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Kriengsak Panuwatwanich
Chien-Ho Ko *Editors*

The 10th International Conference on Engineering, Project, and Production Management

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ISSN 2195-4356 ISSN 2195-4364 (electronic)
Lecture Notes in Mechanical Engineering
ISBN 978-981-15-1909-3 ISBN 978-981-15-1910-9 (eBook)
https://doi.org/10.1007/978-981-15-1910-9

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

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All the papers in these conference proceedings were double-blind reviewed by members of the International Scientific Committee. This process entailed detailed reading of the papers, reporting of comments to authors, modification of papers by authors, and re-evaluation of revised papers to ensure quality of the content.

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Preface

The 10th International Conference on Engineering, Project, and Production Management (EPPM2019) was organized on 2–4 September 2019, in Berlin, Germany. Berlin is a beautiful city full of historical, cultural, and technological backgrounds. EPPM conference is an annual international event rotating around the globe. It is not the first time the conference was organized in Europe, but the first time held in Germany. This conference had started to prepare three years ago, since 2016, when the Board of the Directors, EPPM Association, determined to have this conference organized in Germany.

As the conference is growing every year, we have more and more participants joined in this event from different corners of the world exchanging new ideas. Best Paper Awards and Excellent Paper Awards were issued according to review comments under the double-blind review process involving experts in the field. These papers were then suggested for possible inclusion in the EPPM Journal for explaining more details about their research findings. We continued to implement this process as part of our culture in the EPPM community since 2009.

EPPM2019 endeavoured to provide an enriching event. In addition to research presentations, EPPM Academy, this year provided tutorials for computer simulation courses for participants for both academia and industry. Three renowned keynote speakers from Japan, Finland, and local Berlin shared their state-of-the-art research results and ideas at the conference. Their presentations covered the fields of sustainability, IE 4.0, and civil systems.

This conference cannot be achieved without coherent teamwork. We appreciated the Scientific Chair led the Scientific Committee to uphold our scientific standards. Special thanks were also due to conference suppliers who provided necessary facilities, equipment, environment, and services to our delegates.

Sincerely yours,
Chien-Ho Ko
International Organizing Committee Chair
Clemson University
Clemson, USA

Editorial

The 10th International Conference in Engineering, Project, and Production Management (EPPM2019) marked a significant milestone for the EPPM conference series as it has matured into the 10th anniversary. Over the 10-year period, the EPPM conference has increasingly attracted a wider interest among researchers and practitioners who are operating in the translational fields of engineering, project, and production management across the globe. The EPPM conference contributors and participants operate in various industries such as construction, manufacturing, aviation, transportation, medical and hospitality. Although they might be in different industries, they gather to share and exchange ideas and knowledge that are applicable across multiple industries. Such amalgamation of knowledge applications serves as a catalyst for a cross-pollination of new ideas that researchers and practitioners build upon each other's experiences and lessons learnt gained from fresh new perspectives that are not indigenous to their own industry.

The EPPM2019 proceedings include 54 high-quality papers that passed a rigorous double-blind peer-review process by the International Scientific Committee of well-known experts in the fields. These papers are grouped into four parts representing four main themes: (I) Smart and Sustainable Construction, (II) Advances in Project Management Practices, (III) Towards Safety and Productivity Improvement, and (IV) Smart Manufacturing, Design, and Logistics. "Smart and Sustainable Construction" addresses recent effort to make the building and construction industry smarter and more sustainable through the uses of state-of-the-art concepts and innovative tools such as Building Information Modelling (BIM), Green Building, and Natural Language Processing. "Advances in Project Management Practices" tackles various project management aspects to better understand the complex interactions and interrelationships between salient project elements in order to achieve "best value" outcomes. "Towards Safety and Productivity Improvement" consolidates research studies aimed to make the work safer and more productive through safety and risk analysis, as well as lean thinking approach. "Smart Manufacturing, Design, and Logistics" integrates the advancement in manufacturing, design, and logistics that are built upon the latest development in modelling and simulation, additive manufacturing, and lean industry 4.0 concept.

We would like to express our sincere gratitude to all the members of the International Scientific Committee for taking their time and effort to help uphold the quality of all papers through the peer-review process. We sincerely hope that the proceedings will be of interest and valuable to researchers and practitioners across multiple industries who are seeking to update their knowledge in engineering, project, and production management.

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Peer-Review Process

A rigorous two-stage peer-review process was applied to this conference to maintain and assure the quality of the conference proceedings. In the first stage, submitted abstracts were evaluated by Scientific Chairs in terms of:

- Relevance to conference theme and objectives;
- Originality of material;
- Academic rigour;
- Contribution to knowledge; and
- Research methodology.

Authors, whose abstracts were tentatively accepted in the first stage, were requested to submit full papers for further review. Each paper was reviewed by no less than two acknowledged experts in the field with unidentified reviewers' comments. Authors were requested to submit their revised papers noting and addressing reviewers' comments. Evidence was required relative to the action taken by authors regarding the comments received. These resubmitted and revised papers were re-reviewed again in terms of:

- Relevance to conference theme and objectives;
- Originality of material;
- Academic rigour;
- Contribution to knowledge;
- Research methodology and robustness of analysis of findings;
- Empirical research findings; and
- Critical current literature review.

In the second review stage, authors were provided with additional comments and requested to submit their revisions. The final accepted decision was rendered when Scientific Chairs confirmed that all reviewers' comments were appropriately responded to, having been double peer-reviewed for publication. At no stage was any member of the Scientific Chairs and International Scientific Committee involved in the review process related to their own authored or co-authored papers.

The role of the Scientific Chairs was to ensure that the final accepted papers incorporated the reviewers' comments and arrange the papers into the final sequence as captured in the electronic proceedings.

Contents

Smart and Sustainable Construction

Evaluating the Sustainability of Non-urban Land Development Projects

Wen-Der Yu, Wei-Cheng Ho, Shao-Tsai Cheng and Hsien-Kuan Chang

Abstract Former construction projects usually emphasize more on the cost, schedule and quality objectives, while less on the environmental, economic and social sustainability. The sustainability of a non-urban land development project stands out from the others, not only because it covers a longer project lifecycle but also involves the change of natural planting, the protection of slope and the impact on the culture of the local community. There has been not yet a sustainability evaluation system for non-urban land development projects. Without such an evaluation system, it is difficult for the planners to plan the sustainable project objectives, for the contractors to select the sustainable execution alternatives, and for the facility managers to operate sustainable constructed facilities. This paper proposes a Non-urban Land Development Project Sustainability Evaluation Indicator Framework (NULPSEIF) via the reviews of legal and theoretical backgrounds from literature, focus group meetings, domain expert surveys, and case studies. Finally, a real-world non-urban land development project was selected to verify the applicability of the proposed NULPSEIF. The result of this research provides not only a useful tool to the owners and participants of non-urban land development projects to evaluate the overall project sustainability, but also the right direction to improve the sustainability of land development projects.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_1

Keywords Non-urban land development · Sustainability assessment · Project life cycle · Project management · Performance indicators

1 Introduction

Land development is a special type of project, which usually involves more stakeholders, longer lifecycle duration, more conflict of interests amongst the stakeholders and more serious sustainability issues than construction projects (Janus and Markuszewska 2019; Jin et al. 2019; Verma and Raghubanshi 2019; Antonio and Griffith-Charles 2019). Former construction management usually emphasizes more on the cost, schedule and quality management, while less on the environmental, economic and social sustainability (Yu et al. 2018). The sustainability of a non-urban land development project stands out from the other issues, as it involves the change of natural planting, the protection of slope and the impact on the culture and humanity of the local community (Ho 2019). There has not yet been a project-level sustainability evaluation system for non-urban land development projects. Without such an evaluation system, it will be difficult for the planners to plan the sustainable project objectives, for the contractors to select the sustainable execution alternatives, and for the facility managers to operate sustainable constructed facilities.

To meet the abovementioned requirements, the present research proposes a Non-urban Development Project Sustainability Evaluation Indicator Framework (NULPSEIF) with the methodology including the reviews of legal aspects, theoretical backgrounds from the literature, focus group meetings, surveys with domain experts, and verification with case studies. Finally, three real-world non-urban land development projects are selected to verify the applicability of the proposed NULPSEIF.

The rest of this article is presented in the following manner: the most relevant literature is reviewed in the next section; the third section describes the development of the proposed NULPSEIF; in the fourth section, a real-world land development project is used as a case study to demonstrate the feasibility of the proposed model and its benefits to land development project management; finally, conclusions and recommendations are addressed for future research.

2 Review of Relevant Works

Three pillars (Economic, Social, and Environmental) of sustainability were promulgated in the early 1990s (Munasinghe 1993). Such a three-pillar framework for the assessment of sustainability has been widely adopted by many sustainability evaluation systems, including the sustainability of social systems (Atanda 2019), manufacturing (Saad et al. 2019; Bhakar et al. 2018), urban development (Ameen and Mourshed 2019), automotive (Jasiński et al. 2016), and construction (Yu et al. 2018; Fernández-Sánchez and Rodríguez-López 2010). The sustainability indicators provide decision-makers a useful tool to monitor, evaluate, and review strategies to achieve the organization's long-term development goals (Fernández-Sánchez and Rodríguez-López 2010).

Land development is a special type of construction project. It covers a longer project lifecycle including a time-consuming regulatory review stage, a stricter environmental impact assessment stage, all stages of a construction project, and a long-lasting operation and maintenance stage. Moreover, it also involves the change of natural planting, the protection of slope and the impact on the cultures of the local community. Improper planning of a land development project will not only result in the failure of achieving the developer's objectives (usually relevant to economic benefits), but also the catastrophe of the surrounding community and environment including damaging the water and soil conservation due to slope excavation or becoming a hotbed of crime due to unsuccessful community development. As a result, several researchers had developed sustainability assessment indicator systems from the global (Verburg et al. 2015), national (Jin et al. 2019), city or community-based (Lin et al. 2018), and project-wise (Levine et al. 2017) perspectives.

Fernández-Sánchez and Rodríguez-López (2010) proposed a method to identify sustainability indicators for construction project management. In their report, a case application of the proposed method was simulated for the infrastructure projects in Spain, which resulted in a list of 30 macro-indicators for assessing the sustainability of an infrastructure project. The methodology proposed by Fernández-Sánchez and Rodríguez-López is quite general, so it can be applied to other types of construction projects. Two other similar works for the identification of sustainability indicators of construction projects, but using different approaches, were conducted by Shen et al. (2010) and Yu et al. (2018), respectively. Shen et al. (2010) collected the feasibility study reports of 87 construction projects from China to identify 34 attributes (indicators) related to the sustainability of four types of construction projects. Yu et al. (2018) identified 31 sustainability indicators of construction projects via domain expert interviews and important research literature surveys. A similar methodology adopted by Fernández-Sánchez and Rodríguez-López (2010), Shen et al. (2010), and Yu et al. (2018) will be employed to conduct the current research to develop a Non-urban Land Development Project Sustainability Evaluation Indicator Framework (NULP-SEIF) for management of land development projects. Despite the existing indicator frameworks developed discussed previously, they were essentially suitable for civil or building construction projects, rather than for land development. Most of them didn't consider the government regulations, the characteristics and requirements of non-urban region land development. As a result, this research aims at fulfilling the above-mentioned needs.

3 Development of the Proposed Non-urban Land Development Project Sustainability Evaluation Indicator Framework (NULPSEIF)

3.1 Methodology

The primary objective of a non-urban land development project is to transform a lower value non-urban land (e.g., rural areas or planting fields) into a higher value habitat land (residential communities or industrial parks). Such types of projects are highly restricted by the government regulations as they involved tremendous interests (value-adding of lands) and impacts to the environment (reshaping the lands) (Ho 2019). As a result, in addition to the adopted methodology (Rodríguez-López 2019; Shen et al. 2010; Yu et al. 2018) addressed at the end of the previous section, the government policy documents and the regulations should be considered while developing the proposed NULPSEIF. Moreover, public opinions should also be elicited to ensure the feasibility and social fairness of land development. The 9-step research methodology is described in Table 1.

Table 1 Steps of research methodology

Step	Item
1	Review of relevant works
2	Collect government policy, laws and regulations which related to sustainable development
3	The preliminary sustainability assessment indicators relevant to non-urban land development were collected from Step (1) and (2), and an initial framework of NULPSEIF
4	A focus group of 6 domain experts in sustainable land development for non-urban areas was organized to carefully review the initial NULPSEIF and vote for the appropriate indicators
5	By reviewing the focus group of Step (4) suggested to add three new indicators that should be included
6	A two-step questionnaire survey was conducted with professionals (of land development and construction) and other stakeholders (the community residents, critical opinion leaders, and representatives of the community administration committees), respectively
7	Response data from step (6) were collected to determine the finalized SAIs
8	An operational NULPSEIF was attained, which comprises of four levels: pillars, aspects, indicators and sustainability assessment items
9	A real-world non-urban land development project was selected as case study to test the applicability of the proposed NULPSEIF

3.2 *The Proposed NULPSEIF*

3.2.1 Framework of NULPSEIF

Due to paper limitation, only partial environmental indicators of the obtained NULPSEIF are shown in Table 2. In Table 2, there are 4 levels in the NULPSEIF, including 3 Pillars, 10 Aspects, 20 Indicators, and 62 Sustainability Assessment Items (SAIs).

The definition of the abbreviated notations for all SAIs of NULPSEIF are referred to Table 3. Due to paper size limitation, it is impossible to provide detailed description of all criteria for the 62 SAIs. However, brief description for sample SAIs of Table 2 are explained as follows: (1) the Building Coverage Ratio (BCR) should be <40% and the Building Bulk Ratio (BBR) should be <120% according to the non-urban region building regulation; (2) there should be an energy efficiency plan (EEM), usage of recycled products (URP = Y), water saving measure (WSM = Y), and water recycle facility (WRF = Y) according to the EEWH Green Building certification requirements of Taiwan (http://gb.tabc.org.tw); and (3) it should ensure the balance of cut and fill of soils (BCF = Y) due to the SPECs of the ecological construction method (https://pcces.pcc.gov.tw).

Table 2 Definition and criterion of the NULPSEIF (partial of environmental indicators)

Pillar	Aspect	Indicator	SAI*	Definition of SAI	Abbr.	Criterion
E Env.	E1 resource	E1a land	E1a1	The building coverage ratio should be ≤40%	BCR	≤40%
			E1a2	The building bulk ratio should be ≤120%	BBR	≤120%
		E1b material	E1b1	There is usage of recycled products	URP	Y
			E1b2	Ensure the balance of cut and fill of soils	BCF	Y
			E1b3	There is usage of durable products	UDP	Y
		E1c energy	E1c1	There is energy efficiency plan	EEM	Y
		E1d water	E1d1	There is water saving measure	WSM	Y
			E1d2	There is water recycle facility	WRF	Y

*SAI—Sustainability assessment item

Table 3 List of indicators and SAIs

Pillar	Aspect	Indicator	SAI
E	E1	E1a (Earth)	E1a1 (Building coverage ratio, BCR) E1a2 (Building bulk ratio, BBR)
		E1b (Material)	E1b1 (Usage of recycled product, URP) E1b2 (Balance of cut and fill of soil, BCF) E1b3 (Usage of durable product, UDP)
		E1c (Energy)	E1c1 (Energy efficiency plan, EEM)
		E1d (Water)	E1d1 (Water saving measure; WSM) E1d2 (Water recycle facility, WRF) E1d3 (Water storage facility, WSF)
	E2	E2a (Air pollution)	E2a1 (Air pollution reduction measure, ARM) E2a2 (Air pollution reduction facility, ARF) E2a3 (wheel wash facility, WWF) E2a4 (Watering and air filter, WAF)
		E2b (Water pollution)	E2b1 (Availability of drainage system, ADS) E2b2 (Availability of sewage system, ASS)
Pillar	Aspect	Indicator	SAI
E	E2	E2b (Water pollution)	E2b3 (Availability of sewage treatment system, AST) E2b4 (Availability of settling basin, ASB) E2b5 (Sewage treatment facility, STF) E2b6 (Sludge reduction and recycle, SRR)
		E2c (Noise)	E2c1 (Noise protection device, NPD) E2c2 (Usage of low noise equipment) E2c3 (Installation of noise barrier, INB)

(continued)

Table 3 (continued)

Pillar	Aspect	Indicator	SAI
		E2d (Solid waste)	E2d1 (Waste generation reduction measure, WGR) E2d2 (Waste reduction measure, WRM) E2d3 (Usage of waste reduction method, UWM) E2d4 (Efficient material management measure, EMM) E2d5 (Site classification and recycle, SCR) E2d6 (Resource recycle field, RRF)
		E2e (Toxic chemicals)	E2e1 (Environmental toxic chemicals, ETC) E2e2 (Substitution to toxic chemicals, STC)
		E2f (Development supervision)	E2f1 (Review of development plan, RDP) E2f2 (Environment impact assessment, EIA) E2f3 (Soil and water conservation, SWC) E2f4 (Miscellaneous engineering permit, MEP) E2f5 (Earthquake potential assessment, EPA) E2f6 (Environmentally sensitive area, ESA) E2f7 (Cultural assets survey, CAS) E2f8 (Protection of labor safety, PLS) E2f9 (Construction audit and inspection, CAI), E2f10 (Construction risk assessment, CRA) E2f11 (Lifecycle assessment, LCA)
	E3	E3a (Ecologically sensitive area)	E3a1 (Biodiversity, BID) E3a2 (Usage of ecological method, UEM) E3a3 (Protection of native plant, PNP)
		E3b (Green planting)	E3b1 (Landscaping, LSP) E3b2 (Planting cover, PCV) E3b3 (Planting and conservation plan, PCP)

(continued)

Table 3 (continued)

Pillar	Aspect	Indicator	SAI
S	S1	S1a (Living)	S1a1 (Pedestrian and bicycle friendliness, PBF) S1a2 (Barrier-free access, BFA) S1a3 (Consideration to aging people, CAP) S1a4 (Access free facility, AFF) S1a5 (Adaptation to aging society, AAS)
	S2	S2a (Preservation of cultural assets)	S2a1 (Protection of cultural assets, PCA)
	S3	S3a (Residence participation)	S3a1 (Participation of local residence, PLR) S3a2 (Acceptance of user and local residence, AUL)
		S3b (Neighborly activities)	S3b1 (Neighborhood cleaning activity, NCA) S3b2 (Prevention damage of neighboring house, PDN) S3b3 (Initiating neighborly activities, INA)
	S4	S4a (Self-liquidation)	S4a1 (Interest of stakeholders, IOS) S4a2 (Feedback fee to land development, FLD)
EC	EC1	EC1a (Construction measures to minimize land exhaustion)	EC1a1 (Minimum slope excavation, MSE) EC1a2 (Site preparation along terrain, SPT), EC1a3 (Restriction of construction site, RCS);
	EC2	EC2a (Financial benefits)	EC2a1 (Project financial plan, PFP) EC2a2 (Land value increase, LVI) EC2a3 (Project benefit vs. cost, PBC)
		EC2b (Employment benefits)	EC2b1 (Employment before operation, EBO) EC2b2 (Employment after operation, EAO)

3.2.2 Verification of Applicable SAIs

In order to verify the candidate SAIs in the proposed of NULPSEIF, a two-step questionnaire survey was conducted to 65 (35 responses, 53.8%) professionals (of land development and construction) and 30 (15 responses, 50%) other stakeholders (the community residents, critical opinion leaders, and representatives of the community administration committees) to determine the finalized SAIs, using the average importance value (AIV) $\geq$ 2.5 as the acceptance criterion in order to include more responses to take into account more opinions of the stakeholders. Finally, the 3-pillar, 9-aspect, 20-indicator, 68 SAIs framework of the proposed Non-urban Project Sustainability Evaluation Indicator Framework (NULPSEIF) is attained.

3.3 Applicable Phases for SAIs in Project Lifecycle

The proposed framework of NULPSEIF comprises of totally 68 SAIs in four different levels. However, the 68 SAIs are not readily applicable throughout the 8 phases of the project lifecycle: Initialization (Init.), Planning (Plan.), Procurement (Proc.), Construction (Cons.), Completion (Comp.), Operation (Oper.), Rehabilitation (Reha.), and Demolishing (Demo.). As a result, the second phase of focus group meetings were held to assess the applicability of the 68 SAIs. Finally, a consensus was reached to attain the applicable phases for the 68 SAIs in the project lifecycle is shown in Table 4. Due to the limitation of the paper, only the sample SAIs of Table 2 (partial of environmental indicators) are depicted.

Table 4 Applicable phases for SAIs in project lifecycle (partial of environ. indicators)

SAI	Project phase							
	Init.	Plan.	Proc.	Cons.	Comp.	Oper.	Reha.	Demo.
E1a1 BCR	●	●		○	△	△		
E1a2 BBR	◎	●		○	△	△		
E1b1 URP		●	●	○	◎	○		
E1b2 BCF		●	●	●	◎	○		
E1b3 UDP		○	◎	●	◎	○		
E1c1 EEM		△		●	○	△		
E1d1 WSM		◎	◎	◎				
E1d2 WRF		△	○	●	◎	○		

Note: (1) Legend: ●—Critical; ◎—Important; ○—Medium; △—Minor
(2) Abbreviations refer to Table 2

Table 5 The project sustainability level (PSL) of the project

PSL	Passed items		
	11 critical items	23 important items	34 medium items
Disqualified	Partially (<100%)	–	–
Bronze	100%	–	–
Silver	100%	19 items (80%)	–
Gold	100%	21 items (90%)	28 items (80%)
Diamond	100%	100%	100%

3.4 Assessment of Project Sustainability Level (PSL)

For different phases of the project lifecycle, different combination of SAIs are selected to be assessed as indicated in Table 4. There are three sets of SAIs in Table 4: (1) 11 Critical SAIs; (2) 23 Important SAIs; and (3) 34 Medium SAIs. Should the selected indicators satisfy the predefined criteria in Table 2, they are counted as '1'; otherwise counted as '0'. After assessing the SAIs, the Project Sustainability Level (PSL) of the project can be determined according to Table 5.

In Table 5, 5 different Sustainability Levels (SLs) are assessed for a land development project based on the consensus of the focus group meetings with the domain experts: (1) when there is any item unpassed in the 11 Critical items, it is considered dis-qualified as a sustainable land development project; (2) if all 11 Critical items passed but not carry any important item, it is considered as Bronze SL; (3) if all 11 Critical items and additional 19 Important items (80% of all 23 items) passed, it is considered as Silver SL; (4) if all 11 Critical items, 21 Important items (90% of all 23 items), and 28 Medium important items (80% of all 34 items) passed, it is considered as Gold SL; (5) if all 11 Critical items, 23 Important items, and 34 Medium items passed the criteria, the land development project is considered Diamond SL.

4 Demonstrated Application

4.1 Description of Case Project

In order to demonstrate the applicability of the proposed NULPSEIF, a non-urban land development project located in Shian-Shang District, Hsinchu City, Taiwan, was selected as a case study. The project site area covers 15 hectares of non-urban rural land. The land was a hill covered by grass and trees. Due to the fast growth of Hsinchu Science Park, more residential housings are demanded in the local areas. To

Fig. 1 Aerial view of the case project site

meet the partial demand of the housings, a land development project was proposed by the developer. Figure 1 shows the aerial view of the project site.

4.2 Assessment of SAIs

By applying the proposed NULPSEIF, results of assessment for the three sets of SAIs are shown in Tables 6, 7 and 8.

