves transforming or generalizing a model with a higher level of detail into one with a lower level of detail while preserving salient geometric properties of the original model, such as parallelism or orthogonality.

Simplified space volumes are required for certain applications, such as energy analysis. Thus niches, protrusions, openings, or other detailed features may need to be isolated and removed from a space volume. In other applications, the types and shapes of these features must be determined. An example is floor area and volume measurement, where niche spaces need to be considered dependent on their geometric properties in relation to adjacent spaces [24, 36]. In the second decomposition example, the smaller niche space s_1 is elevated, while the larger niche s_2 extends from the floor (Fig. 1c). In the latter case, the niche area is considered an extension of the living area of s_4. This example shows that distinguishing different niche types requires 3D rather than 2D space geometries. Moreover, in scan-to-BIM applications, source data are 3D geometry data with high levels of detail from which space models are created [25].

3 Decomposition Methods

3.1 Space Decomposition

Space decomposition methods exist for several domains. In indoor navigation and emergency evacuation modeling, indoor spaces are decomposed to derive navigation models with desirable properties, such as paths that avoid obstacles or model people's movement [22]. Common decomposition methods are based on planar grid [21] or irregular cells. Examples for the latter include 2d or 3d triangulations [2, 6] as well as point-based [4] and line-based (or skeleton) Voronoi diagrams of space polygons [11, 20]. The decomposition method developed by Jeong and Ban [18] generates convex sub-spaces for space access analysis [17]. Candidate sub-space polygons are generated from a given space polygon. The 'fattest' polygons with the highest area-perimeter ratios are included in a decomposition.

Each reviewed method is limited concerning at least one space decomposition need (Sect. 2). In most methods, space geometries are modeled as 2d polygons instead of 3d volumes. Decomposition of space volumes by 3d triangulation would, in most cases, result in many small sub-spaces. These are undesirable for visualization, classification, and geometry simplification. Similarly, the number of convex sub-spaces created from Voronoi diagrams is neither minimal nor near minimal. Geometric properties, in particular angles between adjacent edges or faces, are not well preserved by most reviewed methods.

3.2 Feature Recognition and Shape Decomposition

Decomposition methods are relevant for simulation, engineering design, and production planning. In finite element analysis, features such as nuts and bolts may be isolated and removed from a volumetric model of a part in order to reduce the number of mesh elements. This speeds up calculations without reducing accuracy [27]. In a volume simplification method developed by Thiemann and Sester [34], which extends work by [27], building volumes are decomposed (or segmented) into sub-volumes. Examples of segmented elements are chimneys, balconies, doors, and windows. At first, protrusion and holes are detected by one or more cutting planes that are derived from the volume boundary. Next, recognized features are subtracted from the volume by half-spaces that are created from cutting planes. This results in a simplified building volume with a lower level of detail than the original volume while preserving geometric properties, such as orthogonality or parallelism between volume boundary faces. A building volume may be decomposed in multiple ways. Feature quality values are computed to identify and remove the most relevant features.

Feature recognition is relevant for integrating mechanical engineering design and production planning tools [35]. Slots, holes, steps, and pockets are examples of machining features. A feature may be defined as a "region of interest on the surface of a part" [26]. Features may be recognized automatically in a part design using recognition methods. This facilitates the re-interpretation of a design for production planning [35]. Most feature recognition methods assume that part designs are modeled as solid (or volume) Breps.

Topological, heuristic, and volumetric are common feature recognition methods [29]. Topological methods are based on face adjacency graphs that are created from a volume Brep. An example is the attributed adjacency graph (AAG), where nodes and edges correspond to faces and edges in the Brep [19]. AAG edge attributes indicate if an edge is convex or concave. Edges labeled as convex are first removed from the AAG. Next, features modeled as AAGs are matched against the modified AAG using a subgraph search. While topological methods work well for isolated features, recognizing features that interact with each other is difficult [29].

Volumetric methods involve the decomposition of a given volume into sub-volumes or cells. For example, in volume decomposition and recomposition, a non-convex volume is decomposed into 'atomic' convex cells; cells are merged into 'macro' volumes, and the latter are classified as features [29]. Cells may be created by half spaces that are derived from faces that are incident on a concave edge [30]. The method by Sakurai [28] computes maximal convex cells instead of 'atomic' cells. Features are generated by subtraction of maximal cells.