Applying the criteria of Table 2 to assess the SAIs of the project, the evaluation results are as follows: (1) Partial passed in the 'Critical SAIs'—1 disqualified item, S1a4 (AFF)—'Access free facility'; (2) 3 disqualified items in the 'Important SAIs'—E2f10 (CRA)—'Construction risk assessment', E2f11 (LCA)—'Lifecycle assessment', S1a5 (AAS)—'Adaptation to aging society'; and (3) 5 disqualified items in the 'Medium SAIs'—S2a1 (PCA)—'Protection of cultural assets', S3b3 (CNE)—'Initiative to clean neighborhood environment', S4a1(IOS)—'Interest of stakeholders, E2f7 (CAS)—'Cultural assets survey', E3a3 (PNP)—'Protection of native plant'. The criteria and PSL assessment for the case project are shown in Table 9.

According to Table 5 the PSL of the project is considered 'Disqualified', since there is 1 disqualified SAI, S1a5 (CAP)—'Consideration to aging people', in the

Table 6 Assessment result of 11 critical SAIs

E2f9	E2b1	EC1a2	E3b2	E2f8	S1a2	EC2a2	E2a4	E3b2	EC1a1	S1a4
Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N

Table 7 Assessment result of 23 important SAIs

E2a2	E2a3	EC2a3	E2b4	S1a3	E2f10	EC2a1	E2c3	E2f1	E2f2	S1a5	EC1a3
Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y
S3b1	E2b3	E2f3	E2d5	S3a2	E2f4	E3b1	E1a1	E2f11	E1b2	EC2b2	–
Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	–

Table 8 Assessment result of 34 medium SAIs

E2a1	E2b5	E2d2	E2e2	E3b3	S3a1	E2b2	E2d1	E1b1	E2e1	E1a2	EC2b1
Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
S4a1	E2d4	E1d2	E2f5	S3b3	E2b6	E2c2	E2d6	E1b3	E2c1	E2f6	S2a1
N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
E1c1	S1a1	S4a2	E2d3	E1d1	E2f7	E1d3	E3a3	E3a1	E3a2	–	–
Y	Y	Y	Y	Y	N	Y	N	Y	Y	–	–

Table 9 Criteria and PSL assessment for case project

	11 critical items	23 important items	34 medium items
Unpassed SAIs	S1a4	E2f10, E2f11, S1a5	S2a1, S3b3, S4a1, E2f7, E3a3
% passed	91% (10/11)	87% (20/23)	85% (29/34)
PSL	*Dis-qualified (Non-sustainable)*		

'Critical SAIs'. This is due to the lack of Access-Free Facilities (AFF) design in the original plan during the Planning phase of the project. Such a finding was reported to the designer, a new development plan with full consideration of AFF facilities was developed and the disqualified item was then eliminated. It results in a 'Silver' PSL, as there are 20 qualified SAIs in the 'Important SAIs'. From the demonstration, it was found that the proposed NULPSEIF provides a very useful tool for the land developer to conduct a sustainable land development project. It does not only evaluate the overall sustainability of the land development process, but also provides the direction to improve the disqualified SAIs.

5 Conclusions and Recommendations

This paper proposes a Non-urban Land Development Project Sustainability Evaluation Indicator Framework (NULPSEIF) via the reviews of legal and theoretical backgrounds from literature, focus group meetings, domain expert surveys, and case studies. Finally, a real-world non-urban land development project was selected to verify the applicability of the proposed NULPSEIF. Major findings of the research are concluded as follows:

(1) An operational Non-urban Land Development Project Sustainability Evaluation Indicator Framework (NULPSEIF) is proposed comprising of four levels: Level 1—three main pillars; Level 2—9 aspects; Level 3—20 indicators; and Level 4—62 sustainability assessment items. The proposed NULPSEIF does not only evaluate the overall sustainability of the land development process, but also provide the direction to improve the disqualified SAI. The proposed NULPSEIF is verified via focus group meeting with domain experts in land development and question surveys with professional and non-professional stakeholders;

(2) The result of this research provides not only a useful tool to the owners and participants of non-urban land development projects to evaluate the overall project sustainability, but also the right directions to improve the sustainability of land development projects.

Although the proposed NULPSEIF provides a useful tool for evaluating the sustainability of a non-urban land development project, it should be noted that the

NULPSEIF was developed based on the local regulations and requirements of Taiwan. In addition to this limitation, extra efforts and costs are required to collect the required information, some domain expert judgements are also needed in determining the values of SAIs for the assessment of NULPSEIF. Even though, the same procedure and methodology can be adopted for developing the sustainability assessment methods of land development project in other countries.

Future directions after this research can be pursued after this research include: more applications of the proposed NULPSEIF to other non-urban land development projects to verify and fine-tune the SAIs; development of other types of land development projects, such as urban land development projects, industrial park land development projects, etc.; and a dynamic monitoring system with systematic adjustment strategies to avoid non-sustainable land development activities is also worth of future efforts to ensure the sustainable development activities for the community and the country.

Acknowledgements This research project was funded by the Ministry of Science and Technology, Taiwan, under project No. MOST 103-2621-M-216-004. Sincere appreciations are given to the sponsor by the authors.

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Practices of Sustainable Development in Higher Education Institutions: Case Study of Al-Zaytoonah University of Jordan

Subhi M. Bazlamit, Turki I. Al-Suleiman (Obaidat) and Hesham S. Ahmad

Abstract Al-Zaytoonah University of Jordan (ZUJ) has recently carried out a large-scale sustainable energy project in an attempt to reduce its operational expenses. This comes as the university is seeking a sustainable campus in the areas of water, energy use and waste management. A number of sustainable development projects have been completed in the last four years and their benefits are just being realized. This paper will focus on these projects and cover their impact in terms of energy savings, sustainability advancement and environmental preservation. An economic analysis of energy savings that resulted from the installation of photovoltaic panel is also presented. In addition, the university had also adopted an irrigation system which utilizes reclaimed water from its wastewater treatment plant. The university also uses a network of dripping perforated pipes to water the vegetation on its campus. The education and awareness of sustainable development is also being disseminated among the students and faculty to create a partnership in sustainable development throughout the campus aimed at implementing a solid waste management plan. The university had also invested in energy efficient light fixtures, and smart appliances in the air conditioning and heating. This paper will detail the practices of the university in this sustainable development transformation. This research is intended to document sustainable development engineering projects which encompasses lean management and aimed at reducing cost and waste.

Keywords Energy · Sustainable development · Smart appliances · Waste management

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_2

1 Introduction

Sustainable development was defined by the United Nations Development Program (UNDP) as the universal call to implement actions that end poverty, save the planet and ensure that people live in peace and prosperity (https://www.jo.undp.org/content/jordan/en/home/sustainable-development-goals.html). UNDP had listed the goals of sustainable development in 17 objectives, the one related to higher education is the fourth one (Quality Education). During the past decade, Jordan has faced many challenges including the global financial crisis and the sudden change in the population number caused by the influx of refugees fleeing from neighboring countries (Fakhoury 2017). However, in 2018 Jordan has achieved good results in the Sustainable Development Goals (SDG), ranked 80th worldwide and 5th in the Arab world (https://www.jordantimes.com/news/local/study-ranks-jordan-80th-world-5th-region-sdg-index).

Campus sustainability has gained great interest from the higher education institutions globally to pursue the development of long-range plans after the increasing awareness of the universities' influence on the environment (Amherst College News releases 2018). Such plans are intended to reduce waste and promote use of renewable energy resources and become fully divested from the use of fossil fuels (Stephens et al. 2018). Others aim to reduce emissions and reach self-sufficiency to produce its needs of food (Kim et al. 2015). Worldwide, many institutions seek to reach carbon neutrality through reliance on renewable energy sources and Zero Emission Vehicles (Richert 2016).

2 Literature Review

Sustainability development in higher education institutions is being carried out by many institutions in varying approaches. Alshuwaikhat and Abubakar (2008) proposed a framework of an approach to enhance achieving campus sustainability. This framework was designed to overcome the limitations of previous environmental management practices in the universities. This method encompasses the integration of three strategies, which are: Environmental Management System (EMS); public participation and social responsibility; and promoting sustainability in teaching and research.

Cole (2003) designed a framework for assessing sustainability on university campuses by using a participatory action research approach. A team was composed to build a sustainability assessment methodology depending on previous sustainability assessment methodologies, indicator selection criteria, and performance benchmarking tools from government, business, education and community organizations. This work produced a set of over 175 indicators, short- and long-term performance benchmarks of each indicator, and an aggregation process leading to a campus sustainability index. The resulting methodology was called the Campus Sustainability Assessment Framework (CSAF).

Emanuel and Adams (2011) used a method to assess sustainable development in university campuses by investigating college students' perceptions of campus sustainability. The difference between college students' perceptions in two different universities was tested based on three questions: are students concerned about the present/future? What do students know about sustainability? Who is responsible for sustainability? A random sample of 406 undergraduate students was surveyed. The results showed that sustainability programs and practices are being implemented on a number of college campuses. The survey showed that students are highly concerned about wasteful consumption and pollution. The responses showed that there is a difference in the willingness to participate in sustainable practices among students.

3 Methodology

The aim of this study is to provide details and evaluate the impact of sustainable development practices in higher education institutions. A case study approach was adopted with a combination of quantitative and qualitative research methods for data collection. The quantitative data was collected from the system database of the studied organization, while qualitative data was collected from the archived files and reports, and interviews with employees from the university departments. The case study has been carried out in Al-Zaytoonah University of Jordan (ZUJ) to investigate the area of sustainable development in an attempt to capture lessons learnt and best practices. The case study was also used to ascertain motivations and challenges for applying systems for sustainable development.

Normally, case studies aim at studying the reasons why a decision or a set of decisions has been adopted, and the procedure and results of applying such decision (Schramm 1971). Case study approach is one of several strategies of doing research which is highly comprehensive, and recommended when dealing with "how" and "why" questions, having little control over events, and investigating a current phenomenon within real-life context (Yin 2003). Since this research aims to investigate why sustainable development practices have been adopted and how they were applied in a context of a selected higher education institution, the case study approach has been adopted.

The main objectives of this study can be summarized as follows:

1. Review of related practices for sustainable development in other higher education institutions.
2. Describe and evaluate sustainable development practices in the organization of the case study.
3. Provide recommendations for future studies and for further development of the sustainable development in the organization.

4 Case Study

4.1 Introduction

Sustainable development plans and applications at the university were motivated by the support of university management, and regulations of the Jordanian Ministry of Higher Education. In addition, the pressure from governmental environmental protection agencies and the motivation to achieve a better global rank in the UI Green Metrics locally and regionally.

ZUJ historically had fared well among peer institutions at UI Green Metrics after being globally ranked 265 in 2018 compared to the rank of 282 in 2017. To ensure sustaining its global rank, the university focused on implementing international standards in the fields of environment and sustainable development especially in work environment, infrastructure, renewable energy, solid and liquid waste management, water consumption optimization, transportation and recruiting education in sustainable development.

4.2 Electrical Energy

In 2016, the university installed a system of photovoltaic solar panels at a cost of about 1,200,000 JOD ($1,700,000) with an expected payback period of about 2 years and 2 months. It mainly produces 1754 kWh of solar energy and about 3 kWh of wind power to support its annual consumption which is estimated to be around 2,500,000 kWh per year. The solar panels are in the form of roof top farms mounted on the buildings around campus as shown in Fig. 1.

In addition, the university started to use energy efficient appliances for heating, air conditioning, and LED lighting in many buildings around its campus. Eventually, the university is in the process of having all electric appliances and devices equipped with energy saving features that reduce energy consumption.

The average electricity usage is about 303 kWh per person per year. The university is almost electricity self-sufficient and relies mainly on renewable energy resources to meet the demand for electricity on campus. On average, the university consumes about 10 percent of its electricity from the main grid which is generated from non-renewable sources. This corresponds to a net carbon print of about 150 metric tons annually at a rate of 0.018 metric ton per person per year. The actual monthly consumption from the electricity main grid and production of electricity from the solar panels are presented in Figs. 2 and 3. Figure 2 shows the electricity consumption and production in the period from January 2013 to February 2018. The figure shows that solar panels started to generate electricity since May 2016. From that time until February 2018, the electricity grid system required that all the electricity generated by solar panels should be exported to the power grid and all the consumed electricity should be imported from the power grid. A new system applied since March 2018

Fig. 1 Solar panels mounted on building roofs

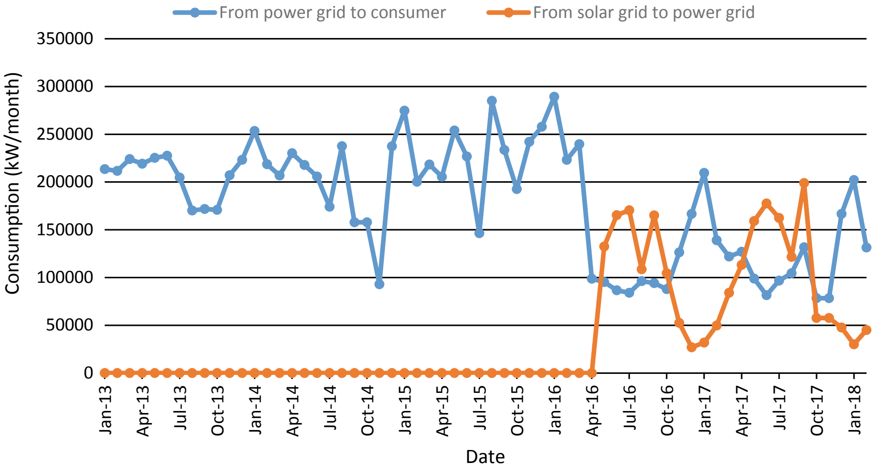

Fig. 2 Monthly electricity consumption and production (old system)

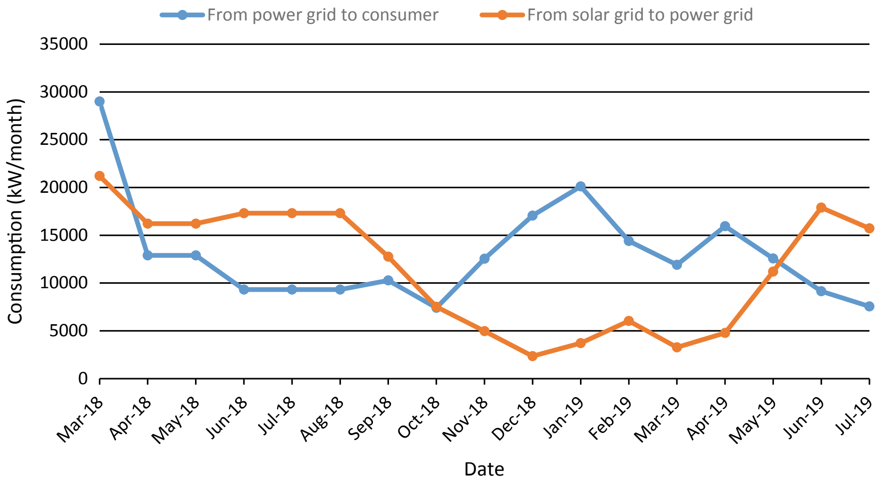

Fig. 3 Monthly electricity consumption and production (new system)

allowed the usage of electricity generated by the solar panels directly by the end users as shown in Fig. 3.

Also, Fig. 2 shows that the electricity consumption from the power grid has also minimized since April 2016 due to the university's strategy toward changing most of existing lighting systems by energy saving systems such as LED lighting. Figure 4 presents the total monthly consumption of electrical power in the university for the time period from January 2013 to July 2019 by subtracting the monthly production

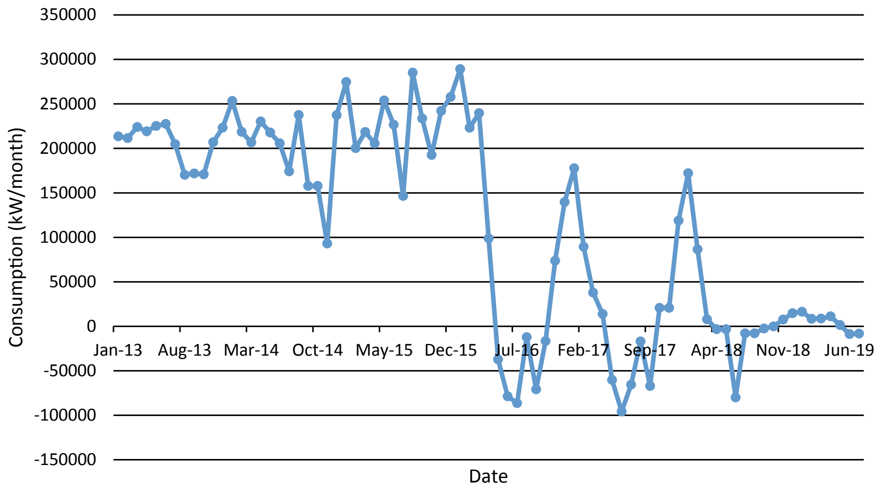

Fig. 4 Total sum of the monthly consumption of electrical power

of solar panels from the electricity imported monthly from the power grid. Negative values showed that the monthly production of solar panels is more than the monthly consumption from the power grid.

The university in its efforts to promote sustainability development is hoping to generate some revenues from charging stations for electric vehicles. These vehicles will also reduce the carbon footprint on campus. In addition, the university will employ incentives for preferential parking and low parking fees for eco-friendly vehicles. Such incentives are employed by some higher education institutions in the US, for example Duke University.

4.3 Water Resources

The water resources in ZUJ are coming from two resources: an artesian well used mainly for potable water, and treated waste water used for irrigation. Rainwater harvesting projects are still under planning. The water is tested and treated prior to pumping on a daily basis and is subject to universal drinking and irrigation water standards. The university also employs its own sewage treatment facility which treats sewage water and reroutes it into the irrigation system of the university. Economic water management systems are used through the university campus such as using economy water tabs, toilet flushes, and drip irrigation networks.

At ZUJ the campus landscape areas were planted with types with low consumption of irrigation water and/or with economic value. In all, the campus has about 1660 trees distributed around the campus and has a natural grass stadium with a green area of 5200 m^2. A good percentage of the trees in the university are olive trees, which have low water consumption rate and have good economic value for producing olive oil. On the average, the volume of reclaimed water used in the university campus is about 120 cubic meters of reclaimed water every week. Example photos of the university landscape are shown in Fig. 5.

Information about the total annual expenditure on water since the year 1997 was collected from the university financial department and illustrated in Fig. 6. In 1997, the cost of spending on water was high because the university was dependent on outsourcing with a high rate of water (1 JOD/m^3), 1 JOD equals about 1.4 USD. Since 1998, the university started to depend on water produced by an artesian well with a rate of 0.25 JOD/m^3. After 2014, the rate of the production of artesian water was increased to 0.5 JOD/m^3.

To estimate the quantities of annual potable water consumption, the total financial expenditure was divided on the rates of water production on each year. The results are presented in Fig. 7. The results show an increase in the water consumption during the time period presented in the figure. The increase of water consumption can be related to the growth of the university in terms of the size of its buildings, landscape areas, and the number of students and employees. According to the university's financial manager, some high values of annual water consumption (years 2003–2005) can be

Fig. 5 Example photos of the university landscape

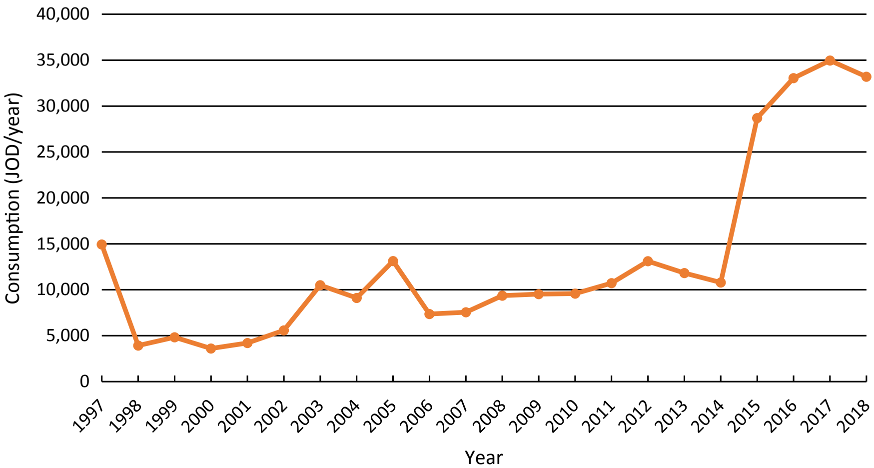

Fig. 6 Total annual financial consumption on potable water

related to the condition of having many construction projects under implementation at these years. The application of water consumption reduction started to show effects only in 2018.

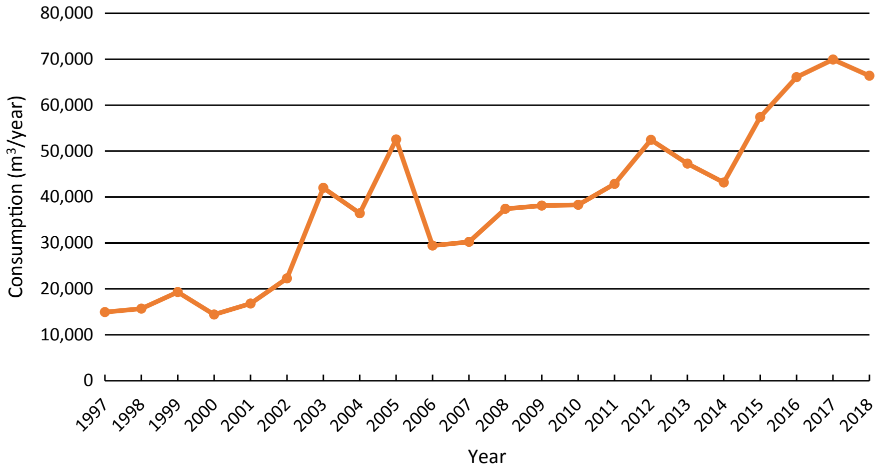

Fig. 7 Estimation of the annual consumed quantities of potable water in the university campus

4.4 Waste

The university implemented introductory partial waste sorting and recycling programs aimed at reclaiming aluminum cans, glass bottles and plastics. The university also is keen on establishing reduction programs of paper and plastic waste on campus. Most of the internal paper work is done electronically through soft document transfer and archiving throughout the campus operating academic and nonacademic entities.

In addition, organic waste from tree trims and cuttings are stockpiled for possible reuse as mulch and pit moss for vegetation. The university is contemplating the use of a wood chipper for this purpose. Inorganic waste including toxic medical waste from the nursing and pharmacy faculties are currently handled by a local specialized contractor and disposed off campus.

4.5 Transportation

The university runs a shuttle bus service to the residential areas within its vicinity to bring students to campus. The campus itself is nonresidential and the students use the university buses twice a day for their round trips. These buses are mostly operated using diesel fuel and are well maintained and checked periodically for emissions as a requirement for licensing by the local traffic department.

The number of vehicles entering the campus on daily basis is between 500 and 600 vehicles including employee vehicles. The ratio of vehicles on campus is about 0.075 vehicles per person per day. Campaigns to encourage bicycle use by students and employees are underway. Zero Emission Vehicles (ZEV) are rarely seen on campus and an institutional incentive may be necessary to increase their use by employees since they are economic vehicles and the university has an abundant source of electricity to charge them for a nominal fee or for free. This may become one of the initiatives of the university to reduce parking space requirements on campus since these ZEV are smaller in size. Pedestrian paths are available and well maintained during inclement weather conditions.

4.6 Education

The university spends annually about 5% of its operating budget to support research activities in various scientific areas. The funding offered by the university also covers sustainability research. Based on historical records, the university dedicates about 12% of its entire research allocations towards sustainability research.

Sustainability is very well covered in the courses offered by the different disciplines of the university. In addition, university staff had published several papers in sustainability research topics. The university encourages student initiatives aimed at sustainability education and awareness and is in the process of formally establishing a sustainable development administrative entity to oversee the achievement of sustainability goals in the strategic plan of the university.

4.7 Security and Safety

During the last few years, the university managed to effectively improve the level of security and safety in the university campus. The installation and updating of security cameras around campus was very useful to recognize the threats and take preventative actions. Furthermore, electronic access control systems were applied to monitor and control who is entering and exiting the university. The installed card readers has limited the entrance only to authorized people and provided useful identification information. The incidents of student violence that had existed for years have almost disappeared on the university campus in recent times.

5 Conclusions

Al-Zaytoonah University of Jordan (ZUJ) has recently made significant achievements in the area of sustainable development in order to optimize its operational expenses and reduce the negative effects on the environment and people. The utilities in forms of electricity and water/wastewater comprise a significant portion of the operational expenses. By installing electricity solar panels, as well as by the application of LED lighting, the university had made great improvements in the area of sustainable development.

In the area of water and wastewater, the university applied a drip irrigation system, treatment of waste water for irrigation use, and the use of water efficient appliances. Based on these improvements, the university has moved up in the GreenMetric ranking to rank 266 in 2018. GreenMetric ranking is used by the university as an external assessment metric to evaluate the extent of sustainable achievement of the university. The goal is to be self-sufficient in energy and water, and to reduce CO emissions.

The university realizes that the accomplishments in the area of sustainable developments are still in its beginning and still need more time and effort to enhance. The smart growth of this sustainable development requires steady efforts in the areas of water saving and management. In the area of transportation more efforts are required to motivate the use of hybrid and electric vehicles to become the most common choice for future movement in and around the campus. The use of solar collectors for domestic water use can be used in the future to make hot water available for very low cost. Moreover, the use of solar conditioning systems for space cooling and heating will be a much better option especially when compared to conventional air conditioning and heating systems. The establishment of periodic and efficient energy audits to identify areas of possible improvement aimed at enhancing the potentials of sustainable development.

Although the university has made achievements in the sustainable development, there are still drawbacks in the existing system that require development in the future. More efforts are needed on applying systems for the reuse of grey water and rain water harvesting. In winter, the university wastes a significant amount of rain water and treated wastewater, that if efficiently collected can save great amount of irrigation water used in other seasons. More efforts are also needed on the application of water efficient systems in the building to reduce the consumption and waste of water. The uses of electrical efficient appliances still need more efforts to be installed in all the university campus. More effective use of electrical smart systems, motion sensors and LED lighting is still needed. Vehicle charging stations for electric and low emission vehicle were planned to be implemented in future, similar for example to the stations implemented in Duke University (https://parking.duke.edu/parking/electric-low-emission-vehicles).

It is anticipated that this study will aid the application of sustainable development practices in other higher education institutions. This will have social and environmental impact as a catalyst for improving organizational culture.

Acknowledgements The authors would like to acknowledge the valuable contributions of Mr. Emad Hamdan, the financial manager of Al-Zaytoonah University of Jordan, who helped to provide important data and had contributed vital statistics to this study.

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The Adoption of Building Environmental Performance Assessment Methods in the UAE Built Environment

Amna Shibeika, Batoul Hittini and Tasneem Abdel Raheem

Abstract Current research in sustainable development of the built environment acknowledge the role of building environmental sustainability assessment methods as market changers for sustainable buildings' design and construction. While most of the existing studies are focused either on developing and comparing assessment methods, or on assessment methods' performance outcomes, this research addresses how assessment methods are adopted in practice. To address this, a pilot study was designed with desktop study of literature and regulation documents, as well as 7 guided in-depth interviews with 8 professionals engaged with assessment methods in the UAE. While, the spread of sustainable design and construction practices is motivated by mandating the assessment methods for all projects, but, with various rating requirements for government and private development projects, the analysis has revealed the continuous development of communication channels for the spread of sustainable design and construction practices between the regulative bodies with: (a) clients through raising awareness activities, (b) projects professionals through training and technical support, and (c) suppliers of sustainable systems and products through quality assurance and certification procedures. Finally, the paper discusses these findings and outlines possible impact on theory, policy and practice.

Keywords Adoption · Building assessment · Innovation · Sustainability · UAE

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_3

1 Introduction

Sustainability is one of the major challenges around the world nowadays. Globally, UAE has one of the highest energy consumptions per capita where buildings are considered the primary consumer of energy, water and materials, this could be attributed to the exponential growth for the UAE's built environment during the last three decades, furthermore, this profile is in line with previous research which found that high-income countries with high Human Development Index (HDI) *has disproportionally larger increase in Ecological Footprint* (Moran et al. 2008). However, since the late 1990s the UAE has started to adopt a pro-active approach for addressing environmental issues by establishing administrative capacities such as the Environment Agency to address climate change and launching pilot projects such as "Masdar City" to raise awareness, which has placed the country at the forefront of environmental sustainability policy and development for the Gulf Cooperation Council (GCC) region (Reiche 2009). Moreover, current UAE sustainability policy and regulations reflects its own social, economic, environmental and governance needs and dynamics, and addresses the nature of the country as high-income emerging economy which doesn't rely on taxation or financial donor packages by international agencies to meet sustainable development goals (O'Brien et al. 2007).

While sustainability is defined to address three main pillars: environment, economy and society, this definition is often extended to include governance. Sustainability assessment is commonly associated with the derivation of indicators to simplify and break down those pillars into smaller units for ease of analysis to better inform evaluation and decision-making (Bond and Morrison-Saunders 2011). Currently, there is a plethora of assessment methods across the world and a wide array of rating schemes which has been developed with different purposes and features to enhance buildings' sustainability, however, it is unlikely to prepare environmental criteria that is pre-designed and sufficient for global use without further adjustments. Examples of such adjustments include using geographically adapted database (Ding 2008), as such, sustainability assessment methods could be considered as an innovation that is context specific, which calls for research to consider the dynamics of adopting this innovation in development projects from a transformational perspective rather than only their performance assessment and measurement outcome (Cole 2005).

In order to understand the role of assessment methods as innovation and market changer, it is paramount to understand the processes and dynamics of sustainable development projects. Previous research has found that project managers and directors' leadership helped drive targets down the supply chain leading to improved understanding and better realisation for the concept of sustainability, furthermore, engaging with suppliers in early stages of design was found to add real value, however, it is often difficult because strict procurement processes need to be adhered to (Epstein et al. 2011). Moreover, challenges facing sustainability adoption where related to the temporary nature of construction projects, and the fact that engineers sometimes join the project at later stages after sustainability conceptualisation and targets have already taken place (Abraham and Gundimeda 2018). Additionally, clients' lack of understanding for the benefits of Whole Life Costing (WLC) continuously influence their decisions when adopting sustainability (Opoku and Ahmed 2014). These are some of the important issues which need to be investigated in order to understand the adoption of assessment methods in the built environment development projects.

The aim of this research is to investigate how assessment methods are adopted in practice; this aim is achieved through a pilot study of the adoption of assessment methods by the UAE built environment. The paper is organized as follows: The following section outlines the approach and tools for the pilot study. That is then followed by the presentation of the analysis and discussion of the findings in relation to communication channels for the adoption of assessment methods as well as some of the captured projects' dynamics and the assessment process. Finally, the paper concludes with outlining the possible impact of this pilot study on theory, policy and practice.

2 Research Method

The research reported here is part of an ongoing research project which addresses innovation and sustainability discourse and practices which are rapidly emerging in the UAE. The research adopts interpretivist and contextualist approach (Pettigrew 1990) to investigate the adoption and diffusion of assessment methods in the UAE built environment. While most of the existing studies are focused either on comparison studies for various assessment methods, or on the outcomes in performance as the result of the assessment process, this research primarily focuses on the assessment process itself and its intersection with project development, while attending to the idea that assessment methods provide objective evaluation and assessment of the performance of the developed facility in relation to its environmental impact is an innovation that has the potential to play a transformational role and act as market changer (Cole 2005).

A pilot study was conducted between June and December 2018, involving two main data collection methods: First, a desktop study of relevant academic literature in assessment methods as well as regulation documents concerned with the two domestic assessment methods in the UAE namely Estidama and Alsa'fat. Second, 7 guided in-depth interviews (Spradley 1979) were conducted with 8 professionals working with both Estidama and Alsa'fat systems. Interviews considered as guided conversations (Yin 2018) to provide "*depth, subtlety, and personal feeling*" (Pettigrew 1990). The interviewees were 3 engineers from Abu Dhabi and Dubai municipalities, and 5 sustainability consultants who work for global construction companies based in the UAE; 3 of them were architects and 2 were mechanical engineers who are all certified by Estidama and Al Sa'fat. While this is a small sample which may lack comprehensive representation of the UAE's construction industry, the pilot study provides a starting point for further data collection and analysis to investigate the adoption of assessment methods in the UAE built environment.

Classic diffusion of innovations model, which defines diffusion as *the spread of new ideas through communication channels in a social system over time* (Rogers 2003), and concepts from the growing research in assessment methods (Schweber 2013; Schweber and Haroglu 2014; Thomson and El-Haram 2018) were used to inform the development of the interviews' questions, and they guided the thematic analysis of the qualitative data (Miles and Huberman 2018) which was gathered using the two data collection methods above. The following section introduces background information about assessment methods in the UAE, before delving into the analysis and discussion of the pilot study findings.

3 Assessment Methods in the UAE

Sustainability regulations has started to emerge in the UAE construction sector from the late 2000s, with the launch of Estidama framework in Abu Dhabi in 2009, which was then shortly followed by Dubai Green Building Code (DGBC) in 2010. Each regulation now has its own associated assessment method. The Pearl Building Rating (PBR) system, which is Estidama's assessment method has been mandated since 2010, and it is part of Abu Dhabi building code. Currently covering approximately over 10 million m^2 and more than 2000 villas. The basic requirement for PBR is achieving 1 pearl for privately owned villas and 2 pearls for governmentally owned projects which could be achieved by the mandated sections and 60 additional points to be selected. Higher pearl ratings are optional and could be gained for implementing other requirements.

Al Sa'fat, the most recent assessment method was also launched by Dubai municipality in 2018. While around 70% of Dubai buildings have already reached Al Sa'fat basic requirements by applying DGBC regulations, Dubai Municipality visualized the need to address the level/ category of sustainability that each building accomplishes. Therefore, Dubai Emirate, having its individual goal and vision towards reducing resources consumption and improving the indoor environment quality has launched Al Sa'fat rating system that was tailored for Dubai's construction field. Al Sa'fat is mandatory on all buildings that built after 2014, with private residential villas and industrial buildings being required to acquire Bronze certification and investment villas, public buildings and multi-story buildings required to meet the Silver certification.

The economic, cultural, social, and environmental pillars of sustainability were addressed in both Pearl and Al Sa'fat rating systems in a way that is suitable to the UAE, its climatic condition, culture, market, and vision. Furthermore, both Estidama and DGBC frameworks adopt performance-based rather than prescriptive approaches, as they specify minimum requirements rather than prescribing specific systems or components. Mandating PBR and Al Sa'fat assessment systems may encourage innovation and diffusion, however, as argued by Gann et al. (1998), this can happen only if these mandated regulations "*be able to translate into a system of incentives and certification which encourage a successful flow of ideas between* *designers and builders responsible for final product development, integration and assembly, and upstream component innovation by materials producers and suppliers*" (Gann et al. 1998), hence, this research focuses on the adoption processes for PBR and Al Sa'fat as transformational innovation in the form of mandated regulations in development projects in the UAE built environment.

4 Analysis and Discussion

4.1 Communication Channels for the Adoption of Assessment Methods

The analysis of the pilot study has revealed that the spread of sustainable design and construction practices in the UAE development projects was driven by sustainability regulations and mandating UAE context specific assessment methods such as PBR and Al Sa'fat. In order to support and enforce this mandate, regulative bodies for both systems were found to be engaged in a continues buy-in process with clients, projects' professionals and suppliers for sustainable products and systems—using various communication channels as discussed in the following sections and summarized in Table 1. Furthermore, these communication channels are necessary to address the needs of different members of the sustainable built environment's eco system, ensuring that they are cautiously maintained, and that they complement one another.

4.1.1 Communication Channels to Clients

The acquired qualitative data recognizes that the two most evident motives for clients and owners to meet the assessment requirements are: financial savings and gaining reputation. To address these two points, motivational strategies for companies to adopt the system are frequently considered by both PBR and Al Sa'fat teams, which are evident in activities such as: a-close monitoring the cost of sustainable construction materials to avoid any unjustified price increases by suppliers, b-issuing various marketing materials, and holding and attending events involving clients and owners to raise the public's awareness of the economic impact of certified sustainable buildings, c-conducting and publishing results for comparative case studies of certified and non-certified buildings to demonstrate savings on energy and water, and d-displaying plaques showing the building rating on a highly visible place in the building in a similar fashion to hotel rating, so the users can stay informed of the building's certification.

Table 1 The adoption of assessment methods communication channels

Communication channel with	Challenges	Mechanism to address the challenges
Clients	Get the buy-in for financial savings and gaining reputation	– Close monitoring for the cost of sustainable construction materials – Marketing materials, and events to raise the public's awareness for Estidama – Comparative case studies to demonstrate savings on energy and water consumption – Display plaques showing the building rating on a highly visible place in the building
Projects' professionals	Spread knowledge and enable easy certification processes	– PQP and Al Sa'fat Certified Engineer training and certification. – Individual support for projects
Sustainable products and systems suppliers	Get the buy-in from suppliers	– Product certification processes – Online library of approved products and systems

4.1.2 Communication Channels to Projects' Professionals

One of the main characteristics of both PBR and Al Sa'fat rating systems is that they have training and certification schemes for development projects professionals. For example, for PBR there is the Pearl Qualified Professional (PQP) training course and certification. Each project requires a PQP to be assigned to the project as the single line of communication linking the Estidama team with project professionals. Which enables the Estidama team to easily monitor and supervise the certification progress. The data shows that sufficient communication and proper handover between the project consultants, contractors, PQP, and Estidama personnel is the key for successful adoption of the rating system, hence, Estidama team offer continuous individual support to projects.

4.1.3 Communication Channels to Suppliers of Sustainable Products and Systems

The data shows that the diffusion of sustainability methods and practices in the built environment through the adoption of assessment methods since 2010 has resulted in the emergence of companies specializing in sustainability services and products, creating new jobs and employment opportunities in the industry. The responsibility of monitoring the market for sustainable products and systems falls on PBR and Al Sa'fat teams along with other government organizations, with quality assurance as a high priority. Therefore, both systems adopt strict product certification processes conducted by third parties in realistic lab conditions. They also publish an extensive online library of approved products and systems hosted on their websites, making it available to projects, which has encouraged suppliers and manufacturers to certify and include their products on these valuable libraries.

5 Projects' Dynamics and the Assessment Process

While Al Sa'fat system has only been launched in 2018, and projects are yet to start seeking certification, the interviews with projects' professionals who have engaged in Sa'fat certified development projects, has revealed that the assessment process actually promotes collective project work, or as one architect puts it: "*it forces people to get out of their silo*". Moreover, working together is challenging because design and construction teams are not static, with professionals often moving from project to project, and while previous experience with the assessment method is important, but this also poses more challenges as the following quote suggests:

> it depends on that project team, how many members are experienced in the past that they can really look in the score card like, "Yeah, got it. I know what you're talking about." Like you know because again we are in a geography that has people coming and going. So I might have, I mean landscape architect who came only last week from Melbourne Australia, what's Estidama? Architect

This not only captures the temporary nature of the involvement of construction project professionals and the importance of their prior experience, but also highlights the construction sector in the UAE as being international with global workforce who might not be completely familiar with local practices and regulations such as Estidama framework.

With Estidama and PBR system having more exposure after nearly 10 years of implementation, projects professionals believe that design and construction practices have in fact improved, however, the awareness and level of knowledge and involvement of clients is considered to be still lagging, this is demonstrated in the following two quotes by one of the participants;

> So yeah we've gotten a better hold of the design side and the definitely construction side. I think we need to improve on clients' involvement to be honest because they tend to think like, "Oh it's you guys." Yes, it does but it's also you;

> Client buy-in can be challenging. convincing the client that maybe this credit is better than that credit. Or illustrating to a client why a particular credit might not be viable or the best solution that we're looking for. Each project is different. Each client is different. Even repeat clients because a repeat client may be asking you to do something else. Or a repeat client might be asking you to build something that you have done before but because of the site location the previous credits are not available. Architect

This shows the need for more sustainability literacy to be communicated to clients by Estidama team for example, in order for them to become more involved and to positively engage in the assessment process.

6 Conclusions

The aim was to investigate the adoption of assessment methods for sustainable built environment in the UAE. This aim was founded on the need to address the emerging discourse for sustainable development of the built environment through policy, regulation and the mandate of assessment methods in the UAE. Guided by diffusion of innovations theory and emergent assessment methods literature, a pilot study was designed and implemented, revealing dynamic communication channels between regulative bodies and clients, projects' professionals, and sustainable products and systems suppliers, which increases awareness and achieves the buy-in from the various members of the sustainable built environment eco system. Furthermore, the pilot study has captured projects' dynamics and the assessment process which is characterized by challenges posed by the temporary and global nature of development projects teams, and the lack of client awareness, involvement, and levels of knowledge.

Despite the limitations of generalizability of the pilot study, the findings presented here can provide guidance to regulative bodies to improve their communication channels in order to address the captured challenges at project levels. Moreover, this paper contributes to the growing literature concerned with the effect of assessment methods in the development process by providing focus for environmental sustainability of the built environment in an emerging economy such as the UAE which is unique due to its climatic, social, cultural, and economic conditions.

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Application of Robotic Technology for the Advancement of Construction Industry in Sri Lanka: A Review

K. G. A. S. Waidyasekara, Madhawa Gamlath and Sonali Pandithawatta

Abstract The construction industry is one of the least automated industries, and robot implementation at the construction site is limited. Moreover, the industry has traditionally not been a favorable area for the application of robotics. However, with the discovery of more cost-effective applications and motives such as reducing the labor force population, the aging of skilled workers, and safety issues, their use will undoubtedly increase, especially in the developed countries. Robotic technology provides many benefits for the advancement of the industry while the local construction industry is not fully geared to entirely implement such increased technological applications. Therefore, there is a need to investigate the feasibility of introducing robotic technology for the advancement of the construction industry in Sri Lanka as a developing country. Hence, this paper aims to review the importance and application of robotic technology to the local construction projects by critically studying the secondary data on global construction automation and to further discuss benefits and challenges. The paper also presents a view on the application of robotic technology in the Sri Lankan construction industry by reviewing secondary data and basing this upon the opinions from the preliminary survey.

Keywords Application · Advancement · Construction · Robotics · Technology

1 Introduction

In highly developed nations, the impacts of human capital reduction are predominantly controlled by supplementing human capital with capital intensity and advances in technology. With this nature, digital technology becomes a vital contribution to

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_4

economic growth by improving the quality of life (Clough et al. 2000). Recently, many organizations proceed with digital technology. It has further penetrated most of the products, services, and operations of many industries. With the fourth industrial revolution (Industry 4.0), most countries bring digital technology innovation to a world of process control and operational technology domains (Woodhead et al. 2018). Further, in this context, the term Industry 4.0 includes a variety of technologies to allow the advancement of an automated and digital manufacturing environment and the digitization of the value chain (Lasi et al. 2014). Moreover, extra value for the user is acquired through digital innovation with better functionality than analog options. In every industry, digital technology is utilized to achieve better output. Hence, there is a need to investigate the application of Robotic Technology (RT) for the advancement of the construction industry in Sri Lanka as a developing country, since it is successfully applied worldwide. This paper is organized as follows: First, an introduction to RT, discussing its applications in different industries with more emphasis on the construction industry, followed by reviewing benefits and challenges in implementing. Next, the RT in Sri Lanka is discussed.

2 Research Method

In any research work, conducting a methodical literature review reinforces and enriches the research process initially. Iqbal (2007) stated that a literature review is essential in order to identify any gap in the knowledge, and a researcher can successfully claim a gap with evidence in the existing knowledge. This paper was written based on the comprehensive literature review of on-going research on application of robotics for the advancement of the construction industry in Sri Lanka. The paper elaborated the existing research gap and the way forward. Mainly, literature evidence was taken by referring to books, journal articles, conference proceedings, published and unpublished bibliographies, industry reports and documents. During the literature survey, key terms like robotics, construction industry, drivers, and barriers were used. Further, three preliminary interviews were held with industry experts with more than 25 years of working experience in the construction industry and knowledgeable about innovative technologies before the detailed survey.

3 Introduction to Robotic Technology

Robots could be identified as machineries or devices that function automatically or by remote control (Kurfess 2005). They are sophisticated and valuable systems employed in the industry for several decades (Liljebäck et al. 2012). With the development of the technology, the utility and capability of robots have improved dramatically (Robins and Dautenhahn 2014). After the introduction of the word “construction robot”, more than 550 systems have been developed for the unmanned operation, automation, and robotization of construction works in Japan (Obayashi 1999). As per the International Association of Automation and Robotics in Construction (IAARC 2004), compared to Japan, pure industry-based work in North America is far less apparent, but most of the universities are collaboratively working with Japanese companies to invent RTs. However, in Europe and other countries, work related to RT is on a minor scale and they still focus on other specific areas of construction.

As per Gambo and Balaguer (2002), research activities related to robotics and automation in the construction industry can be divided into two main categories as civil infrastructure and building. As per IAARC (2004), construction robots and automation can be elaborated under three main headings; (1) improvement to existing construction plant and equipment (2) task-specific dedicated robots (3) intelligent machines. As per Bernold (1987), smart technologies will find their way into construction related issues such as safety, quality, job enrichment, fading craftsmanship, and preventive maintenance, and optimal usage of resources are the basic enablers to study the application of robot systems to the construction industry. Hewit and Gambatse (2002) identified that contractors who used robot technology in projects have advantages such as cost savings, reduced project duration, improved quality, and consistency. In construction, the scope of RT application is relatively broad, encompassing all stages of the construction life cycle. Even after completing the building or the structure, technologies can still be applied for the maintenance, and demolition or dismantling of the structure. However, the degree of application varies significantly from one stage to another (IAARC 2004).

4 Applications of Robotic Technology

Robots are intensely beneficial to various industries as their positive impact is increasing while they provide services to multiple areas of daily life (Calo 2014). Table 1 describes various applications of RT and its benefits to the respective industry as depicted in literature.