The approach to decompose a volume into convex sub-volumes by cutting planes that extend faces adjacent to concave edges is adopted in a recursive decomposition method by Eftekharian and Campbell [10]. At least one concave edge disappears with each cutting operation, which ultimately results in convex sub-volumes. A volume is partitioned recursively into convex sub-volumes with planar and cylindrical cutting surfaces. The decomposition can be represented as a tree where the nodes correspond to complex or simple volumes and the edges to cutting directions. There are two cutting directions for each concave edge. The given volume is at the root, and simple volumes are at the leaf nodes. The latter are typically convex. The depth of the decomposition tree corresponds to the number of concave edges. There are between $n + 1$ and 2^n sub-volumes, where n is the number of concave edges. Since the exhaustive exploration of potentially large solution spaces is impractical, concave edges are classified and ordered according to a ranking strategy. The most promising cutting direction for the top-ranked edge is identified based on sub-volume metrics.

A common issue in decomposition methods is remote and local over-cutting [23]. In remote over-cutting, extending a face by a cutting plane may cause undesirable cutting in remote locations. As a result, a decomposition may have more sub-volumes than necessary. In local over-cutting, more cutting planes than necessary are used to create a convex sub-volume locally. Remote over-cutting may be avoided by using selected volume faces to constrain the cutting locally. Multiple cutting planes may be aggregated into a single cutting unit or operation to avoid local over-cutting [23].

Applying feature recognition and volume decomposition methods to architectural space decomposition is promising for two reasons. First, their scope is volumes rather than polygons. Second, these methods are flexible. That is, they may be adapted to meet domain-specific decomposition needs.

4 Problem Formulation

The problem for architectural space decomposition using feature recognition and volume decomposition methods is formulated as follows:

Given goals, feature types, and data about a space s, including its volume v, boundary elements, and space elements, find a decomposition of s into n sub-spaces $s_1, s_2, \cdots, s_n$ ($n \geq 2$) based on features that are recognized in the boundary of v or space elements. Sub-space volumes must not overlap and $v = v_1 \cup v_2 \cdots \cup v_n$.

Decomposition goals guide the search for decomposition solutions. Goals may include convexity of sub-space volumes [17], finding a minimal set of convex volumes [8, 16], finding a decomposition with the largest convex volume [28], or optimizing the differences between volumes [10]. A feature type is a rule or pattern to recognize features in spaces. Examples of feature types are niches or openings. Similar to decomposition goals, feature types influence the search for decomposition solutions.

It is assumed that source building data, which include space data, are prepared by a designer or planner using a commercial BIM authoring system and exported as an IFC file. Space data are extracted from the IFC file as described by Suter [33]. Semantic and geometric space properties are separated, which allows the reuse of computational geometry and solid modeling libraries for implementation [5, 31]. In addition to geometric properties, semantic ones may also be considered to recognize features.

Space volumes are modeled as boundary representation (Brep) solids with planar faces. Brep data structures facilitate feature recognition and the application of existing volume or cellular decomposition methods [7, 32]. In the latter, a solid is decomposed into internally connected cells. The decomposition of spaces with curved faces, particularly curved concave faces, is considered out of scope as it is significantly more challenging than spaces with planar faces.

A space is bounded by several virtual or physical space boundary elements. Virtual space boundary elements exist between adjacent sub-spaces. There is a one-to-one, uni-directional relationship between space boundary elements and the faces in a space volume Brep. Space elements are either space enclosure elements, such as doors and windows, or elements that are contained in a space, such as furnishing, sanitary, or technical elements. They are related to space boundary elements and spaces, respectively. These spatial relationships must be derived for each sub-space that is created in the decomposition process.

A space is typically decomposed based on features detected in its volume's boundary. Space element features may be used for decomposition as well. For example, the cooking space in Fig. 1c is created from features detected in the shape of the kitchen element.

Decomposition solution spaces may be large. For the convex decomposition method by Eftekharian and Campbell [10], the solution space size is n in the best and 2^n in the worst case, where n is the number of concave edges in a given volume. According to the method, the number of solutions for decomposing space s in Fig. 1a, which includes 11 concave edges, would be between 11 and 2048. An exhaustive exploration of a potentially large number of decomposition solutions is generally impractical. Thus decomposition procedures are desirable that explore only a subset of these alternatives. They should be able to identify promising alternatives that best meet given decomposition goals.