5 Involvement of Robotic Technology in the Construction Industry (CI)

The technological level of the construction industry was very high during the historical period. For example, the ancient societies have built long lasting structures such as pyramids, acropolis, canals, and churches, and these innovative methods are also used within the modern standard building procedures (Deplazes 2008). Some of the present construction processes have undergone fewer changes. For instance, the building construction process has not altered largely over the past centuries. However, the old pulleys are replaced by cranes, and they are more developed than

Table 1 Application of robotic technology in different industries

No.	Industry/sector	Uses	Benefits
1	Medical	• Preparing medications • Used in surgeries and prosthetics	• Capability to perform surgeries with minor incisions • Minimal scar tissue • Minimal recovery times
2	Space exploration	• Use as flyby probes, landers, rovers, atmospheric probes, and robot arms • Transmitting information back to earth	• Useful assistants for science exploration • Possibility to reach remote planets • No need to return to earth
3	Military	• Use to remove humans from a dangerous place • Send into the field to sweep for landmines	• Eliminating the danger • Performing tasks better than humans • No human loss
4	Education	• Support to learn difficult subjects • Support to teach subjects that are directly related to robotics field	• Ability to perform repetitive tasks precisely • Develop cognitive and social skills of students • Flexible robots have the potential to engage young people with a broader range of interests
5	Agriculture	• Used in crop cultivation, transplanting, water spraying, and selective harvesting	• Improved harvest • Minimal cost • Reduced negative environmental impacts
6	Oil and Gas industry	• Used for inspection, maintenance, and renovation of plant facilities with increased frequency and precision	• Increased productivity under extreme environmental conditions • Eliminate health and safety issues • Reduced production cycle, floor area, and number of workers
7	Textile	• Sewing, cutting, folding, and packing • Carry out endless repetitions with persistent accuracy	• Improves the efficiency and quality of production • Mitigate impacts of the rising labor cost • Remove the employee's inefficiencies relating to the working environment

Sources Lin et al. (2013), Chang and Wagner (2015), Ratnakumar and Smart (2007), Kurfess (2005), Calo et al. (2016), Cheng et al. (2017), Felicia and Sharif (2014), Bloch et al. (2017), Bechar and Vigneault (2017), Shukla and Karki (2016), Nayak and Padhye (2015), Gries and Lutz (2018) centuries ago, but still operate with the same old principles (Balaguer and Abderrahim 2008). Recently, the most important researches of the service robotics field were focused around the construction industry. Warszawaki (1984) explained the sequential stages in construction automation considering five basic classifications as illustrated in Fig. 1. During the 90s, the research and development activities in the robotic and automation construction field were mainly manipulated by Japanese organizations and universities (O'Brien 1991).

Using electronic and mechanical means in construction tasks has been described as Construction Automation (CA) (Hewitt and Gambatse 2002). As per the authors, the primary purpose of CA is to attain automatic operation to reduce time, effort, and potential exposure while maintaining or improving the quality of work. Construction Robots have been identified as intelligent machineries that use ingenious control and designed to enhance the speed and precision of operations in the construction field (Stein et al. 2002). These robots can be useful to automate various construction processes in building and infrastructure construction and they are also suitable for interior building finishing, bricklaying, modular building erection, tunnel construction, road paving, excavator controlling, infrastructure inspection and bridge construction (Thomas 2008). During the 19th century, when more technologically improved constructions were increasingly commissioned, many efforts were taken to automate the construction process to increase the speed and productivity. However, mechanically operated fabrication, assembly, and erection were identified as early forms of automation (IAARC 2004). Warszawaki (1984) suggested four different groups of building activities, which can be designed at the optimal robotic systems. They are (1) handling and positioning of large elements, (2) interior finishing and connecting activities, (3) finishing of large horizontal surfaces and (4) finishing of exterior walls. The author mentioned that activities like plastering, painting, spraying, trowelling, further welding, bolting and jointing can be robotized in buildings having proper adaptation of sensory devices. Moreover, Table 2 presents examples of robots used in different stages of construction processes, by reviewing the secondary data.

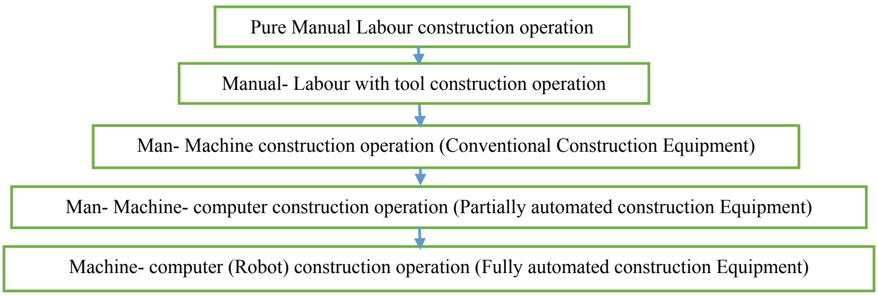

Fig. 1 Sequential stages in construction automation process. *Source* Kangari (1986)

Table 2 Robots in construction projects

Robot	Description
Bricklaying robot	• A New York-based company developed the first bricklaying machine in 2014 *Partially automated robots* • Lay 2000–3000 bricks per day • Use conveyor belt, robotic arm, gripper, and a concrete pump for operation • An onboard propane generator provided electrical power and air • Use lasers and sensors to measure important operational variables e.g., SAM 100 *Fully-automated robots* • Lay around 1000 bricks per hour • Creates 3D CAD brick laying designs of the structure by identifying the location of every brick through calculations • Cut and lay the bricks from a fixed location by creating a program • With a sequence determined by the program, pressurized mortar is delivered to the laying head and applied on the brick • Within 15-h time period, the robot can complete an entire masonry work of a house e.g., Hadrian X
Additive manufacturing/contour crafting	• Often termed as 3D printing • This technique can be utilized to fabricate building components with a fully-automated operation • It has not achieved the stage of building a whole structure with a satisfactory precision • Produce components with high geometric complexity • Aimed at constructing concrete houses, storerooms, commercial buildings, free-standing structures and prefabricated modules • Reduce cost of transportation, time duration and material wastage e.g., Cazza X1, Cazza X1 Core, and R 3Dp
Autonomous ground vehicles	• The concept hasn't been used in the construction industry yet • Komatsu, one of the largest construction companies in the world, has built a working prototype • Use augmented global positioning system (GPS) for navigation • By combining satellites and on-site base station, location information is produced with a centimeter resolution • Ability to withstand environments with high vibrations • Robot's responsibilities can be defined with an iPad by establishing the site perimeters and inserting project details • Can measure the quantity of material in the scoop

(continued)

Table 2 (continued)

Robot	Description
Unmanned aerial vehicles (Drone)	• Use the support of sensors and high-resolution cameras for the operation • Used for site surveying, progress monitoring, health and safety evaluation, possible hazards detection, transport logistics, inventory monitoring, promotional photography and marketing • Ability to translate sensor data into topographical maps, three dimensional structural models, and volumetric measurements with suitable computing tools • Reduce the risks of survey workers and provide economic benefits
Concrete crusher robot	• Faster and quieter robot. Even take place at night. • Adjacent work can continue uninterrupted
Demolition robot	• Used in the confined space and for selective demolition works
Prefabrication robots	• Mainly employed to manufacture modular and prefabricated segments such as ceilings, roofs and walls • Three projects have used robotic prefabrication in construction: (1) ROCCO, (2) FutureHome, (3) ManuBuild *ROCCO* • Includes a software system which assists in wall partitioning, logistics planning, and layout planning • The software system was capable of generating automatic manufacturing commands and robot assembly tasks to build prefabricated elements
	FutureHome • The project aimed to produce fully-manufactured houses instead of building only prefabricated parts • Automatically perform the construction process AUTOMOD3 software system generated assembly sequences and motion paths for robots • Provides a simulation tool which allowed to visualize and inspect the assembly process before the execution *ManuBuild* • The project facilitated the incorporation of mass customization in the construction industry

Sources Bogue (2018), Dakhli and Lafhaj (2017), Howard et al. (2017), Bang et al. (2017), Kespry 2019, Kasperzyk et al. (2017), Akshatha et al. (2017), Jaillon et al. (2009)

6 Benefits and Challenges of Using Robotic Technology in the CI

This section presents the common benefits and challenges of implementing new technologies relating to robotics within the field of construction. These benefits and challenges were mainly identified through a comprehensive literature review.

6.1 Benefits

Labor shortage is a primary factor that forces industries to mechanize production in many countries. This makes a positive impact on economies with serious labor shortage issues and with full employment to reduce the rising pressures on wages (Mahbub 2015). Foreign labor is also a national issue for most developing countries. Implementing a structured and effective robotic and automation in the construction process will help to overcome this issue by reducing the foreign labor component in the economy (Kamaruddin et al. 2015). Problems connected with the construction industry such as declining quality and productivity, workplace safety, and inferior working conditions have highlighted the importance of integrating advanced solution to the industry, such as further use of industrialization, CA, and robotics application on site (Mahbub 2015). Robotics and related technologies have proven the improvement of the construction process in all aspects.

The most popular advantage of robotics and automation in construction is that it speeds up the construction processes by reducing the production time. Moreover, it is accepted that mechanization and automation are quicker than labor at work operations. Therefore, contractors can complete their projects faster to save money with the use of these technologies (Idoro and Bamidele 2011). Robotic and automation can also improve working conditions of the environment, avoid dangerous work, stabilize quality, increase the degree of design freedom, reduce debris, and undertake work that is difficult for people to perform. Adopting robotic and automation will minimize the number of construction activities on site, and thus, become less complicated. Further, cost reductions can be achieved due to the reduction in workload per task such as eliminating or reducing the scaffolding usage, security system and supplementary transport equipment (Kamaruddin et al. 2015).

6.2 Challenges

Capital cost, skill resources, maintenance, and availability of technology are the obstacles to implementing robotic and automation in the construction industry identified (Kamaruddin et al. 2015). Out of these challenges, purchasing cost of plants and machinery is the main barrier. Moreover, robotic and automation is a specialized area, which requires high technological machines and skilled operators, which will always lead to an increase in the overall cost. Further, the operational and maintenance cost of robotic and automation should be considered before its implementation in the industry. Investments on heavy equipment and mechanized construction systems are low due to its high investment cost. Moreover, it is challenging for new local companies to compete for opportunities with international competitors that are stronger in terms of financial capability, technology, or specialization. Therefore, the contractors prefer not to use automation as they find it easier to stick to traditional construction methods. This is because adopting a new system means there is a need for a substantial and sustained budget, allocated time for training of labor, and specialized equipment and machinery (Rahman and Omar 2006).

In addition, Mahbub (2015) identified many challenges to the application of automation and robotics in the construction industry. They are the financial costs in purchasing and maintaining the technologies, fragmented nature of the industry which limit the application of new technologies, technologies that are difficult to use and understood, incompatibility of the technologies with current construction operations and existing practices, inadequate technological knowledge of project participants, the need for re-training of workers, difficulties in acquiring the technology that are unavailable locally, and non-acceptance of technologies by workers. As per Neubauer (2017), the insufficient experience of contractors in using robotic and automation, and inadequate knowledge to apply it in projects, limit the industry to implement robotic and automation to realize its full potential. High complexities of the robot control system and programming procedure leads to its awkward introduction in the construction industry (Kahane and Rosenfeld 1999).

7 Robotic Technology in Sri Lanka

This section elaborates literature findings and the opinions of the experts relating to the application level of RT in Sri Lankan construction industry. During preliminary interviews, it was revealed that the local construction industry is challenged by a shortage of skilled workers due to insufficient training facilities, low interest in the construction sector shown by younger generation and worker migration to overseas countries. Due to this skilled labour shortage, project delays, poor quality of works and less productivity of labour is experienced. Thus, while technology is developed by making everyone's lives convenient, robots and artificial intelligence are likely to substitute citizens in Sri Lanka in the next 50 years. Moorthy (2018) mentioned that experts from the apparel, property, travel, and innovation sectors accepted that technology has taken over some of the work that people have been doing. Further, the author stated that the future of Sri Lanka looks bright to some extent as people are talking and communicating with computers and robots. As revealed from preliminary interviews, historically, Sri Lanka was equipped with a craft-based construction technology, developed through the experience collected over 2000 years. This level of technology was adequate to fulfill the construction needs even during the post-independence era. However, as stated by Silva et al. (2008), due to the rapid development occurred in the fifties in large-scale projects such as irrigation, power, and industrial building, construction work was launched demanding a massive technology input. However, it revealed the local construction industry was not fully prepared to meet this increased technological demand. Due to this lack of technological development, some major construction projects were performed by foreign contractors. As per Moonesinghe (2017), Sri Lanka needs to utilize industrial robotics to survive in this economic climate. It cannot perform with a haphazard rush but must be carefully arranged by the government in co-operation with the universities and the corporate sector. One interviewee highlighted that it is first necessary to identify the fields which are in the extreme need of automation, and whether the requirement can be satisfied by off-the-shelf products, or whether customized robots must be made. Reducing accidents and greatly increasing prodcutivity are highlited as some benefits of implementing robotic in cosntruction projects. Requirement of research and development towrads this end in Sri lanka is identified. While considering the current usage of RT in the Sri Lankan construction industry, central expressway project is using unmanned aerial vehicles or drones to review site progress and ensure site safety. Department of Forestry and Environmental Science (2016) initially planned to use them for aerial surveys; however, due to lack of resources and techniques, only desktop studies and surface surveys are performed. As per the interviewees, great opportunities are available through the application of robotics in the construction industry such as efficiency and reducing cost, but its impact on the initial overall construction cost is identified as a leading negative aspect. Further, they believe that the rise of robotics is likely to create new job roles and opportunities in construction that cannot be imagined today.

8 Conclusions and Way Forward

Robotics are considered an essential part of the next technological revolution. Although robotics solution may be possible for the labor shortage and increase quality and speed of construction outcome in Sri Lanka, automation needs to be more carefully managed. Further, the government and private sector can play a significant role since this promotes the requisite innovative capacity of the country. This paper mainly considers the theoretical aspects to review the application of RT and presents the finding of the preliminary survey. The next step of the study investigates the feasibility in terms of economic, technical and need-based aspects in Sri Lankan Construction Industry. Further, future trends & opportunities, real challenges and benefits of implementing robotics technology in the construction industry in Sri Lanka as a developing country will be discussed. Moreover, the study will make recommendations to encourage the use of robotics and automation in construction. Therefore, the findings of this study will be beneficial to other developing countries during the process of adopting RT in construction projects to overcome challenges and to strengthen benefits.

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Prefabrication and Waste Minimisation in Construction Projects: Perspectives from New Zealand

Olivia Luo and Wajiha Shahzad

Abstract The benefits of prefabrication are well known and include increased efficiency, greater economy, and safety in construction operations. There have also been anecdotal references to the reduction of construction waste as a result of prefabrication but there are little empirical studies to support this assertion. The current study undertakes an investigation to establish the influence, prefabrication can have on the amount of construction waste generation. Data was gathered through the collation of the perspective views of 47 construction practitioners and stakeholders who have professional experience in the New Zealand construction industry. Quantitative method of analysis was chosen for ease of understanding. The results indicated greater levels of prefabrication corresponded to lower levels of construction waste generation. However, the key to achieving construction waste minimisation targets lies in better supervision of the quality of prefabricated products. The study concludes that more training, education, and awareness is needed within the prefabrication sub-sector to realise waste minimisation on construction projects.

Keywords Construction waste · New Zealand · Prefabrication · Waste minimisation

1 Introduction

The activity level of the construction industry in New Zealand is in full swing to fulfil the residential and infrastructure requirements of the country's growing population (MBIE 2018). It is a well-established fact that construction activities consume a

This article is based on a Master's dissertation (unpublished work) submitted to Massey University, New Zealand.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_5

lot of natural and man-made supplies and yield enormous volumes of construction waste as a by-product (Tam et al. 2007). One-third of the world's greenhouse gases are produced due to construction activities and buildings consume 40% of energy (UNEP 2009). Construction industry is responsible for up to 40% of waste generation in many countries, where enough measures are not been taken to reduce construction waste (Chung and Lo 2003).

A New Zealand study (Jaques 2013) reports that around 1.7 million ton of construction waste is sent to landfills each year. This translates into 50% of all the waste transported to the country's landfills annually. This is an alarming situation for the country. Not only a lot of materials, that has potential to be reclaimed and reused in going to the landfills without any check, but this will also have long term implications including but not limited to wasting a large area of land filled with waste, causing harm to the environment by adding scores to air and water pollution. Another impact of this waste is soil contamination that leads to serious health threats (Tam et al. 2007).

As per synopsis of Jaques (2013), the best way of controlling the amount of construction waste is to curtail its production i.e. avoid generation construction process as much as possible. Various researchers have acknowledged that more uptake of prefabricated construction technology is an effective way of reducing the construction waste generation (Shahzad 2016; Tam et al. 2012; Jaillon et al. 2009). New Zealand construction industry is the fifth largest industry of the country in terms of employment opportunities and contributes to 6% of nations' GDP (MBIE 2018). But still, it's a traditional industry where the majority of construction activities take place onsite and use of innovation is very low (Shahzad et al. 2015). However, some recent demand-based developments in the country present new opportunities for prefabricated construction as traditional and old-school practices are unlikely to create a supply-demand balance. Prefabrication technology offers many benefits like reduced cost, shorter project duration, better quality workmanship, improved wellbeing of construction workers and reduction in construction waste generation. Some recent studies have provided shreds of evidence that prefabricated construction can offer a substantial amount of cost savings, time savings and enhanced productivity benefits to the New Zealand construction industry (Shahzad 2016). However, not enough research has been done to investigate waste minimisation aspect of prefabricated construction. This study aimed at knowing the impact that prefabrication technology can have for New Zealand in terms of reduction of waste generated by construction industry.

2 Literature Review

2.1 Construction Waste in New Zealand Context

Many researchers have defined construction waste differently. However, the definition of construction waste provided by the United States Environmental Protection Agency (USEPA) is by far the most widely used definition, which states "waste generated during the construction, modification, and demolition of building structures (including bridges, roads, buildings, etc.)" (EPA 1998). Further to this construction waste is broadly classified into four categories according to the guidelines of the European Commission. These categories are (i) demolition waste (ii) construction waste (iii) waste generated during renovation and refurbishment (iv) waste generated by roading works (Symonds and COWI 1999). Another definition of construction waste is established by Hong Kong Environmental Protection Department, according to which any byproduct of construction activity, whether it is disposed off or stored for later disposal (EPD 2012).

The variance in the definitions of construction waste curbs any direct appraisals and use of construction waste data from different countries. For this study, Jaques's (2013) definition of construction waste is adopted who defines construction waste as solid waste, this includes the wrapping of new construction materials; bits and pieces of wood, plasterboard and metal; concrete, and gravel scraps.

According to the estimates of Building Research Association of New Zealand (BRANZ), 3.5 tons of construction waste is generated by new residential development (BRANZ 2012). Of all the waste that goes to New Zealand landfill's half of the waste comes from construction industry (Jaques 2013). In summary, 1.7 million tons of waste originating from construction industry making its way to landfills in New Zealand every year. This construction waste is occupying and continues to rule a large area of land. This land being occupied by construction waste contributes to air pollution, water pollution and soil contamination (Jaques 2013; Tam et al. 2007).

2.2 Types and Sources of Construction Waste

As New Zealand construction industry is timber based, most common form of construction waste is various forms of timber followed by concrete, fixings, roofing, etc. (Jaques 2013). The composition and content of construction waste, however, fluctuate depending on the factors like type of structure, selection of construction material and technology, etc. For example, the proportion of wood is more in construction waste generated by residential construction rather than commercial or infrastructure projects. Wood waste is also generated by wet works on a traditionally built project. Careless handling by the labourers can easily lead to damage of plywood and wooden board, contributing to construction waste. If the wood is properly stored and protected against weather, it is easily damaged by the weather. Lack of care during transportation can also lead to damage and consequently adds up to wasted wood (Poon et al. 2004; Osmani 2012; Tam et al. 2006).

Broken brick also constitutes construction waste. Primarily, bricks are used for construction of load-bearing walls and retaining walls. Many factors can lead to the production of broken bricks: wrong placement, design errors, selection of wrong quality or the wrong size of brick, fragile nature of bricks, transportation and handling, poor quality of the purchased bricks etc. (Jaillon et al. 2009; Tam and Hao 2014).

Mortar waste is another type of prominent construction waste. Tam and Hao (2014) investigated the reason of mortar waste generation and observed following aspects: waste of material due to oversize orders for masonry works, waste generated during surface decoration, unused materials, unusable waste generated during rework and lack of workers responsibility to pay attention to the waste of mortar caused by saving. Luo (2018) observes that when the concrete is processed on site, the waste is generated during the mixing and production process of the concrete, running of the slurry, improper installation of the formwork, the waste of concrete caused by the improper operation of the pouring of the workers and the wrong calculation of the required amount of concrete.

Although steel is a fully recyclable material, steel on construction projects can go to waste due to workers attitude, who cannot make full use of steel bars. Bending deformation of steel makes it useless for construction works and hence it is sent to landfills (Osmani 2012; Tam et al. 2006).

Construction materials are often delivered to the project site in packaging to protect them during transportation and storage. This packaging generally does not recycle and hence become part of the construction waste that goes to landfills (Osmani 2012).

2.3 Minimising Construction Waste

Continuous development of the built environment has drastically increased the amount of construction waste, which not only causes enormous waste of resources but endangers the environment and wellbeing. And hence, reduction and treatment of construction waste have become a topic of global interest (Luo 2018).

The United States has laws related to waste generation stipulating: "Any company that produces industrial waste must properly handle it and cannot pour it without authorization". This law limits the amount of construction waste generated. Reducing waste generation at the construction site and reusing it as much as possible is the main principle of Japan's disposal of construction waste. By setting standards and regulations, stakeholders are involved in limiting construction waste to "zero" emissions. The source control approach reduces resource extraction, reduces manufacturing and transportation costs, and reduces environmental damage, making it more effective than treatment at the end (Luo 2018).

Construction industry in Germany has some best practices in place. It is a prevailing culture that every role player of construction waste generation cycle has to contribute in some manner to result in the reduction of waste generation. to reducing waste and recycling (Gavilan and Bernold 1994; EPD 2012).

Further to this, the designers and builders are educated to minimize the construction waste generation. Reducing waste from sources is considered a better environmental and economic benefit option.

The above discussion concludes that construction waste reduction is achieved differently by different countries. Some countries employ prevention of waste generation and other go about effective management. Similarly, New Zealand requires a rigorous policy to minimize construction waste generation.

2.4 Prefabrication in Perspective

Prefabrication is a construction technology that shifts the bulk of construction activities from the project site to a remote factory or workshop area (Shahzad 2016). The remotely manufactured components or modules are transported to the project site, where they are assembled. It is also known as off-site construction (OFC) and off-site manufacturing (OSM) (Cao et al. 2015; Boafo et al. 2016; Page and Norman 2014). Shahzad et al. (2015) have presented categorization of prefabrication as "(i) component prefabrication, (ii) wall panel prefabrication, (iii) modular prefabrication, (iv) mixed prefabrication and (v) complete construction prefabrication".

In New Zealand's construction industry, almost all new buildings use some percentage of prefabricated components, ranging from simple building elements such as doors and window frames to complex prefabricated building modules (Shahzad 2016; Luo 2018). A New Zealand study documents that the share of prefabricated components for residential buildings is about one third and is on an upward trajectory (Roberti 2014). New Zealand recognizes prefabrication technology as effective, productive and of good quality (Chiu 2012; BRANZ 2012).