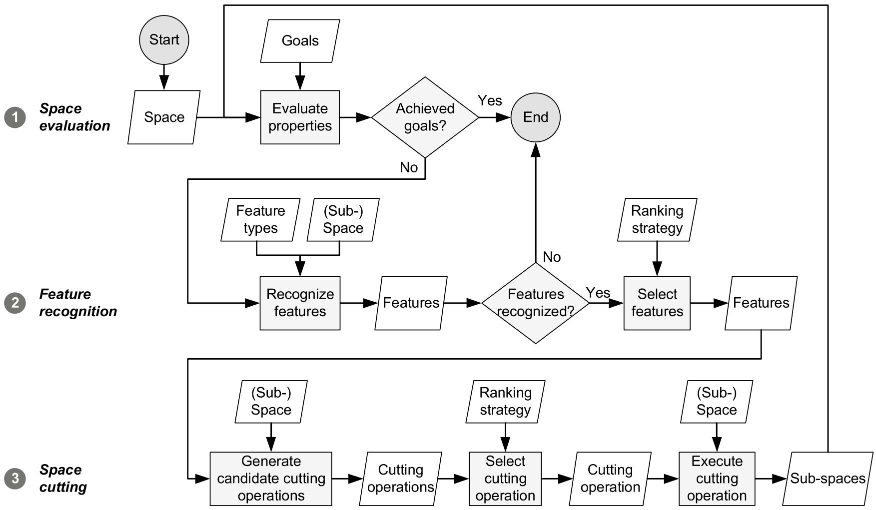

Fig. 2 Flowchart for feature-based space decomposition.

5 Decomposition Procedure

Decomposition-recomposition and recursive decomposition approaches could address the architectural space decomposition problem defined above. For spaces with many features, the former approach may result in a large number of fragmented cells after decomposition, and hence there would be many solutions for recomposition. Both steps would be computationally expensive. Cell fragmentation is less of an issue in recursive decomposition since only one cutting operation is executed at a time. The effectiveness of this approach depends on identifying promising features and cutting operations. Steps in such a recursive decomposition process are outlined in the following (Fig. 2). It can be divided into space evaluation, feature recognition, and space cutting phases.

In the space evaluation phase, a given (sub-)space is evaluated against decomposition goals. Evaluation relies on basic geometric space properties, such as height, floor area, volume, or concave edge count. Semantic properties may be considered as well, such as the number of doors or windows. Decomposition goals may be defined in terms of desirable values for space properties. An example of a goal is that all subspaces in a decomposition must be convex. The procedure ends if the space meets decomposition goals.

In the first step of the feature recognition phase, feature types are used to recognize features in the space. If no features are recognized, decomposition of the space ends. Next, promising candidate features are selected among recognized features using a ranking strategy that is based on feature properties. Examples are a feature's type, concave edge counts or lengths. One or more of the highest ranked candidate features are selected for further processing.

In the space cutting phase, candidate cutting operations are first created from selected features. A cutting operation consists of one or more planar cuts. Multiple candidate cutting operations are typically created for each feature. For example, there may be two cut directions for a concave edge that are extensions of its incident faces. Additional cut directions may be co-planar with pairs of parallel or co-planar edges. All candidate cutting operations are evaluated and ordered according to a ranking strategy. Finally, the highest ranked candidate cutting operation is executed to decompose the space into sub-spaces. The latter are passed to the next iteration of the decomposition procedure.

Two approaches are conceivable to evaluate candidate cutting operations. In the first approach, each candidate cutting operation is executed [10]. The highest ranked set of candidate sub-volumes is retained to create corresponding sub-spaces while other candidate sub-volumes are discarded. Examples for sub-volume properties are volume difference and number of concave edges [10]. A benefit of this approach is that actual sub-volumes are evaluated. However, the computational cost is already high in the case of only a few candidate cutting operations. This is because solid modeling operations that are used to execute cuts are computationally expensive. In the second approach, cutting operations are evaluated based on cut rather than volume properties. An example of a cut property is the cut length, which may be defined as the shortest distance between a midpoint on a concave edge and its projections on boundary faces that intersect with a cut plane. A ranking strategy may prefer cutting operations with short distances.