A New Zealand study by BRANZ (2012) notes that when compared with traditional build, prefabrication offers huge efficiency in time performance of the projects. Prefabrication offers low risk alternatives to complex construction related issues (Shahzad 2016). Mass standardization achieved with prefabrication reduces the construction cost during all phases of construction. Chiu (2012) notes that precast technology not only reduce the on-site cost but also eliminates the cost over runs. The probability of little or no reworks greatly reduces the amount of waste generation. Improved quality workmanship offered by prefabrication makes the entire building life cycle more affordable (Shahzad 2016). Use of this technology can hugely improve the management of site operations. The layout and environment of the construction site improves as prefabrication technology reduces the need for processing and storage of raw materials (Luo 2018). Prefabricated construction addressed issues like labour shortage and construction technology defects. Prefabrication can also effectively reduce other risks associated with construction, such as workers' health and safety issues, fire risks, and limited construction sites and material damage caused by accidents (Li et al. 2014; Shahzad 2016).

2.5 Role of Prefabrication to Reduce Construction Waste

Prefabrication technology is known for its effectiveness to reduce construction waste. Here, "Reduce" refers to minimising the amount of construction material entering the solid waste stream and also to reduce the overall environmental degradation (Gavilan and Bernold 1994). Reducing the amount of materials used or by reusing existing materials can effectively minimize the construction waste generation. As prefabrication is carried out at the factory in a standardized manner construction materials and workers are less vulnerable to natural disasters, such as cold/hot temperatures, wind and rain. This factory mode of production helps to improve the process and quality of construction (Tam et al. 2007). Factory-controlled production and quality audits of building components can improve the consistency of construction standards and construction quality and reduce construction defects (Shahzad and Razeen 2018). It also simplifies on-site work during installation and enables site workers to greatly increase work efficiency without being interrupted by others and avoiding the possibility of duplication of effort (BRANZ 2012).

Prefabricated construction reduces generation of construction waste compared to traditional construction methods, as waste generation is prevented from occurring at the source of construction waste. Some studies have documented that through the use of prefabrication, different building materials an achieve 80–100% reduction in waste generation (Tam et al. 2007; Jaillon et al. 2009; Li et al. 2014).

Tam and Hao (2014), compared traditional construction with four projects constructed by prefabrication technology and observed that prefabrication technology can reduce plastering waste up to 100%. Similarly, timber formwork waste can be reduced by 80%, and the concrete waste can be reduced up to 60%. In a study, Cao et al. (2015) noted that prefabrication has potential of reducing construction waste compared to traditional construction methods between 25 and 81.25%. This result is consistent with findings of Tam et al. (2007) that documented reduction of construction waste generation by up to 84.7% compared to conventional methods.

According to Luo (2018), there are some possible shortcomings of the above presented studies. Firstly, the definition of construction waste was not the same for each study. Secondly, the number of samples were small and were based on different building types. In contrast, few studies have quantified the construction waste generated in New Zealand's new residential projects or assessed the perception of professionals on waste reduction. Foregoing in the view, this paper aims to study the effects of prefabricated technology used in recent residential projects in New Zealand to reduce waste. The purpose of this research is to compare prefabrication with the traditional method of construction, and to quantify their benefits in reducing waste; to investigate the factors of prefabrication technology that contribute to minimisation of construction waste generation; to explore the measures that can help to improve the current state of construction waste generation.

3 Research Objectives

The aim of this study was to investigate the impact of prefabrication technology of construction on reducing the generation of construction waste. In order to achieve this aim, two research objectives were developed (1) Investigate the factors that contribute to minimisation of construction waste generation by the adoption of prefabricated construction. (2) To explore the measures that can help to improve the current state of construction waste generation. The scope of this study is limited waste generation benefits of prefabrication technology and the findings are based on the views of construction industry professionals in Auckland New Zealand only.

4 Research Methodology

This is a three-stage study that started with the review of existing literature in the subject area, this process enabled the understanding of current state of research and knowledge that led to the identification of gaps in the existing literature. Information for this research was sourced from academic publications and New Zealand construction industry reports including the reports of PrefabNZ, Building Research Association of New Zealand (BRANZ) and Ministry of Business, Innovation and Employment (MBIE). In the next stage four (4) pilot interviews are conducted with project managers to get more information on the subject matter (Saunder and Lewis 2017). These interviews captured the experience of construction professionals on the various features of prefabrication technology that can help to minimise the construction waste generation. During the interviews, questions were also asked to know what some of the measures are that can improve the current state of construction waste generation in New Zealand. Based on the findings of the literature review and pilot interviews, a survey questionnaire was developed to collect data from the construction industry practitioners including consultants, contractors, prefab manufacturers, and suppliers. Questionnaire surveys have the ability to collect views of the larger populace. This method of data collection also facilitates the collection of data in a comparatively shorter period of time (Denscombe 2014). The questionnaire was pretested before the start of data collection. This pre-testing was done by construction industry practitioners who provided feedback to improve the questionnaire.

5 Data Collection and Analysis

The questionnaire contained closed-ended questions based on 5-point Likert scale answering options. A scale from 5 points—1 point was used to record the participants' response. In this scale, 5 represented 'Strongly Agree', 4 represented 'Agree', 3 represented 'Somewhat Agree', 2 represented 'Disagree' and 1 represented 'Strongly

Disagree'. To eliminate any prejudice in participants' responses a "No Idea" answering option was also postulated. The questionnaire divided into three sections, at the end of each section, open-ended questions were asked to have a better understanding of participants' point of view. The target population for this survey included professional members of the trade and professional organisations including members of New Zealand Institute of Architects (NZIA), Architectural Design New Zealand (ADNZ), New Zealand Institute of Building (NZIOB), New Zealand Institute of Quantity Surveyors (NZIQS) and Building Industry Federation (BIF). Denscombe (2014) recommends the use of the snowball method of sampling to improve the effectiveness of the survey due to the ability of this approach to spreading the questionnaire to a larger populace. With the foregoing in view, the snowball sampling method was adopted for this study. The multi-attribute analytical method was employed to analyse the data, that was collected using the questionnaire survey. In the multi-attribute method, ratings provided by the survey participants are analysed to ascertain the mean rating value. Mean rating value also abbreviated as 'MR' is calculated for each of the factor included in the questionnaire.

Shahzad et al. (2015) supports this technique of analysing the ratings provided by the respondents to ascertain the mean rating value (MR) for each sub-set in a set which represents various rating points assigned by the respondents. Ranking of factors was based on the mean rating values. Computation of mean rating values was carried out using the equation No. 1, presented below as recommended by Shahzad et al. (2015).

$$MR_i = \sum_{n=1}^{5} (R_{pjk} X\% R_{jk}) \tag{1}$$

Here: MRj = Mean Rating value for factor j, R_{pjk} = Rating point k (value range 1–5) and $\%R_{jk}$ = Percent response rate at point k, for factor j.

The factor that has highest value of MR is regarded as most significant factor that has high impact and vice versa. Factors having an average or higher value will have impact on reducing the construction waste with the use of prefabrication technology.

For a 5-point Likert rating scale 1 < MR < 5 on, flowing applies:

$$\text{MR} > 2.5 = \text{Factor is significant}$$

$$\text{MR} < 2.5 = \text{Factor is non-significant}$$

6 Findings and Discussion

A total of 47 usable survey responses were obtained for research. These responses came from members of PrefabNZ (30%), NZIA (30%), ADNZ (13%), NZIQS (12%), NZIOB (9%) and BIF (6%). Findings of this study are dominated by the views of architects. This is a good deduction as architects play a vital role is selection of construction technology to be adopted for the project delivery as well as the selection of construction materials. Awareness of architects on the issue of construction waste generation can immensely change the future practices.

6.1 Features of Prefabrication Facilitating Minimisation of Construction Waste

The first objective of this study was to find out the various features of prefabrication technology that help to minimise the construction waste generation. Nine features of prefabrication were identified to be the reason that leads to minimisation of waste generation in the construction process. Computed mean rating values reveal that all of these features are significant and carry a huge impact on waste minimisation (Table 1). It is evident that the New Zealand construction industry is aware of waste minimisation benefits of prefabrication technology. However, this potential of prefabrication technology is not fully utilised due to the overall low interest of New Zealand's construction industry in prefabrication (Shahzad 2018).

The first four highest ranked and most significant features of prefabrication technology are associated with the opportunity of closely and carefully monitoring the manufacturing process of prefabricated components, which is otherwise not possible in on-site construction. The first ranked feature is that: better supervision under factory setting improves the quality of process and products, which facilitates the minimisation of construction waste generation. The second most significant feature of this technology that helps in minimising waste generation is careful packaging and transportation of prefabricated components that curtail the probability of any material going wasted during transportation to the site. Additionally, prefabrication technology employs a process that involves careful calculation of construction materials curtailing the excessive order of the materials that ultimately becomes part of

Table 1 Prefabrication features contributing to waste minimisation

Features of prefabrication technology facilitating construction waste minimisation	MR value
Precision and better supervision of prefabrication process	4.23
Careful transportation of packaged prefabricated components	4.04
Prefabrication process involves careful calculation of material quantities	3.89
Use of CNC machines in prefabrication process	3.83
Construction material is not exposed to direct weather	3.81
Fewer chances of material stealing	3.72
Leftover construction materials can be used later on	3.68
Possibility of reusing and recycling construction materials	3.51

MR (Mean Rating value)

construction waste generation. Similarly, the use of CNC (Computer Numeric Control) machines in prefabrication yards saves a lot of usable material going to be wasted.

Next set of facilitating features of prefabrication are associated with sheltered factory setting environment. In prefabrication yards, construction materials are not directly exposed to harsh weather conditions which reduces the wastage of construction material. These yards/factories have proper raw material storage sheds. Secure storage also inhibits the chances of material stealing. The finished products are also stored to prevent damage. The probability of any extra and left-over materials to be used in future rather than directly going to waste landfills is higher in case of prefabricated construction due to the secure storage facilities and direct stake of prefabrication manufacturer. According to survey participants, prefabrication technology allows the potential of reusing and recycling construction material more than in traditional construction practices.

6.2 Measures to Improve the Current State of Construction Waste Generation

The second objective of this study was to investigate the various measures that if taken can enhance the current state of practice. Table 2 presents the results of the industry survey with regards to this research objective.

The construction industry has a consensus that more training and education is vital in reducing the amount of construction waste generation, as this was pointed out to be the most significant factor. Respondents indicated that due to the lack of knowledge about construction waste, most workers are not aware of the potential of reducing waste generation, neglecting the classification and recycling of on-site waste. Furthermore, they do not see a benefit in hiring someone to be responsible for supervision. This observation is in line with current situation of New Zealand

Table 2 Measures to improve current state of waste generation

Measures to improve current state of construction waste generation	MR value
Training, education and awareness about construction waste	4.19
Tax relaxation and fiscal subsidy for sustainable practices	4.10
Rewards for companies to re-use and recycle construction materials	3.93
A dedicated team member to manage material requests and avoid over orders	3.82
Professional are involved in all phases of project	3.81
Management of entire construction process to ensure waste minimisation	3.75
Selection of construction process that minimises waste generation	3.72

MR (Mean Rating value)

construction industry, that faces acute shortage of skilled workers and relies heavily on a work force that is poorly educated (MBIE 2018).

Next most important factor to improve current practices was "Tax relaxation and fiscal subsidy to the developer for sustainable practices". In this way, stakeholders will see a direct benefit in adopting sustainable practices.

Findings reveal that construction workers have an important role in reducing the construction waste generation and they can play a vital role in many different phases of construction. Technicians should be familiar with the drawings to implement on-site supervision to meet the requirements set by New Zealand Building Code (NZBC), make a budget for building materials, and reduce the probability of converting excess building materials into construction waste. According to survey participants, establishing a sound system that will allow workers to recognize the dangers of wasting building materials to individuals and society as a whole can effectively change the behaviour towards material handling. Material personnel should strictly control the quality, communicate with the construction management personnel, carefully approve the request list, and avoid the waste caused by excessive material demand. Ensuring quality control and durability of buildings reduces the need for unnecessary maintenance, reinforcement and even reconstruction works.

Management methods are vital to improving construction waste generation. The ratio of construction waste is different for different construction forms and the amount of garbage varies greatly from site to site due to different construction management conditions. Professional work is handled by specialized departments and can greatly reduce the generation of construction waste. Individual projects can be contracted to individuals in a subcontracted manner, and contractors can find ways to reduce the generation of construction waste in order to ensure efficiency.

Reducing construction waste generation from the construction process was also identified to be of significance for example replacing the wood form-work with a reusable steel form-work can reduce the generation of waste wood, using assembly instead of on-site production is also a good way to reduce construction waste; using industrial production methods, the building's components can be mass-produced at the factory, which was ranked 10th in these options. It reduces various unstable factors on the traditional construction site, which can save building materials and reduce construction waste.

7 Conclusion

The study establishes that more use of prefabrication technology corresponds to a reduced amount of construction waste generation during the project. New Zealand construction industry has a good understanding of this potential benefit of prefabrication technology. It is evident that precision and better supervision of the prefabrication process is a key factor for achieving waste minimisation targets. Careful packaging and transportation and carrying out work in a covered factory setting that also has the provision of secure material storage sheds also adds to the value of the overall process and significantly minimises the waste generation. The study concludes that more education, training, and awareness is needed within the prefabrication sub-sector to realise waste minimisation on construction projects. In addition to awareness, management methods and the right choice of construction process can further improve the current state of construction waste generation.

In conclusion, prefabrication technology is a construction method that can effectively reduce construction waste generation in New Zealand due to its high quality and precision. More uptake of prefabrication technology will be a sustainability value addition that can hugely minimise the amount of construction waste going to the country's landfills.

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Sustainable Performance in the Earthworks Sub Sector: Exploring the Machinery Selection Framework in New Zealand

Ryan Davenport and James Olabode Rotimi

Abstract Sustainability is becoming more engrained in the culture of the New Zealand construction industry. More so when it portends social, environmental and financial benefits to organisations that are already operating under slim margins. This study explores means by which an appropriate machinery selection framework can be implemented in the earthworks sub-sector. Data was gathered through a qualitative analysis of the perspective views of six Project Managers involved in infrastructure delivery. The focus is on financial, environmental and social sustainability issues, and the potential impacts of machinery selection framework. Data obtained were analysed thematically, permitting an insight into key issues, challenges and success criteria for sustainable performance of organisations operating in the earthworks sub sector. The research findings could contribute to improved decision making in machinery use and increased efficiencies, which ultimately enhances organisations' social, financial and environmental ratings.

Keywords Earthworks · Efficiency · Machinery selection framework · Sustainability

1 Introduction

Sustainability is becoming more engrained in the construction sector with practices in New Zealand, not being an exception. There is anecdotal evidence to suggest that the culture of the New Zealand industry is changing with regards to sustainability. For example, there is mounting pressure on companies operating in the earthworks

This article is based on the Masters dissertation (unpublished work) submitted by the lead author to Massey University, New Zealand.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_6

sub-sector to be more sustainability aware. The case for an understanding of the social and financial aspects of sustainability in addition to environmental aspects is also rising for the earthwork sub-sector in the construction industry.

A focus on machinery selection frameworks has been made in literature (Gomes et al. 2016; Waris et al. 2014). Machinery selection frameworks are successful at demonstrating robust and logical systems within construction firms. Such frameworks ensure that the right machinery is selected in construction jobsites to perform not only productively but sustainably. The current study examines the viability of a machinery selection framework which has a focus on sustainability in the running of earthworks operations in New Zealand. Furthermore, an examination of the constraints that will need to be overcome, so that the implementation of a successful machinery selection framework is achievable.

2 Literature Review

Literature on sustainability suggests that its considerations require a multi-faucet approach (Waris et al. 2014). The evaluation of sustainability is often approached from three different but complementary aspects: social, financial and environmental. Each of these aspects assist in evaluating the sustainability of a project, business or venture. Any method of improving sustainability would need to be measured against these three aspects. The following sub-sections provide brief outlines of each of the aspects with key ideas drawn from the seminal works of Gomes et al. (2016) and Waris et al. (2014).

2.1 Financial Sustainability

Financial sustainability relates to an understanding of the balance between the capital injected into a project, and how capital is being managed to ensure greater returns (Shan et al. 2017). To improve the financial sustainability of earthworks projects for example, it is pertinent to note the different constraints that can impact on the efficiency of earthworks activities. The efficiency of tasks has been established to have a big influence on cash outflows and consequently the financial standing of a venture project (Durdyev and Mbachu 2011). Several constraints are linked to earthworks, ranging from physical factors such as material conditions and site topography, to external factors such as, legislation and compliance, financial and constraints that are associated with methodology (Lau and Kong 2006). All these impacts can affect efficiency and add extra cost to site operations which negatively impact on the financial sustainability of earthwork projects. Another dimension to financial sustainability is in the reduction of energy consumption. Reduction in energy uses is significant to operational efficiency in earthworks activities. Research into energy management suggests that machinery selection is a viable approach to ensuring operations are carried out to their optimal efficiency and achieving financial sustainability (Alkass and Harris 1991).

Machinery selection frameworks can enhance financial sustainability by showing optimal machinery combinations to implement for a project. This way, operations could run at optimum efficiency, with minimal cash input. Furthermore, the foresight that a machinery selection framework allows, means that long term procurement strategies can be determined or modified to suit a project type, thus more certainty around capital investments (Sustainable Built Environment National Research Centre 2018). The biggest challenge of machinery selection frameworks is that of the mass of data input and time required for carrying out the required evaluations. Operations on an earthworks site tend to be very fluid with activities changing hourly. This may not lend itself to the collation of mass data and analysis for each new operation (Martínez 1998).

2.2 Environmental Sustainability

Environmental sustainability relates to all activities that are undertaken to ensure that the impact on the environment is minimal. Tseng et al. (2013) studies on the improvement of environmental sustainability in earthworks construction, suggests that can be split into two facets: design and practice. These two facets are briefly described in the following subheadings.

2.2.1 Design

Davenport (2018) suggests that the design of an earthworks project can greatly impact on its environmental sustainability. Tsai and Chang (2012) explain how different design considerations such as: biodiversity, stormwater, erosion and sedimentation control, drainage, air and noise pollution mitigation and low maintenance roadsides, are important in any sustainable design consideration.

Current literature suggests that the focus of earthworks design is on designing projects that require little energy consumption as much as possible (Gomes et al. 2016). There seems an opportunity for machinery selection frameworks to become a tool to model the quantity of resources required to construct a desired design. Therefore design teams are able to optimize designs by ensuring an appropriate balance between best designs and the resources required to construct.

2.2.2 Practice

As was previously described under financial sustainability, the machinery selection process can have significant impact on the design and financial performance of earthwork projects. Similar to the design facet most of the literature around physical construction, focus on minimizing the quantity of resource inputs on projects. Therefore an emphasis on machinery selection as a means of minimizing carbon footprints and the resources consumed during construction (Heidari and Marr 2015).

2.3 Social Sustainability

Social Sustainability refers to the ability to operate within a community so that it aligns with the local community's societal provisions and expectations. Davenport (2018) suggests that contractors struggle with this alignment, yet there is limited literature on how to do this successfully. Hadi (2001) provided a list of physical impacts of construction activities on local communities; These include: air and noise pollution that are particularly relevant to the earthworks industry. Whereas Gramling and Freudenburg (1992) explain that there are a range of more intangible, emotional socio-economic factors which may have the ability to affect a community's feelings towards a project or company. With machinery selection framework, these impacts are considered and inputted as constraints that will help to determine the most efficient machinery combination to operate within certain societal constraints.

2.4 Machinery Selection Framework

Selecting the right machinery for the right jobs at the right time, is essential to the most efficient running of projects (Phogat and Singh 2013). The purpose of a machinery selection framework is to deliver a robust, structured means of understanding all the constraints of given tasks and evaluating them to establish the most efficient machine combination for different tasks. Machinery selection plays a huge role in the efficiency of projects, hence there have been different frameworks created with different approaches to the input and analysis of project constraints. These range from qualitative opinion-based interpretation of circumstances to quantitative numerical calculations. The current review focuses on two different approaches to a machinery selection framework: a Multi-Criteria Decision-Making Criteria 'manual' approach and a software-based approach.

The multi-criteria decision-making criteria establishes main criteria to test each machinery combination. By evaluating each of the main selection criteria, one is able to score each machinery option based on its measurable values such as production capacity and production outputs. The advantage to this approach to a machinery selection framework is that it acts as a guide for considering all the constraints, when evaluating earthworks operations. Furthermore, many different constraints can be inputted and evaluated to establish a comprehensive understanding of a project's constraints through such a simple program. Thus the machine or combinations selected will be one that is best suited to mitigate or manage those constraints. However, the main disadvantage to this system is that, being a manual process, it incorporates an extensive use of formulas which can take a long time to work through, or it can produce data that can be difficult to interpret.

A potential solution to the disadvantages of the 'manual' framework is a sophisticated software framework in which the desired constraints are input along with pre-set machinery options (Gašparík et al. 2013). The software is then capable of calculating what machinery options can achieve a desired solution. Despite the benefits of limited user calculations, the software requires a large volume of data entry and machine type is limited to that uploaded to the software. This limitation means less flexibility of the system, because it is not capable of readily adapting to changes to working conditions and production rates. These were referred to previously as crucial to ensuring the most efficient equipment utilization. Furthermore, it will be more difficult with such a rigid software-based process, to evaluate the perception-based social constraints.

In conclusion, sustainability needs to be measured not only by environment and financial aspects, but also needs to be acknowledged that social factors can play a big role in projects sustainability. Davenport (2018) concluded that machinery selection frameworks can positively influence these different aspects of sustainability on projects globally. There is dearth of literature that discusses the implementation of any such framework in the New Zealand construction industry. This is a key aspect being covered in the current study.

3 Study Method

The study adopts a qualitative approach to gathering exploratory information on the implementation of machinery selection criteria in New Zealand. Six interviews were conducted with practitioners with over 100 years of contracting experience (see Table 1). These interviewees were selected for their wealth of knowledge of the issues, and challenges in resource and machinery use in earthworks operations in New Zealand. The participants were influential within their respective organisations for procurement choices in machinery used on their various development projects.

This study approach allowed for rich, in-depth informative discussions which offered the true perspectives of the participants. This could have been more challenging had a quantitative approach been employed. Clear common themes emanated from the interviews confirming consistency of thoughts on the subject matter.

Each participant was interviewed for approximately 40 min during which conversations ranged through various relevant issues confronting the industry in relation to machinery selection and use. The conversations were guided through the three main topic areas: financial, environmental and social sustainability, and the potential impacts of machinery selection frameworks. A thematic analysis of the interview transcripts was undertaken to identify the core issues within the subject matter. The findings are presented in the next sections.

Table 1 Study participants

	Role	Years' experience	Background
Interviewee 1	General Manager	16	Project Manager (Clients Rep.) Project Manager (Contractor) Operations Manager (Contractor)
Interviewee 2	Commercial Manager	50	Quantity Surveying (Client Rep.) Project Manager (Contractor) Estimating Manager (Contractor)
Interviewee 3	Project Manager	20	Project Manager (Clients Rep.) Project Manager (Contractor)
Interviewee 4	Contracts Manager	23	Overseas Mining Project Manager (Contractor) Project Manager (Clients Rep.)
Interviewee 5	Procurement Manager	11	Quantity Surveying (Client Rep.) Project Manager (Contractor)
Interviewee 6	Project Manager	6	Junior Estimator (Contractor) Project Manager (Contractor)

4 Presentation of Findings

The study findings are split into the five thematic in line with interviewee responses. These are outlined below with brief discussion that provides some evaluation of the perception of practitioners from New Zealand stacked up against ideas from the literature reviewed. This also outlines specific problems which could impact on the successfulness of a machinery selection process in New Zealand.

4.1 Environmental Sustainability

The integration of a machinery selection framework was seen as a useful tool for the planning and management of operations within a project, as it would be able to illustrate the most efficient machinery combinations per task. Where an optimal machine combination would be adapted, interviewees recognized that this gave great opportunity to reduce the amount of fuel, oil and grease, and labour required for earthwork activities. When directly linking the combination with environmental sustainability, all interviewees recognized the influence in how this would reduce problems such as carbon dioxide, noise, dust, and water pollution. Findings throughout the literature have found that CO_2 can be baselined and measure against when using machinery selection frameworks, a practice that is seldomly carried out in New Zealand. Further benefits accruable to machinery selection framework is its ability to highlight areas that may be hindering projects from running efficiently.

There were concerns raised by all the interviewees that a disadvantage of implementing a machinery selection framework could be around its flexibility and the potential for being short sighted. Each interviewee shared their concerns that during the inception of machinery framework the full scope of the environmental factors, resource consent, and regulatory constraints cannot always be foreseen and therefor, and there was a question raised about the machinery selection frameworks ability to adapt its delivery. In recognizing these constraints, opportunities were also outlined where the machinery selection framework would act as a robust tool for demonstrating how design and/or scope changes would have knock-on effects the way the project would have to be carried out. This transparency would not only help in regard to demonstrating extra cost and the extra resource requirements to complete the job, but also demonstrate the knock-on effects to the projects programme.

4.2 Financial Sustainability

The machinery selection framework was seen to be able to offer several opportunities, which were likely to produce financial benefits for projects or businesses, if integrated. Upon these financial benefits having effect on company process or project management, all interviewees recognized the opportunity of a machinery selection framework to add significant value through efficiency.

Amidst the opportunities this framework demonstrates, one of the most influential advantages was seen to be having a robust system to be able to illustrate the development and strategy of long-term procurement. In turn this would allow companies or projects to confidently purchase the most efficient machinery combinations for the task. This would also allow for the identification of projects or businesses have lacked in the appropriate resource. Upon recognizing these shortfalls, this will help to ensure projects run physically well, and better utilize machinery. This would then give confidence in the knowledge that a company is maximizing their return on investments. It was also recognized that the development of this procurement strategy was an opportunity to align business culture and processes with a sustainable model, in order to help successful delivery of projects.

The most consistent comments amongst interviewees was that the best time to implement such a framework would be at the estimating/tendering/bid forming stage. During this stage of a project, the framework is identified of having the greatest impact due to planning of physical works and pricing taking place. If the framework were to be implemented at estimating stage, knowledge of previous projects with machinery selection framework can help to indicate best combinations. By integrating in early stages, best pricing can be put forward and this information can be put forward to the construction teams, to give them a better knowledge of how the project was priced. Thus, work could then be carried out in line with this methodology, optimizing the financial sustainability of project.

From a financial perspective, the interviewees held the view that the size and scale of the New Zealand industry could be the biggest constraint as the most efficient resource could not be procured, because there may not be a sustainable future workload to justify realistic implementation. This negates foreseeable financial benefits. In the circumstance of mixing machinery brands, it was viewed that this would have significant negative financial impacts on the contractor. This was as a result of the credit from loyalty schemes and buying power incentives from suppling companies. It was also seen that the consistent buying or leasing of a single brand of machinery, brings a better understanding in the operation process.

There was a shared hesitation amongst the interviewees when discussing a shift in purchasing more new, efficient and ‘eco’ machinery. This was mostly due to the lack of supporting evidence behind how effective and efficient the machines may be in New Zealand market. Therefore, although new machinery is typically seen as providing more efficiency, financially, old machinery is preferred due to uncertainty around new machinery life cycle costing.

4.3 Social Sustainability

The general consensus from respondents around machinery selection framework was that it was viewed as having limited impact on social sustainability when, or if, integrated into projects or companies. When considering social sustainability on a project or development, the majority of interviewees noted they felt little emphasis to introduce the issue through planning or any other means of enhancing social sustainability into projects. The reasoning behind this was due to social sustainability having very little or no importance during tender evaluation stage.

Though social sustainability is currently viewed as having low importance, it was also recognized by interviewees that the awareness around social sustainability has potential to develop more importance in the future. The literature review has also shown similarities in this study. A machinery selection framework was considered to be able to show benefits around social impacts on projects and developments in outlining issues and opportunities that may arise. Ultimately this framework outlines good prospects of developing solutions in social environment that can be engrained into projects to help implement and improve social sustainability.

4.4 Machinery Selection Framework and Competitiveness

Interviewees were asked to comment on the potential for business competitiveness through machinery selection frameworks. The majority of interviewees discussed that implementation of machinery framework selection would not hinder or better the contractors bid. However, in the event of clients generating a better understanding of the significant benefit a machinery selection framework may have on a project, it is was considered that this framework could be encourage the implementation of this requirement. If the demonstration of a machinery selection framework became something that contractors were measured against at the time of tender, then it was agreed that this would encourage contractors to more readily implement these processes as it all of a sudden has a near tangible benefit, In the sense it is a tool that can be used to generate work.

4.5 Implementation of Machinery Selection Framework

The interviewees provided two shades of opinions on the implementation of a machinery selection framework in New Zealand. Their views on the challenges with the implementation of the framework are briefly described as follows. Firstly, the biggest challenge New Zealand encounters and continues to face, is the issue around skilled labour shortage. It was considered that poor machinery selection was currently attributed to a lack of skill rather than selection for sustainability reasons. However, as a result the availability of skills frequently determines the machinery to be selected rather than other sustainability factors. Unfortunately, the skills challenge is likely to continue into the near future in the construction industry in New Zealand, and therefore the implementation of a machinery selection framework was seen not to be efficient.

The second challenge highlighted by interviewees is that the size and dollar value of typical earthworks projects within New Zealand are not deemed to be large enough to warrant such a complex machinery selection framework. Because of the time and money that has to be spent on interpreting all the different variables of a project to be able to implement a machinery selection process, it was perceived that the value these frameworks would generate would be outweighed by the cost of implementation, making them a non-sustainable financial model.

5 Discussion of Findings

This study was able to draw common themes and opinions from all the study participants. All of the participants could see the potential improvements a machinery selection framework could offer, in regard to improving the environmental, financial, and social sustainability of the earthmoving industry in New Zealand. There were issues identified that if rectified would encourage the implementation of a machinery selection framework. However, there were some more significant issues that currently underpin the New Zealand industry, that would need to be overcome before the true benefits of the machinery selection framework will be realized.

One of the largest issues that was identified was the dollar value and scale of projects that are typically carried out by the earthworks sub-sector. Typically, these projects are $20 million or less and typically privately funded. It was agreed that typically the clients of these projects do not put enough emphasis on the contractors to demonstrate any sustainability processes, and it not considered when evaluating contractors at tender. In addition to this lack of emphasis on the sustainable processes, these projects are typically not deemed complex enough to warrant a sophisticated machinery selection framework.

Another problem identified, which underpins a lot of the current issues within the New Zealand, is the huge skills shortage that is plaguing the industry. This is seen to majorly constrain the ability to successfully implement a machinery selection framework on two different fronts. At one front, the few highly skilled machines operators in the market are being offered extremely lucrative employment opportunities, on whichever machine they are conversant in order just to secure them in their work force. When machinery is being selected out of preference, it can often mean the most efficient machine is not always utilized. However, on the other front the shear lack of skilled workers means that the most efficient piece of machinery isn't being used due to the lack of a suitably skilled person to operate it. This is a problem that other, larger earthworks sub-sectors around the globe do not face due to there much larger employment base. What makes this problem currently unique to New Zealand is that we have such a small employment base, the majority of which has low skill levels. This means we are having to run operations at the lowest levels of complexity, just to ensure that the labor force can carry out the task safely. In turn, this has significant detrimental impacts on the potential opportunities to improve the environmental, financial, or social sustainability of projects.

It was identified that in order to be able to successfully implement a machinery selection framework capable of improving the environmental, financial and social sustainability of earthworks projects in New Zealand. Then there would need to be a cultural mindset change to the way the New Zealand earthworks industry approaches sustainable practices, such as machinery selection frameworks. The mindset of the industry needs to be shifted from sustainable practices being a "nice to have" to a "must have".

In order to implement this change, it was identified that a holistic look at the industry needs to be undertaken, and that the responsibility of implementing this change does not lie solely with the contractor. Currently developers are rushing to workflow as much as possible in the construction boom, it is perceived that these clients are typically more worried their projects balance sheet or profit before considering any sort of sustainable attributes of these projects. In order for the contractors to see a benefit in the development and implementation of machinery selection frameworks then clients and developers need to put more emphasis on evaluation of these sustainable practices when considering contractors tenders. Once contractors see that this could have potential financial benefits for them, they will then be incentivized to implement such sustainable systems. This has proven to be a means of enforcing industry standards recently, with the introduction of the Health and Safety at Work 2015 legislation. If contractors did not meet the minimum requirements set out by this legislation, then this would have a financial impact on their business as they would be unlikely to win any further work until this standard was met. This model could also be followed to as a means of accelerating the implementation of sustainable practices such as machinery selection frameworks, and in turn it was perceived that this would ultimately increase the environmental, financial, and social sustainability of the New Zealand earthworks industry.

6 Conclusions

In conclusion, this study has identified that machinery selection frameworks have demonstrated to be an effective means of improving environmental, financial, and social sustainability practices within the New Zealand sub-sector of the industry. However, there are a few constraints within the industry that are unique to New Zealand that need to be addressed before a machinery selection framework can be implemented successfully. These constraints are similar to those in more advanced economies. However, ultimately to be able to successfully implement machinery selection frameworks within New Zealand then they need to become nimbler and more adaptable.

This study takes the view that machinery selection frameworks will inevitably become a regular and integral part of the earthworks industry. Currently there is reluctance to change, driven by specific industry constraints. The real challenge is for developing industry champions to take the steer and demonstrate the benefits of implementing these new technologies (Toor and Ofori 2008). Once implemented they will change the way the industry operates forever, and will hugely benefit the environmental, financial, and social sustainability of the New Zealand Earthworks industry.

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Integrating Lifecycle Thinking in Asset Management Through BIM: Opportunities for the Water Sector

Emiliya Suprun, Rodney A. Stewart, Sherif Mostafa, Oz Sahin and Edoardo Bertone

Abstract The water industry worldwide has been gradually transitioning towards digital asset management practices. Australia is no exception. However, these practices are often complicated by a lack of consistent models for gathering and maintaining up-to-date asset information across the industry. There is a need for innovative digital platforms and asset management solutions for making decisions that suit the increasing needs of the water sector. Building Information Modelling (BIM) can potentially be the conduit to asset management databases as it goes well beyond 3D models developed for use in the design and construction phase. The overarching goal of this research was to address the water industry challenge of implementing BIM to integrate digital data for the facility lifecycle as well as to provide information and decision support to asset management, and operation and maintenance. A number of workshops with asset managers and maintenance operators were held on the basis of a case study of a bulk water supply company in Australia. Stakeholders discussed specific expectations for the visualisation of information to ensure that data is used, understood and managed over the whole lifecycle. The barriers to the implementation of digital techniques for the purpose of efficient asset management were also explored.

Keywords Asset information model · Asset management · BIM · Lifecycle thinking · Water industry

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_7

1 Introduction

This study is timely in an Australian context where the Federal and State Governments are establishing policies and guidelines for the use of Building Information Modelling (BIM) and related digital engineering technologies on Government projects with both new and existing assets. For example, one of the objectives set by the Queensland Government for the development of BIM practices is "to promote consistency and interoperability in the information requirements for state infrastructure projects to facilitate a harmonized approach for industry" (DSDMIP 2018).

BIM is much more than just 3D design. BIM is an object-based approach to organizing information that can be described as a digital representation of physical and functional characteristics of a facility and its aspects (ABAB 2018). BIM is also a knowledge resource for information that allows for each project participant to share their discipline-specific data within a single project model (Wong et al. 2018). As a result, digital data derived from BIM acts as a reliable unified point of reference for decisions during assets lifecycle.

The water industry continually relies on the public sector infrastructure, such as drainage systems or water treatment plants (WTP), which are typical projects delivered by contract private water and construction companies in Australia. According to the Australian Bureau of Statistics (ABS 2017), the water industry in Australia had an estimated annual revenue of $22.71 billion, adding $13.06 billion to the Australian economy in 2015–2016. It goes without saying, that safe water quality and appropriate sanitation are essential to sustaining economic growth and the high standard of living in Australia. Hence, the importance of BIM for water infrastructure has become greater than ever before (Yin et al. 2014). However, where some industries are already successfully incorporating BIM workflows into their business processes and distribution networks, the water industry has been relatively slow to adapt to this change.

In recognition of the lack of digital integration in the sector, this study addresses the readiness of the Australian water industry to implement BIM throughout the facility lifecycle for making decisions that suit the overall duration of the lifecycle. The study also aims to capture the key decisions required in asset management, by considering lifecycle thinking during the design, construction, operation and maintenance (O&M) phases of water facilities. The challenges of the water industry to BIM implementation along with the digital data integration for the facility lifecycle and efficient asset management were discussed on the basis of a case study of a bulk water supply company in Australia.

2 The Role of Information in Asset Management

In the majority of cases, BIM models are developed for use in the design and construction phase, however, the O&M of a facility take up most of its lifecycle (Wong et al. 2018). According to Akcamete et al. (2010), the O&M of a building equate to 60% of the overall costs and time of a project. Hence, the potential benefits of using BIM for facility operations are compelling. First of all, BIM enables provision of the asset management systems with information relevant at the time of operation of a certain asset.

Potential BIM benefits for asset management are well documented in the literature (Becerik-Gerber et al. 2012; Love et al. 2014; Hafeez et al. 2015; Araszkiewicz 2017; Hosseini et al. 2018):

- enhanced capacity for maintaining and monitoring an asset over its entire lifecycle;
- proactive interventions and earlier decision making;
- better informed maintenance activities;
- more efficient asset management especially in the operational phase;
- better predictive analytics;
- an ability of all organization's departments to access high quality digital data about the assets;
- better understanding of an organization's needs by BIM compliant partners;
- facilitation of required savings;
- better risk management throughout design, construction, operation and maintenance.

Nevertheless, the utilization of BIM during O&M of the facility is falling behind the BIM implementation for design and construction (Akcamete et al. 2010). First of all, efficient management at the operation stage requires integrating a very large amount of information and data accumulated at earlier stages of the facility lifecycle, with information that appear in the course of a facility maintenance. Moreover, the effects of management during O&M stages result from decisions taken at earlier stages. As such it is critical that asset management processes can be fully engaged in the BIM process in order for the potential benefits and savings to be fully realized in operation.

It is also very important to use harmonised and consistent data formats, standards, systems and tools across the asset life cycle. Structured asset information for the commissioning, and operation and maintenance is used to supply data to the asset owner or operator to populate decision-making tools and asset management systems. In order to improve the information exchange and issuing of information that supports the delivery of a project, a common data environment (CDE) is recommended to be used (ABAB 2018). It allows a company to keep not only assets created in BIM environment but also documentation related to the assets. For the purpose of data transfer the data handovers are to be in open data format, such as industry foundation classes (IFC), BuildingSMART, or Construction Operations Building information exchange (COBie) standard (ABAB 2018).

3 Approach

A literature review and a case study serve as a basis for unlocking opportunities for innovative asset management solutions suited to the increasing needs of the water sector; assessing current systems for managing water asset information; identifying the key asset information requirements for effective management of specific key bulk water distribution assets and; establishing directions to follow in further research. The literature review included an assessment of the current methods adopted for utilizing project and asset information within the international water industry firstly, and then an Australian sector specifically. The study is aligned with the national and international requirements for integrating lifecycle thinking in asset management (e.g. ISO 55000) and information management (e.g. ISO 19650) (ISO 2014, 2018a, b).

Dawood and Vukovic (2015) state that a lack of managers' expertise is one of the key barriers to BIM implementation. Various problems the water industry faces while integrating digital technologies with asset management practices were discussed on the basis of a case study of a bulk water supply company in Australia. Two workshops with asset managers and maintenance operators were held. Stakeholders were asked to specific expectations for the visualisation of information to ensure that data is used, understood and managed over the whole lifecycle. Some of the questions that guided the workshops included:

- How mature is the water sector in terms of BIM implementation?
- What are the main obstacles to increasing BIM use in the water industry?
- What potential benefits does BIM offer for the water sector?
- How well are the models from the water projects integrated with asset management systems?
- What could potentially drive wider use of BIM for water projects?
- What is the most important next step to drive wider BIM utilization in the water sector?

4 Case Study

As mentioned above, the barriers to implementation of digital techniques for the purpose of the efficient asset management were discussed on the basis of a case study of a bulk water supply company in Australia. The company provides drinking water to more than 3 million people. It also provides essential flood mitigation services, managing catchment health and providing irrigation services to more than 1000 customers. Overall, the company manages more than $10 billion of water supply assets and parts of the natural catchments to supply their services. These assets include WTPs, dams, weirs, reservoirs, pumps and pipelines. The company's functions are but not limited to:

- carrying out water activities;
- supplying water services;
- developing water supply works;
- improving the supply, delivery and quality of water;
- promoting efficient use of and investment in water infrastructure;
- ensuring the safe, secure and reliable supply of water.

With numerous construction and engineering partners working on a multitude of water infrastructure projects and providing various formats of design documentation information, the company requires integrated and/or interoperable digital asset management tools to ensure efficient operation and maintenance of its current and future planned infrastructure, plant and expansive natural assets. Moreover, the Queensland Government takes the first steps towards implementation of a policy to gain the maximum advantage of digital engineering and has committed to implementing the use of BIM on all major state infrastructure projects by 2023 (DSDMIP 2018). Hence, this study's outcomes aim to prepare the water company to strategically position themselves to transition to digital engineering in order to align with upcoming legislative requirements. It is also expected to improve the company's ability to make strategic and sustainable investments throughout the lifecycle of its assets as well as to help the company to build capacity related to the adoption of structured digital data to make better informed decisions.

In relation to integrating different digital platforms throughout the facility lifecycle, the following challenges were identified through a number of workshops:

- a very diverse asset base;
- the usability, accessibility and relevance of the data in the systems;
- the quality of the digital data in the systems;
- the ability to find asset information;
- the use of unrelated spreadsheets to complete basic asset management functions;
- the duplication of information;
- the lack of information sharing;
- the understanding the information flows associated with the end to end processes;
- an inconsistent asset information framework;
- information might become distorted or irreversibly before the operation and maintenance stage.

Stakeholders also agreed that information exchange through the water asset lifecycle remains fragmented and the asset management is disconnected from the design and construction phases. This proves the necessity of including asset managers in the entire lifecycle of a facility. During multiple discussions, it was concluded that understanding the key needs of asset managers enables to define detailed scope and priorities amongst information and data necessary for the efficient asset management. This in turn aids the design of a precisely formulated effective BIM implementation roadmap to be used to trigger the digital data collection requirements during the lifecycle of the project. As a result, the governance and the ongoing maintenance of asset information become more efficient; there is only one 'source of truth', i.e.

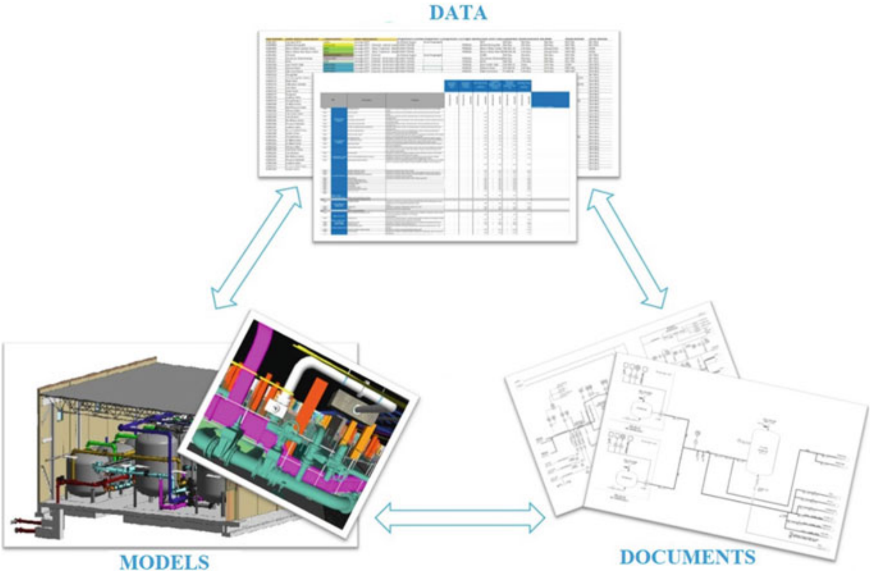

Fig. 1 An anticipated asset information model

database that links all asset related data sources and enables accurate reporting; asset management decisions are based not only on 'expert judgement'; the ability to run meaningful analysis increases and; interoperability between various water asset management systems and data sets is facilitated properly.

By overcoming the identified challenges, the company anticipates the following benefits to emerge:

- development of an asset information model that supports all asset management processes (Fig. 1);
- lead the Australia water sector in BIM adoption;
- better risk and uncertainty management;
- better business plans along with asset condition and performance as a result of better asset information processes;
- lifecycle cost saving;
- ability to produce better scenario plans and models;
- customer engagement;
- better informed decision making;
- improved accuracy and consistency of design information;
- improved cost predictability;
- better collaboration between project team members;
- high quality information base for maintaining water facility over the lifetime.

5 Conclusion

The main goal of this research was to address the challenge of BIM implementation within the water sector for integrating digital data embedded in water facilities' existing and future proposed digital models across a facility lifecycle. This goal lay in getting participants involved in the various stages of a facilities project (e.g. designers, builders, operators and maintenance staff) to engage with asset managers in an integrated and coherent manner. BIM is not only a 3D model; it is a collaborative process that delivers value, efficiency and safety, recognizing the whole life of asset knowledge and asset lifecycle information management.

Obstructions to the implementation of digital platforms for water asset management were identified, to improve the efficiency of water asset management practices in an Australian water supply company. Overcoming these barriers will enable to develop a necessary strategic direction to transition towards a comprehensive digital asset management agenda. This in turn ensures that awareness of lifecycle thinking and its impact on decision making is better understood by the Australian water industry. Moreover, the digital integration could help achieve economic, social and environmental benefits; enhance the value of assets over their lifecycle; and also provide avenues for educating clients and society on lifecycle thinking.

Further work is associated with providing an asset management agenda that demonstrates the value of lifecycle costing as opposed to short-term thinking. Moreover, there is a need to develop methods to educate water professionals and the broader urban water industry on long-term lifecycle thinking for facilities.

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Information Systems Supporting the Optimization of the Prefabrication Process in the Construction Industry—Case Study of a Steel Plant

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Abstract Dynamic changes in the macroeconomic environment of enterprises make it necessary to constantly improve production processes in order to maintain a competitive position. This article presents results of a case study on the implementation of digital tools to improve information management and production planning in a steel plant for construction purposes. Presented solutions will be an example of the possibility of using parametric models developed in accordance with the assumptions of the Building Information Modelling method in prefabrication. Tools for task planning and monitoring of material supply, transport to construction and assembly are described. A solution enabling planning changes is also presented, including automatic assignment of machines, employees, according to the importance of their tasks. The case study allows the identification of potential benefits, both organizational and economic, that result from the use of digital tools in the production of prefabricated steel structures. Application limitations, established on the basis of the case study, related to the use of digital solutions, are also indicated. On this basis, an attempt has been made to indicate the direction of further research in the field of digital prefabrication and its impact on the optimization of the production processes of construction companies.