A tree that models the decomposition of the large space s in the example (Fig. 1a) is shown in Fig. 3. The goal is a convex decomposition, that is, to decompose the s into convex sub-spaces (Fig. 1c). Each tree node represents an iteration of the decomposition procedure (Fig. 2). Each edge corresponds to a sub-space created by the selected cutting operation. For simplicity, all cutting operations are assumed to be selected and executed by a user. A *'C'* label indicates a non-leaf cut node where a cutting operation is executed. The type of the selected feature from which the cutting operation is derived is shown next to the node. An *'E'* label indicates a leaf node where the decomposition of a sub-space ends. All sub-spaces that are passed to leaf nodes are convex, and thus the decomposition goal is achieved. The ranking strategy for feature selection is by feature type. Feature types *['Niche', 'Space Element', '2 Vertical Concave Edges']* may be recognized, where *'Niche'* is the top-ranked feature type. If a feature type is detected multiple times, then the ranking strategy considers additional feature properties, such as the total concave edge length. For example, small niches may be preferred.

Space s is passed to the root node for recursive decomposition. *'Niche'* features are the highest ranked recognized features at the root and its child cut node. Cutting operations that consist of single planar cuts are executed. The output of each node is a small niche and a copy of s where the niche space is subtracted. Niche spaces s_1 and s_2 are convex and thus not decomposed further. A convex cooking space s_3 that contains the kitchen element is created at the second-level cut node where a *'Space Element'* feature is highest ranked. The corresponding cutting operation consists of four cut planes which are derived from the shape of the kitchen element. A *'2 Vertical*

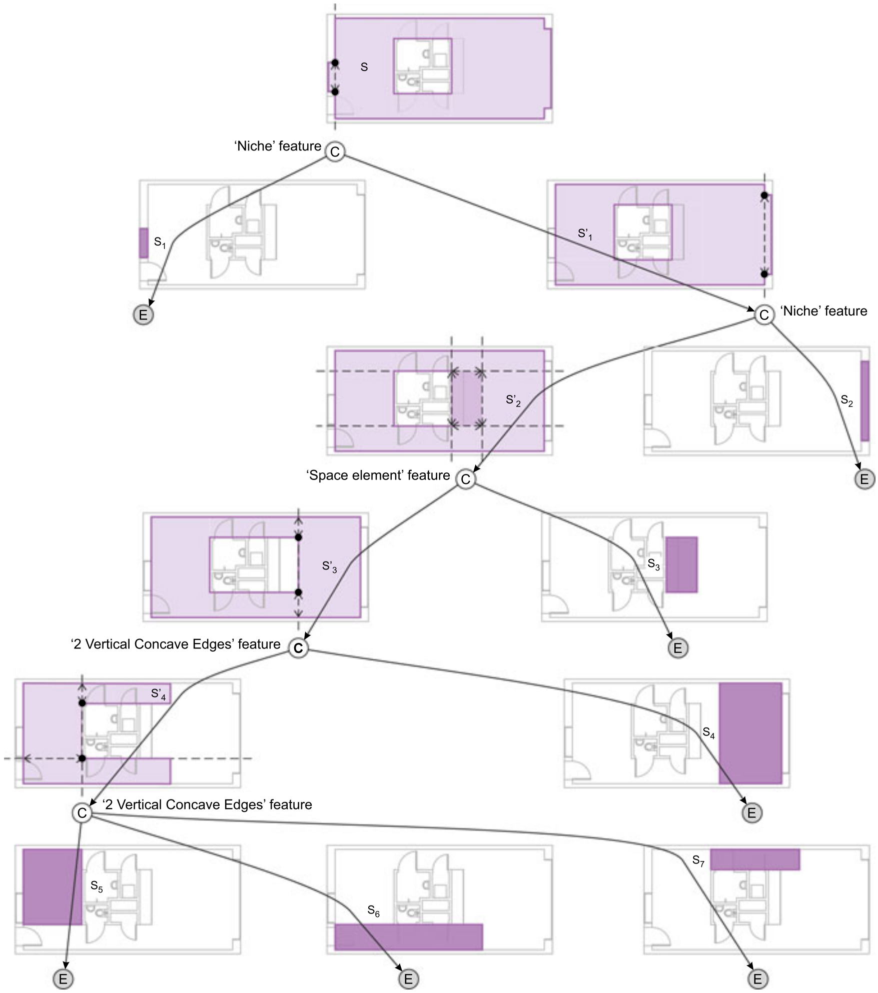

Fig. 3 Decomposition tree for space s in Fig. 1a. The type of the feature selected to create cutting operations is shown next to cutting nodes. Sub-spaces $s_1, s_2, \ldots, s_7$ that are passed to leaf nodes correspond to sub-spaces in Fig. 1c.