Keywords Digitalization · Prefabrication · Construction sector · BIM

1 Introduction

The production of prefabricated elements of building structures requires the processing of a large set of information of a diverse nature encompassing such basic production data as information on material consumption necessary for accounting purposes (technical manufacturing cost), planning purposes, purchasing purposes, logistic information related to the displacement of materials and components within the supply chain or between warehouses and production halls.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_8

A number of enterprises use software supporting individual processes of planning and manufacturing developed specially for a given company or operate using the ERP integrated system. The functioning of these tools and their technological advancement may substantially influence the enterprise's productivity and effectiveness (Hallin et al. 2017).

The objective of this article is to present the results of a case study on developing and implementing digital solutions designed to streamline information management and production planning at a steel structure plant providing designing, manufacture and assembly of steel elements services, related to the implementation of building ventures.

2 Method

The article was prepared on the basis of the results of a case study, carried out in using the non-participating observation method during the first stage of implementation of the system described in the article. The case studies can be considered both in terms of the process, but also as an object or as a result of the study, while taking into account such distinctive features as: limited subjective character, considerations in a broader context of events, multidimensionality of the analyzed variables and interdisciplinarity (Stake 1995). As a kind of qualitative study, the case study makes it possible to understand the situation, in terms of its uniqueness, the nature of a specific phenomenon, its context and interaction with its other elements (Ellinger et al. 2005). The observation method was also applied as it makes it possible to directly learn workers' behavior in the course of implementing the digitalization system subject to examination in their natural conditions and circumstances.

The development of cognitive methods in research on project management and organization makes it necessary to adopt an open approach requiring the combination of many methods. In this research, a case study was used in conjunction with the observation-intervention method (participant observation), which was carried out as part of the transformation activities in the surveyed company. The authors directly observed the process of changing the organisation of the work in the company, introduced by implementing digital solutions, participating in this process as external experts supporting the change process in the company. The observations were made during the working day, for an average of 6 h during the day. The results of the observations were recorded on an ongoing basis in the form of working test reports, which were then used for analysis along with the documentation of the implemented system. The observations were carried out during one week-long and 10 two-day visits to the company, which took place within six months of starting the procedure for the development and implementation of the new system.

3 Literature Review

The use of new digital solutions in steelmaking processes can bring very large benefits associated with the optimization of the entire production chain including the integration of business processes along the life-cycle of production facilities. The digitalization of a company is connected with the integration of (Herzog 2017):

- systems across the classic automation levels from the sensor to the ERP system,
- systems along the entire production chain,
- the entire life-cycle of a plant from basic engineering to decommissioning.

The advantage of implementing digital solutions in production processes is also the fact that they enable the creation of new design possibilities, through the increased flexibility of fabrication (Kerber et al. 2018). Regarding production processes in companies offering design, production of prefabricated structural elements and their assembly at the construction site, the possibility of optimizing these processes by using parametric BIM models as a source of information at the beginning of the production process of prefabricated elements is pointed out (Joosung and Jaejun 2017; Qi et al. 2018). The authors describe assumptions of a system of a logistics planning and control model for site assembly of prefabricated building systems using BIM 4D modelling. The results of the application of the production system with the support of BIM 4D modelling, aligning this process with the Last Planner System of production control in a steel fabricator company are presented (Bortolini et al. 2019). The possibilities of utilising the BIM model in order to enhance the production of prefabricated structural elements of multifamily residential buildings are analysed in a broader context referred to in literature as a combination of the BIM model and the building (*BBB—bridging BIM and building*) (Chen et al. 2015).

Studies show the benefits of such a combination in relation to prefabrication. These benefits include productivity increase due to the model-based process reduction of material consumption and waste from production processes (Ocheoha and Moselhi 2018; Lu and Korman 2010; Jones and Laquidara-Carr 2016).

In analysing the processes of implementing the digital solutions, it should be noted that these solutions are largely utilised by workers; therefore, a major stream of research related to digitisation concerns the influence of digitisation on people and their work, both in terms of streamlining and impediments regarding implementation of the changes connected to the digitisation of enterprises (Won et al., 2016; Chen and Tserng 2017; Babič et al. 2010; Kulkarni et al. 2018).

4 Case Study

The Steel Structure Plant (SSP) provides services that include designing, manufacture and assembly of steel structures for the purposes of building such facilities as: industrial halls, sports arenas, commercial centres, roofing for parking lots and sports facilities, masts and towers, bridges, or special purpose facilities (overhead power lines, airport control towers). The production preparation process is distinctive due to a large number of variables and high degree of complexity. The Plant performs short run production for specific orders, unconventional due to the diverse line of products. The production process at the SSP is characterised by the following features:

- structural elements are manufactured based on an individual order, for required quantities, and deadlines expected by the client,
- building project documentation, most often supplied by the client, is the basis for workshop projects developed for production purposes,
- materials are ordered in line with individual orders,
- there are no production inventories,
- workshop reports concern primarily the performance of tasks as part of individual orders,
- workshop documentation is drawn-up directly before tasks are transferred for production.

The progress of the Plant's major processes is illustrated by the process map (Fig. 1). Further main tasks (steps) covered by the major production processes at the SSP can be defined as follows:

- receiving an order from the client,
- drawing-up a production plan budget,
- preparing technological and workshop documentation (if not supplied by the client), or analysing and verifying the documentation received from the client,
- preparing for production (making a list of materials, calculating appropriate paint volume, performing cut-outs, preparing project technology),
- verifying free stock against quantity list,
- removing items that are in storage from the list (status: free stock),

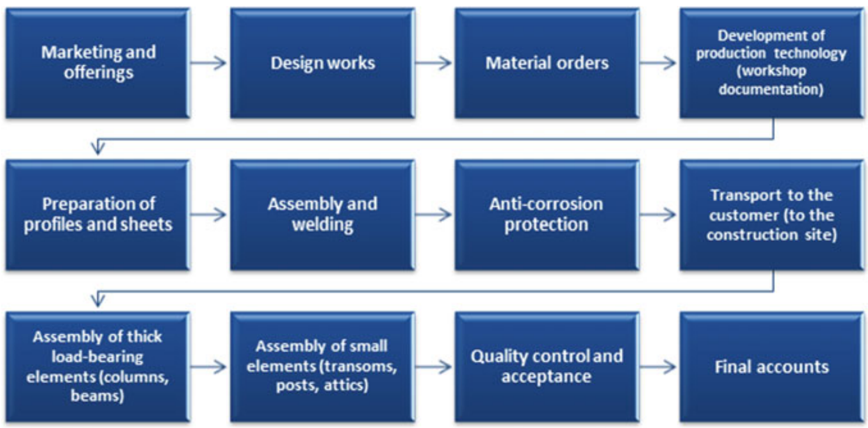

Fig. 1 Map of major processes at the SSP—from design to embedding

- sending requirements to material suppliers for the purposes of processing the order,
- ordering metallurgical and painting materials (if not supplied by the client),
- receiving materials to storage,
- preparing production (allocating metal sheets to machines, profiles, uploading NC files to CNC robots),
- releasing material from storage assigned to specific order,
- cleaning metallurgical materials,
- providing production workers with technological documentation,
- performing the production preparation process (burning contours, burning chamfers, drilling, cutting, chamfering, machining),
- installing assemblies and sub-assemblies of structural elements,
- manual and machine welding of assemblies and sub-assemblies,
- cleaning prior to anti-corrosion protection application to the level provided for in the documentation,
- applying anti-corrosion protection according to the technical documentation of product (painting, metal plating, hot-dipped galvanised coat, or galvanisation)
- packing and dispatching finished structure,
- settling the order.

The process is overseen by a quality control team (internal quality control or an external company—depending on the plant). On completion of the anti-corrosion protection application, the structure is stored waiting in queue for the dispatch time to the client scheduled in advance. Depending on the structure type, the manufactured elements are properly packed and marked. In case the order also includes assembly, the process map allows for an adequate extension which facilitates the organisation of installation works on site.

The production process at the SSP is supported by the ERP system, but it is not integrated in nature. The existing ERP solution is not adapted to the specific needs of implementing the production of steel structures. The scope of IT tools used within the system encompasses a storage system and several small applications supporting pre-production processes (list of steels, profile database, application to create cut-outs).

Having audited the production processes and mapped these processes, problems requiring solutions were identified to optimise the production operation of the SSP. Key impediments included a long time allotted to production planning (this stage was pointed out as a “bottleneck”). The reason why this impediment occurred was first of all the long time allotted for the analysis of data resulting from the client’s project documentation, and then the time-consuming development of workshop documentation, and planning the tasks of individual workers. In addition, both the determination of material demand and processing of the order necessary to launch the process were time consuming and lowered the SSP’s productivity.

The most significant causes behind the decision to begin working on the new digitisation system of the SSP can be defined as follows:

- lack of the possibility for unambiguous identification of the bottleneck in the process,

- lack of the possibility for monitoring workers' productivity by means of objective indicators,
- lack of the possibility for monitoring technological shutdowns and identifying their causes,
- the problem of quick location of details and products,
- lack of the possibility for accurate assessment of production costs and process effectiveness,
- lack of access to the costs of a specific production stage.

With respect to the problems mentioned above, the objective of the analysed research and implementation project was the technological and procedural justification of tasks performed by production workers, as well as engineering supervision, and replacement of traditional communication based on printouts of project documentation between the designer, the project manager team and the production workers, with operations using digital files in the cloud space.

A working team was appointed to implement the project composed of the digitisation manager, IT programmer—author of the solution used for the purposes of the described process automation, and the SSP production manager. As part of project planning, the working team defined the scope of the first stage of the process of digitisation of the production process of steel structures expected by the enterprise. This scope included:

- the use of BIM models—three-dimensional parametric models received from the designer. BIM models are designed to analyse the project, perform measurement and cost calculation, develop a schedule of orders and material supplies using Autodesk BIM 360, and draw-up follow-up documentation. In addition, it was planned to utilise the BIM model in the procedures of acceptance and verification of the quality of manufactured elements of steel structures,
- Smart Work and mobility of production workers—using tablets, mobile applications and "Smart Kiosk" solutions developed for the SSP—access point to applications, project documentation and OHS training for the workers,
- documentation—unifying the working standard using digital data and their replacement between the designer—contractor—project manager team,
- sensors—reporting results of structure behaviour inspections—using QR codes for the purposes of tracking elements made in-factory and delivered to construction sites (manufactured, delivered, embedded),
- measuring tools (laser scanning)—follow-up analysis of manufactured steel elements to reduce the costs of faulty performance—the reduction, and ultimately the removal of test installations from the process.

The schedule of developing applications to optimise the production at the SSP included the following framework tasks:

- solution for the purposes of working time standardisation—automatic calculation of time necessary to perform a given order based on the BIM model,

- solution defining detailed technology of order processing—quick development of manufacturing documentation (technical specification of work performance, key performance aspects),
- solutions allowing for the automatic determination of a production schedule—on the premise that after entering the scheduled date of delivery on site by the engineer, production times according to standardised times are set automatically,
- solution allowing automatic assignment of tasks to workers, including generating task sheets for every worker from the system with a possibility of printing them,
- solution for the purposes of performing assigned tasks—worker panel on tablet containing access to a digital version of the documentation, workshop drawings, task sheet.

The system was equipped with consoles made available to the workers with the following options:

- exchange of information,
- records in a virtual production log,
- records in diary and notebook,
- making messages available to other workers by means of an internal messenger,
- transferring data to workers from other shifts.

5 Discussion

5.1 First weeks of System Implementation—Observation Results

The greatest difficulties in implementing the system observed during the initial stages of implementation were not related to the technological area, but the area of the workers' education, and their attitude towards the change. An example can be a case of equipment used during work by operation workers, which was designed to ensure the mobility of said workers and facilitate access to necessary documentation during their work. In accordance with the original assumptions, A-branded tablets were ordered, which meet very high standards of durability, software functionality, and enable easy integration with the company's existing IT infrastructure. After the first tests, it turned out that the type of this equipment should be changed to cheaper B-branded tablets operating with the use of an application available in every segment of the IT market, ones that the workers were already familiar with, and who were using this application on their private devices.

The solution that was very quickly accepted by the workers was the Smart Kiosk, the access point to the workshop documentation and the reporting system. This point was organised so that the workers could solve technical problems jointly in team on a current basis.

The results of the first stage of implementing the system can be summed-up as follows:

- tablets and computers were introduced that were used by the workers during production, which enable easy access to the new production management system, including monitoring the workshop documentation in a digital version,
- workers use the access to the digital version of the task sheet at every production stage,
- workers receive partial digital documentation illustrating a segment of the relevant technology directly related to the assigned task (not the whole documentation as has been the case to date),
- on completing their tasks, workers mark the manufactured elements, and indicate their location in the system—due to this, another production group has access to the information on what has already been done, or where the already manufactured elements are,
- next stage workers receive full information on the completeness of the details of an element, and can easily determine the location of the set of details,
- construction site workers receive a digital shipping list, and they can more easily verify the completeness of deliveries,
- the quality control team receives information on the completion of a work stage on an ongoing basis,
- production engineers can monitor operation progress informing of percentage progress of a relevant stage,
- the supervision team has ongoing access to the state of production.

For the purposes of production process monitoring, the system provides the following:

- detailed reports on the workers' work in particular production stages,
- detailed reports on technological shutdowns (enabling determination of the reasons for the shutdown and its time),
- reports that enable comparing the actual time of performing the relevant process with the scheduled time calculated automatically according to the project based on labour standards,
- reports on submissions to quality control,
- client shipping lists.

The reports are saved in OpenXML (xlsx) files, which enables their editing, comparison and comfortable management.

6 Results in the First months of Implementation—Technological and Process Streamlining

Upon completion of the first preliminary stage of the implementation, the system automating the production process at the SSP and possessing the above-mentioned functionalities enabled the following:

- quick and precise monitoring of production time with reference to the time calculated at the stage of production planning,
- determining the capacity of individual production processes,
- monitoring technological shutdowns—their type and the duration of every shutdown,
- precise location of the elements produced,
- easier supervision over the observation of standardised working time in a given production group,
- collecting and sharing information on the time allotted for additional work, e.g. cleanup work, which improves scheduling the processing of subsequent orders.

The system allows for the control of the process of manufacturing individual elements of steel structures in respect to the time of their execution. The generated data is processed for the purposes of analysing the productivity of production groups. This leads to the identification of so-called “bottlenecks”, or weakened production links, which, in turn, facilitates quick reaction of the management to production process disruptions.

Moreover, the worker receives precise and clear manufacturing documentation with indications of all the elements and detailed solutions and the defined treatment type, which relieves the supervision workers the responsibility of assigning tasks. The solution that enables the workers to access sub-assembly locations which are part of the shipping element is a significant advantage in the supervision of the production process. As a result, the production manager can more easily track the progress of the production process and the stages of processing the order, which enables forecasting when a given element will be ready for shipment to the construction site, and thereby enables ordering dispatches in advance.

7 Conclusions

The ERP systems used in a number of enterprises are often insufficient to effectively support production processes and individual tasks in the processes, particularly those connected with production planning and logistics. An often identified limitation is the small range of possible modifications to schedules based on ongoing events, lack of access to a production process that is already underway and the lack of complete information on the minimum level of the stock of a given product. In addition, a big impediment is lack of the possibility for the quick determination of production capacity.

The system of digitising the SSP's production described in the article has not fundamentally changed the production processes but may considerably facilitate the Plant's effectiveness due to easier communication and smooth access to information for the purposes of production and current process control, with results easily available for the engineers supervising the production. The information gathered from the relevant production process is entered into the enterprise's knowledge base, and can be utilised in pricing subsequent orders, thereby improving the accuracy of the pricing, and lowering the risk of underestimating production costs. The implemented software also helps to identify shutdown causes during production.

One major limitation identified in the first stage of implementing the digital solutions designed for the SSP was the workers' resistance to the changed method of work, which is often observed when changes are being introduced in an organisation. Therefore, in the next stage of research, it will be extended towards an in-depth examination of the workers' adaptation to operate in the new system, so it is also possible to formulate proposed actions streamlining the implementation of digitisation in production enterprises. Furthermore, the authors see the necessity to thoroughly examine the tangible economic effects related to the implementation of the system.

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Immersive Virtual Reality Environment for Construction Detailing Education Using Building Information Modeling (BIM)

Maha ElGewely and Wafaa Nadim

Abstract Construction site visits are real-life practical experience where the AEC students' conceptual knowledge is developed and serves as an extension of in-class learning tools. Nevertheless, very low rates of construction site visits have been reported worldwide due to certain limitations, such as the limited visit time, the lack of visit objective, potential hazards, etc. In addition, site activities may also meet specific class needs. During a construction site visit, students mainly learn through their own observation, not by involvement in the site work or having the possibility to take decisions. Besides, students have only the chance to attend one phase of construction. Virtual reality (VR)—as a game-friendly, interactive, and immersive technology—may facilitate virtual construction site visits to meet learning needs and provide the learner with a near-real experiential learning environment where he/she can "learn by doing" in a zero-risk environment. In this essence, this paper describes "VRConDet" project which builds on the VR technology as a medium and Building Information Modeling (BIM) as a source of technical information taking into consideration adults' active learning and gamification of learning materials. "VRConDet" is a computer-assisted learning (CAL) conceptual framework for construction detailing that aims at enhancing the learning experience and learning outcomes for construction education within architecture curricula. This paper focuses on "VRConDet" system architecture and the design of its diverse, scalable, and adaptive modules according to the correspondent complexity and intended learning outcomes of construction education. The results of this first phase feed into a second phase of VR environment development and the validation thereof.

Keywords Building construction education · Building information modeling (BIM) · Computer assisted learning (CAL) · Virtual construction site · Virtual reality

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_9

1 Introduction

If not supported by practical experience, construction-related education is arguably limited. Real-world experience cannot be conducted through traditional lectures and teacher-centered way of education. Construction site visits help students to relate what they study in books to real-life situations (Eiris Pereira and Gheisari 2017). Construction site experiential learning's benefits have been highlighted by a number of researchers (Aliu and Aigbavboa 2019; Irizarry et al. 2012), such as enhancing students' understanding of real construction practices, improving students' knowledge of industry expectations, and addressing different learning styles for students, especially that a construction site visit is mainly considered an auditory and visual learning environment, which may arguably result in a better understanding of course material and consequently qualified future workforce.

1.1 Challenges of Construction Site Visits

Despite the benefits with which construction site visits support the construction education and learning experience, low rates of such visits are reported in extant literature. Many challenges prevent such visits from taking place on a regular basis during an academic semester. Based on a survey conducted on a number of construction programs in USA universities, graduates have had zero or one to two site visits for each construction core subject areas taught throughout their careers (Eiris Pereira and Gheisari 2017). Inclusion of site visits within a course schedule is not always feasible due to varying reasons, such as unavailability of construction sites meeting the intended learning outcomes (Haque et al. 2005), time conflicts with other classes, large class sizes, and safety issues. In addition, other aspects limit the benefits of construction site visits; for example, during a site visit, students are able to see one set of activities on a particular type of project (e.g., high-rise building). This does not allow students to see how the activities fit together in the dynamic nature of the construction process; therefore, they are able to learn from observation, but not from experimenting and active participation (Messner and Horman 2003). Furthermore, a lack of clear objectives for site visits can also lower the benefit for students (Eiris Pereira and Gheisari 2017). In this respect, the need for supplementary methods for experiential learning is needed to make site visits both more often and more beneficial.

2 Virtual Construction Site

Advancements in information technology have allowed innovative ideas to bring construction site to the classrooms to bridge the gap between AEC—Architecture, Engineering and Construction—industry and academia. One of the most significant applications is virtual construction sites. Virtual site visit is introduced from different points of view in multiple studies as semi- to all-immersive virtual experience of construction projects that might be accessible anytime, anywhere by construction students employing some sort of photo/video-graphic medium as a teaching aid to either observe the construction project or interact with construction professionals (Eiris Pereira and Gheisari 2017). Virtual site visits may include tours by PowerPoint, time-lapse videos of large construction projects, and video conferencing between class and jobsite (Eiris Pereira and Gheisari 2017). With the help of cellular Internet service, a hand-held computer, and standard digital video camera, students are engaged in "Virtual Project Tours"; and are allowed to view and hear real-time construction activity being completed at remote project locations without leaving the classroom (Becker et al. 2011). "Virtual Supervision" is another research-based project that has been developed at the University of Calgary which is a web-based enabled view and recording cameras that include remote-controlled functionality, such as directional movement and close views for specific construction operations (Becker et al. 2011). Furthermore, adaptive e-tutorials were introduced by Kamardeen (2014) as a time- and place-flexible learning system in construction education following active engagement and interaction aspects to promote deep learning. These innovative ideas adopted technology in various ways to overcome the challenges and risks of typical construction site visits which may not be possible due to safety concerns or other project-related constraints. Neverthelees, these innovative approachesrequire cooperation and flexibility between industry and academia. Furthermore, these unconventional ways of learning have other social and technical challenges that might limit their application as a main stream; for example, reforming the lecturer's pedagogical input in digital, adaptive, and stand-alone media is time- and effort-consuming relatively to the traditional approach of teaching. In addition, unfamiliarity with new computer-assisted learning (CAL) systems may need more time and effort from both teachers and students in order to get used to the new technology and is also challenging to achieve with large numbers of students (Kamardeen 2014).

3 Building Information Modeling

BIM holds different meanings to different people. From a technical point of view, BIM represents sophisticated software that enables technical industry standard. On a deeper level, it describes a philosophical framework that offers a paradigm shift within the construction sector (Khosrowshahi 2017). Isikdag (2015) defined BIM, from a process perspective, as a facility that enables information management throughout the lifecycle of a building, while building information model is the (set of) semantically rich shared 3D digital building model(s) that form(s) the backbone of the process itself. There exist worldwide trials to integrate BIM in AEC curricula as part of preparing students for the workforce through educating BIM approach

(Ghosh et al. 2013; Sacks and Pikas 2013). BIM visualized models and associated property databases provide an enhanced platform for teaching and training (Clevenger et al. 2012). It is confirmed that BIM, as a learning and teaching tool, has the potential to assist construction education as it can make information available in a manner that is much more accessible to visual learners (the majority of learners). In addition, BIM's 4D capabilities enable students to better understand the assembly process through the production of assembly animations (Boon and Prigg 2011; Le et al. 2015; Gledson and Dawson 2017; Irizarry et al. 2012).

In light of the above, BIM can be used as a teaching/learning tool targeting a wide spectrum of topics and courses as it provides the faculty with an interactive tool and information repository to facilitate teaching of engineering and construction concepts in a more visual and interactive manner, extending along the way the learning environment beyond the classroom boundaries; thus, having the potential to considerably enhance the educational experience of students (Irizarry et al. 2012).

As a user-friendly, interactive repository of information, BIM has been integrated with other technologies such as virtual reality and augmented reality in different forms (Horne and Thompson 2008; Vassigh et al. 2018; Gheisari et al. 2016; Gledson and Dawson 2017).