Concave Edges' feature is selected at the fourth-level cut node. In this feature, a pair of vertical concave edges bound the same face. The cutting operation consists of a single cut plane and creates two spaces s_4 and s'_4. The smaller is the convex living space. At the fifth-level cut node, a second feature of the same type is selected. In this case, the cutting operation consists of two cut planes which create three convex spaces, including a sleeping and two circulation spaces (s_5, s_6 and s_7).

6 Research Challenges

6.1 Feature Taxonomies

The effectiveness of feature-based space decomposition methods is partly dependent on comprehensive architectural feature taxonomies. Therefore, features relevant to architectural space decomposition need to be systematically identified. Potential sources for features include professional and research publications on architectural design and heritage [1, 9, 15]. Vertical or horizontal concave edges in a space volume boundary are examples of basic geometric features. Such features may be grouped. Examples are loops of convex or concave edges in a face [12] or a pair or vertical concave edges that bound the same face. If known, features may be further specialized according to the classes of related space elements. For example, a vertical concave edge whose adjacent faces are related to walls may be classified as a wall corner.

Some features are generally useful, such as openings and wall niches, while others are more domain specific. For example, steps and ramps are mostly relevant for the circulation domain. Granular feature sub-types may be required for certain domains. For example, a wall or window niche may extend from a floor or parapet to a lintel or ceiling. These distinctions are relevant for floor area measurement [36]. Features are not necessarily restricted to spaces but may also cover space elements. Examples include furnishing or kitchen element corners (Fig. 1).

As the examples illustrate, architectural features may range from generic to specific. While the former are geometric, the latter combine semantic and geometric properties. As a result, architectural feature taxonomies are expected to be significantly larger than those for machining features.

6.2 Feature Recognition

Architectural space features need to be formally defined to be recognized. Definitions of such feature types or patterns may include topological, geometric, and semantic properties. The topology may be represented as a feature sub-graph matched against the AAG of a space volume [19]. Other feature representations are concave or convex edge loops or edge lists. The latter may capture patterns of concave and convex edges. Similar to regular expressions [14], these patterns could be matched with edge loops in faces. An example of a pattern is an edge loop consisting of a pair of vertical concave edges separated by one or more edges.

Feature interaction is an issue that limits the effectiveness of existing feature recognition methods, in particular topological methods [13]. Two features interact if the intersection of their volumes is non-empty. For example, consider a volume with a hole and a slot feature. The two features interact if their intersection is non-empty, e.g., the slot may split the hole into two parts [29]. The occurrence of such feature interaction in architectural spaces needs to be studied.

6.3 Cutting Operations

A rich set of features would be complemented by flexible cutting operations to decompose a volume in multiple ways, as illustrated by the example in Fig. 1. Cutting planes as face extensions appear promising for architectural space decomposition because convex angles in the original space volume would typically be preserved, and the number of sub-spaces would either be minimal or near minimal. The latter is relevant for functional space decomposition (Sect. 2). Neither of these properties is preserved in triangulations or skeletons of space polygons (Sect. 3.1). Ideally, cutting operations may consist of single or multiple planar or curved cuts. Solid modeling libraries support single planar cuts. An example of such a library is the cellular topology component in the ACIS solid modeler [32]. Multiple simultaneous cuts [23] are currently not supported. Implementing single cuts, followed by post-processing to merge cells due to local and remote over-cutting, is computationally expensive. Thus algorithms that process multiple cuts and are easy to implement are desirable.

7 Conclusions

Feature-based architectural space decomposition is a non-trivial problem due to the need to navigate potentially large solution spaces and advanced geometry processing. A decomposition procedure was outlined that uses goals and feature types to guide the search for decomposition solutions. It was shown how the recursive decomposition of a space could be modeled as a tree structure where nodes correspond to iterations of the decomposition procedure and edges to spaces.

Several research challenges related to feature taxonomies, feature recognition, and cutting operations need to be addressed to apply and extend existing approaches and methods to space decomposition. Among these, the development of cutting operations that support multiple planar cuts while avoiding local and remote over-cutting appears particularly relevant as a foundation for future work in this promising area.

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