4 Virtual Reality

According to Collins Dictionary (2014), virtual reality is "a computer-generated environment that, to the person experiencing it, closely resembles reality." From a technical point of view, virtual reality represents an advanced Human—Computer Interaction (HCI) and interface tool. VR environments provide an immersive experience in which participants wear tracked glasses to view stereoscopic images and listen to 3D sounds, while being free to explore and interact with a 3D world (Chan 1997). It has been proven that VR became an area of increasing research and development activities in architecture and construction (Leinonen et al. 2003). The research areas may include e.g. design methods, architectural theory and history, performance evaluation, human interaction, representation, process and management, etc. (Freitas and Ruschel 2013). The majority of studies primarily emphasize means to apply VR and AR, with a focus on how to use them for visualization as well as how to use them in practice; this is followed by the use of VR and AR in education. Virtual-reality and mixed-reality concepts are now being introduced into gamification, game enhanced learning, and pure education (Shavinina 2013). Publications in the field of virtual reality in education have been exponentially increasing over the past 20 years (Liu et al. 2017). According to Lui et al. (2017), 160 worldwide peer-reviewed papers were published in 2016 on virtual reality in education. Scientific research has proved that VR enhances students understanding, allowing them to learn by doing and engaging learners in a learning environment close to reality; thus, stimulating various information perception points (Blazauskas et al. 2017). In this respect, virtual reality arguably opens new ways of learning in the field of education.

5 Computer Assisted Learning

According to Knowles et al. (2012), adults learn best when learning is active, self-directed, based on problems, related to their experience, and perceived as relevant to their needs and they are intrinsically motivated. Integrating BIM and VR may facilitate the principles of computer-assisted learning (CAL) which emphasizes *"learning by doing"*. Traditional CAL resources consisted primarily of tutorials, which were essentially computer-based forms of programmed instruction (PI) or intelligent tutoring system (ITS) that typically contain a sequence of contents broken into sections and questions in between (Dalgarno 2001). In addition, CAL may take a form of gamified learning materials or simulation of real-life situations which focus on the learning experience leading to better understanding and behavioral outcomes, which is the core of the learning process (Hamari et al. 2014).

6 VRConDet

Building on the potentials of integrating BIM and VR, this paper introduces the first phase, the architecture, of a learning environment to enhance construction education. VRConDet is a computer-assisted learning (CAL) conceptual framework for construction detailing that aims to enhance the learning experience and learning outcomes for construction education within architecture curricula. It builds on the VR technology as a medium and Building Information Modeling (BIM) as a source of technical information following aspects of adult's active learning and gamification of learning materials. VRConDet is a head-mounted display (HMD), interactive, virtual-reality construction-detailing environment for educational purposes. It focuses on construction detailing which is considered a continuous thread in almost all vertical curricula of construction education. According to a survey—conducted by the researcher—on one hundred architecture students in different semesters, construction detailing represents the highest challenging topic to students in all construction courses. VRConDet is not proposed to replace the traditional ways of learning Building technology and Building Construction; it is meant to assist as a computer-assisted learning (CAL) tool to overcome limited construction site visits and to offer a contemporary active way of learning to increase student motivation through different complexity levels based on the intended learning outcomes (ILOs).

6.1 Scalability

VRConDet was designed to be a modular expandable system in order to be able to expand vertically to cover advanced BIM dimensions as well as horizontally to broaden the tackled topics.

6.2 Soft System Methodology

The soft system aims to map the main functions of VRConDet in regards to its potential users, in other words, who is able to do what? Besides, it defines the process behind the user interface. Primarily, VRConDet has two types of users: the instructor and the student (Fig. 1). Each has their own interface and controls. The instructor mainly interacts with VRConDet through a desktop interface, whereas students have their own VR environment and another desktop-based interface for rechecking what they have done in the virtual environment. The instructor interface empowers students to determine which approach of construction detailing classifications is the most appropriate for the session's objective. The system supports classifications based on materiality, function, or building element. The instructor can also define the course and level of complexity, according to which the VR system adapts by filtering the information displayed and the complexity level of problems which the student is required to solve. The instructor has control over what is displayed to the students through a desktop interface, which also facilitates feedback and assessment. The instructor can also add any BIM model (exported as .fbx) and its correspondent information in a form of ".csv" schedules either exported from a BIM platform or prepared by the instructor him/herself. The system attaches scheduled information to its correspondent object by its unique ID using a dynamic parsing code. Besides, the system is able to request numeric data from online calculators or offline documents such as environmental data, fire rating, or any other relevant numeric input. For the other type of users, the student has a customized portal where he/she enters their

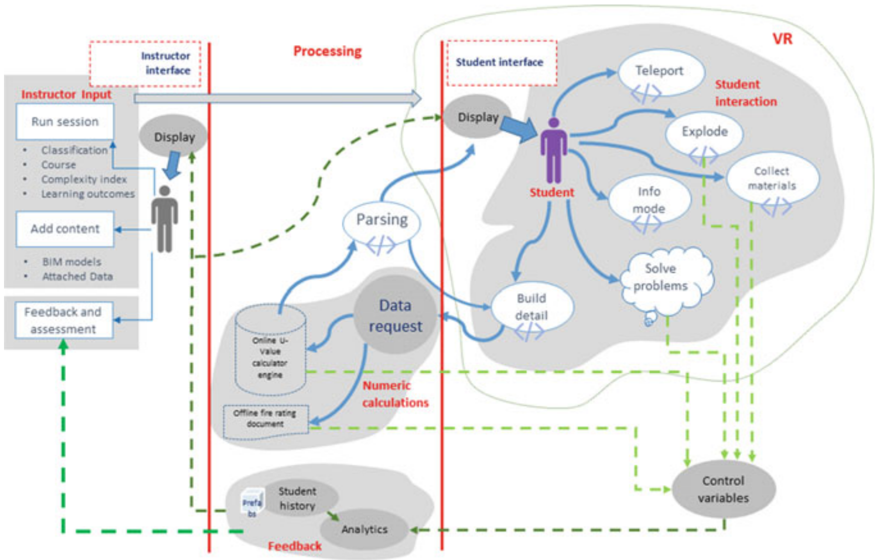

Fig. 1 Soft system methodology

name and ID as a player. This will help later in generating the analytics and in giving feedback to both the instructor and student with his/her earlier plays and results to point out the progress.

With regards to students interface, a student is able to teleport or move to explore space, select objects to get information, collect different building materials, solve problems, and explode and build construction details. There are also hidden control variables which direct the gameplay and lead upgrading from a module/game level to another, in order to ensure knowledge transfer to the student. Furthermore, there exist control variables containing number of collected building materials, exploded details, solved problems, etc.

Through the instructor's portal/interface, he/she has access to the history of the gameplay of each and every student. The system provides analytical feedback to the instructor (e.g. achievement percentage, achievement time, how many problems have been solved, number of wrong trials, etc.). In addition, the system automatically archives the student gameplay history for a later accessibility.

6.3 Curricular Unit

The above scenario is supported by a curricular unit, which is a three-level environment that follows four methods out of five construction detailing self-study and in-class exercise methods (Allen and Rand 2016) which include the following: analyze and modify existing details, design variations of existing detail, design from scratch, and use the patterns (see Fig. 2). VRConDet three-module curricular unit adapts to several construction detail approaches and different complexity levels.

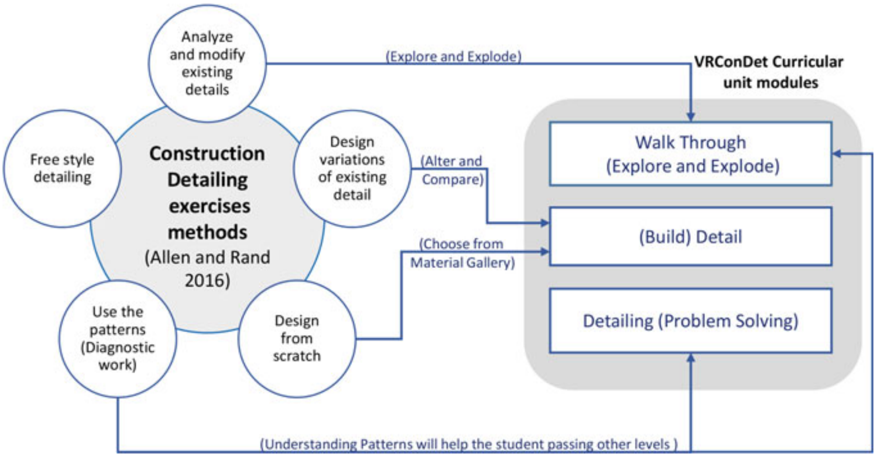

Fig. 2 Curricular-unit modules to their corresponding exercise method(s)

6.3.1 Module 01: Walkthrough (Explode and Explore)

The student walks through a BIM model, enjoying the ability to explore construction materials and products, technical installations, and different connections. Adding to this, he/she should explode few construction connections and explore their components, understand patterns, and get technical information. This helps the student to pass to the next modules. During the journey, the student finds tokens of construction materials or tools that he/she is required to collect and acquire knowledge about in order to use it in a later stage in the problem-solving module.

6.3.2 Module 02: (Build) a Detail

This level allows the student to build a construction detail using different components and construction materials. The detail is determined by the educator input and adapts to the course content. The student should be able to choose the various layers or components of the construction detail and their order relative to each other. The VR system provides feedback on the constructed detail. The feedback appears in the form of overlaid information representing performance as both numeric values such as U-Value (heat transfer indicator) or fire rating and constructability deficiencies extracted from BIM constraint and conflict detection.

6.3.3 Module 03: Detailing (Problem Solving)

In the problem-solving level, the user meets multiple technical problems building a construction detail. The clues to solve those problems have been reviewed through the previous two modules. The solution might need an extra component or a certain tool to be achieved. In this case, the user employs the material objects or tools he/she has collected previously during the walkthrough module. Once the student solves a problem, another with higher complexity appears. This happens recursively until a certain number of construction details are resolved. Figure 3 shows a flowchart of the user scenario moving from one module to another.

6.4 Main Considerations

During implementation of curricular-unit prototypes, many aspects related to BIM, VR technology, learning styles, and game mechanics should be considered, such as:

- Edutainment: the balance between game-like environment and the learning atmosphere is intended to avoid putting the student under the stress of game challenges that may block his/her willingness to read or try out.

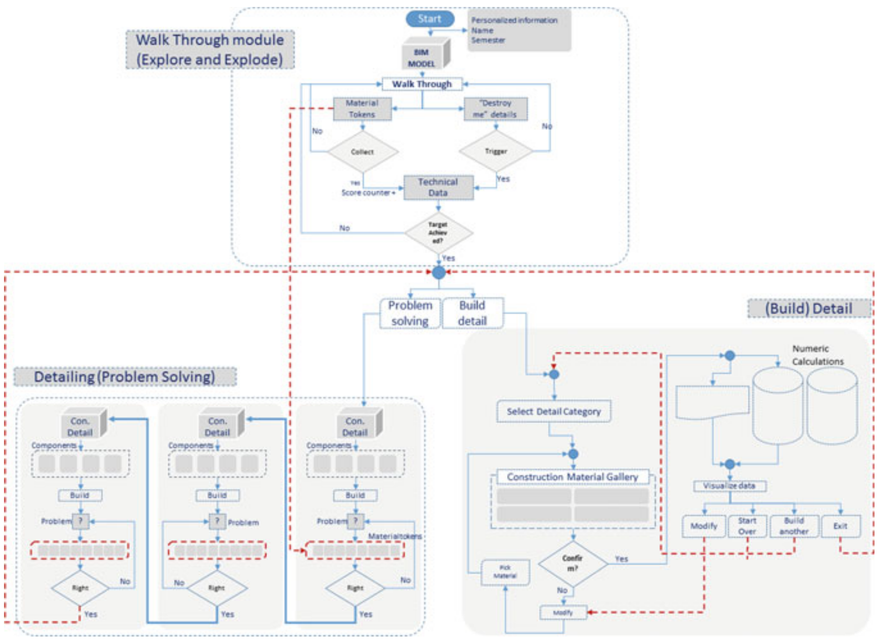

Fig. 3 VRConDet user scenario

- Avoid repetitive challenges to keep the student alert and always thinking about his/her cognitive input to avoid any mechanical actions.
- Consider virtual reality constraints and potentials trying to overcome constraints (such as field of view (FOV), teleportation, and VR sickness).
- Environment, interaction, UI, and objects physical behavior are not forced to look real. For example, environment can sometimes disappear to focus on certain function detached from its context. However, user interaction is meant to be intuitive and consistent in all modules.

7 Limitations

VRConDet as a main stream in construction education has a few challenges: for example, preparing teaching materials with a different approach following BIM is time-consuming. Besides, due to hardware limitation, VR headset is single-player equipment, this does not support multiuser decisions which may enhance the learning experience. Furthermore, and as long as it is new to construction educators to integrate such technology, proper training should be provided to them.

As long as BIM has a huge volume of data behind the scene, mobile-based VR—with a limited data storage capacity—is not suitable to run such an application unless a reduced version is developed. As mentioned earlier in this paper, VRConDet, as computer-assisted learning (CAL) tool, is not supposed to replace the traditional teaching; it is mainly concerned with supporting and enhancing the learning experience and filling the gap between academia and industry.

8 Conclusions

Building construction education requires the agreement between academia and industry to allow students to learn from real projects' BIM database documentation. This would be a huge source of information which enriches both the learning process and the outcome. According to literature, virtual reality is an effective and motivating educational medium that enhances the students learning experience and learning outcomes in various disciplines. BIM-integrated virtual construction site, as a concept, is expected to be widely applied in the very near future to be a main stream in AEC education, as well as in industry as a decision support system for project and construction management. In this respect, integrated virtual construction site bridges the gap between industry and academia by facilitating more experiential learning and bringing real construction projects to the classroom. Adopting a new technology naturally implies adapted ways of teaching and course materials. This will require strong agreement between academia and industry to employ real projects' documentation in the educational process. In this essence, endeavors of capacity building on the scale of universities and architecture and construction firms are expected to be increased fostering the up-to-date technology.

This research paper introduces the first phase of VRConDet which is a computer-assisted learning (CAL) conceptual framework for construction detailing that aims to enhance the learning experience and learning outcomes for construction education within architecture curricula. VRConDet builds on the VR technology as a medium and Building Information Modeling (BIM) as a source of technical information following aspects of adult's active learning and gamification of learning materials. The paper strictly focuses on VRConDet system architecture and module design that will feed in the second phase of developing and validating a prototype environment and interface covering a vertical spectrum of learning outcomes of construction courses.

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Analysing the Resilience of Hospitals' Surge Procedures Using the Functional Resonance Analysis Method

Farhad Mahmoudi, Sherif Mohamed and Fahim Tonmoy

Abstract Hospitals are a critical element of the healthcare system and their continuous function is highly important to the wellbeing of communities. In accordance with the criticality of their functional performance during disruptive events, several modelling and analysis approaches have been developed to investigate the extent of various aspects of hospitals' vulnerability and resilience. However, these approaches fall short in addressing either the degree of absorption, adaptation and, in some cases, degradation of the hospital as a system before its fundamental breakdown or fail to differentiate their performance in normal conditions versus surge circumstances and protocols. In this paper, these issues were addressed via deployment of the Functional Resonance Analysis Method (FRAM) and a macro analysis of the interactions among hospital system functions under surge conditions. The use of FRAM as the modelling technique helps to address the extent of system adaptability to changes and explore the hidden impact of different functions on overall system performance. The modelling involved identification of surge functions and fulfilment of conditions for the functions generating the outcomes. The study identifies the limitations existing in hospital surge procedures and highlights the difference between work-as-imagined and work-as-done regarding hospital surge procedures.

Keywords FRAM · Hospital functional performance · Resilience

1 Introduction

Hospital facilities, in the centre of the healthcare network, play a critical role in delivering healthcare services and enhancing society. Addressing their socio-economic

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https://doi.org/10.1007/978-981-15-1910-9_10

role requires these facilities to focus on enhancing the effectiveness and efficiency of the services they deliver. The main step in improving hospital functional performance (HFP) is identification of work-as-done (WAD) compared with work-as-imagined (WAI). In addressing these issues, various authors have studied hospital/healthcare processes from various angles and focusing on different services. Most papers will start with an introduction and end with conclusions. The conclusions section must be followed by references.

- Implementation of guidelines (Clay-Williams et al. 2015; Saurin et al. 2017).
- Identification of the factors contributing to the gap between WAI and WAD (Laugaland et al. 2014; Saurin and Werle 2017; Wachs and Saurin 2018; Damen et al. 2018).
- Understanding of how complexities affect healthcare processes (Raben et al. 2017; Raben et al. 2018; Ross et al. 2018).
- Enhancement of patient safety (Alm and Woltjer 2010).

The above publications examine hospitals' functional resilience from a resilience engineering perspective by addressing HFP from various dimensions in delivering different services. However, the issue of dealing with disruptive events requires a different approach, as hospitals perform under different sets of procedures and guidelines when a surge in number of patients is expected. Hence, the current paper aims to address HFP in the face of a surge of patients. The paper fulfils this objective by analysing HFP from a systemic perspective, by considering organisational, technical and external dimensions. For this purpose, a model is developed to cover a series of functions required to facilitate the flow of patients, from their registration at the Emergency Department until their discharge, using the functional resonance analysis method (FRAM). The remainder of this paper presents the chosen methodology, the findings of the application of FRAM and a discussion, before concluding with a summary.

2 Methodology

The FRAM, first introduced by Hollnagel (2004), identifies and measures performance variability. The FRAM is a qualitative analysis technique for identifying nonlinear dependencies between sub-systems, and functional performance variability, considering complexity and socio-technical factors (Woltjer and Hollnagel 2008). These factors suggest that the socio-technical system's performance is complex and possesses emergence, which assumes performance variability is an inherent factor necessary for coping with changes within and outside the system (Furniss et al. 2016). The outcome of combinations of performance variability can be observed as the occurrence of emergent accidents in the absence of any major technological failure (Macchi 2010). Hence, via the application of FRAM, the emergent risks can be addressed, and the extent of their impacts can be reduced, mitigated or eliminated (Macchi 2010). The method is based on four pillars (Hollnagel 2004):

- The principle of equivalence of success and failure: failure is the product of shortcomings in the system’s adaptability for coping with change in operational conditions, which is a consequence of complexity. In other words, success can be defined as the ability to anticipate the changing shape of risk before exposure, while failure is a permanent or temporary absence of that ability.
- The principle of approximate adjustments: because of the dynamics of random changes in operational conditions, the capability of finding effective ways of overcoming problems is crucial. Hence, the coincident and combination of inadequate adjustments create overall instability, which can become the reason for malfunctions or failures.
- The principle of emergence: under normal operational conditions, variability of performance is unlikely to have a major impact on the overall system’s functional performance. Yet, variability of multiple functions might combine in unconventional ways, leading to major consequences and impacts that are nonlinear in nature. Hence, the intractability and adaptability of socio-technical systems in response to conditions and demands make it impossible to describe all couplings in the system and anticipate more than the most regular events.
- The principle of functional resonance: the FRAM suggests resonance principles replace traditional cause–effect relationships. Interdependencies make it possible for impacts to spread around the system, rather than in traditional cause–effect links, as described by the Small World Phenomenon (Travers and Milgram 1977).

Based on these principles, FRAM focuses on the functions needed to generate system outcomes, their potential variability, the way they may resonate and how to manage functional performance variability (Hollnagel 2004, 2012). Using FRAM provides understanding on functional variability and appropriate actions to reduce the likelihood of such variability. Hollnagel (2004, 2012) outlined the steps to analyse a system using FRAM:

- Step 0: recognise the purpose of the FRAM analysis. FRAM can be used for accident investigation and safety assessment purposes; however, the details needed for each purpose differs from other purposes.
- Step 1: identify and describe the functions. A function is a normal activity performed in a socio-technical system to achieve a specific objective. Each function can be related to other functions via six aspects, as described below:

  (1) Input: what is processed and transformed by the function or what is needed for the function to start?
  (2) Output: what is transformed or produced via performing the function?
  (3) Precondition: what needs to exist before a function is carried out?
  (4) Resources: what needs to be consumed to produce the output?
  (5) Time: what temporal constraints affect the function?
  (6) Control: what is needed to control and monitor the function?

- Step 2: determine the potential for variability. Identification of how individual function outputs may vary even when not affected by input variation.

- Step 3: define functional resonance. This step deals with the potential impacts of upstream functions on downstream functions (DFs).
- Step 4: manage performance variability. Identification of existing risks and opportunities and management of performance variability.

In the current paper, FRAM was applied to a public hospital in Queensland, Australia. The selection of subject matter experts was based on certain criteria such as knowledge and experience with the subject matter. Particularly, the interviewed experts were selected based on their expertise in Emergency, disaster and business continuity management practices and/or having expertise in patient flow management. The application of the FRAM started by brainstorming, reviewing and analysing documents, through which the general flow of patients and resources were identified. We followed the guidelines published by the US Department of Homeland Security (2007) and the series of publications, policies and guidelines issued by the NSW Ministry of Health to draw a preliminary model. The primary FRAM model was then assessed for flow of the critical functions, and their relative aspects were finalised in an interview with disaster management experts. Next, the primary model was presented to disaster and emergency experts in the chosen hospital, to conduct a case study to identify missing links and functions performed. In the final step, the experts identified each function's output variability as well as the impact of variability in upstream functions on outputs.

3 Results

In the current paper, the focus of the FRAM is on the hospital system variability when operating under a surge caused by a disruptive event. Although the general purpose of applying FRAM is accident analysis or risk assessment, the aim of the current analysis is to assess the interaction among various dimensions of HFP involving patient flow, hospital surge procedures, availability of utilities and redundancies, and external stakeholders. The focus of this paper does not involve human factors resulting in unwanted events; instead, it identifies the impact of current policies and practices on HFP from a socio-technical perspective.

Overall, 29 functions were identified for FRAM analysis. In the second step, 171 couplings were identified among function aspects (an example is presented in Fig. 1). Based on the identified functions and their aspects, a visual representation of the hospital's patient flow model is visualised via the use of FMV software (FRAM Model Visualiser) (see Fig. 1). In Fig. 2, hexagon colours represent various types of functions: green = patient flow; red = hospital surge procedures; yellow = system maintenance, availability of utilities and redundancies; purple = organisational readiness; and phosphoric green and burgundy = functions performed by external stakeholders.

In the next step, the experts were asked to clarify the extent of expected variability in each function's output. These variabilities were identified regarding the timing and

Re-assessment and prioritisation of surge patient flow	**Description**	*Review triaging of all in-patients and transfer/discharge patients with lower priority*	
	Aspects	**Description of the Aspect**	**UF Function's Name**
	Input	*Expected number of casualties exceeds the hospital capacity*	*Assess the Nature and Scope of the Event*
	Precondition	*Execution of the surge plans*	*Procedures to execute the Surge Plans*
		Having agreements for medical facilities and equipment	*Establish Disaster Cooperation Mechanism*
	Resource	*Availability of the Information/Communication System*	*Maintaining Information/Communication System*
		Supplying Power	*Maintaining Power Supply*
	Control	*Calculated number of Available Beds*	*Number of Available Beds*
		Transition from pre-event bed utilization to access surge capabilities and Adding surge beds.	*Activate Medical Surge Capacity*
		Available Surge Plans	*Availability of Emergency Plans*
	Output	*Prioritisation of available beds*	

Fig. 1 Example of a function and its connections to UFs

Fig. 2 The complete FRAM for HFP under surge conditions

precision of the outputs that functions produce. As indicated by experts, the patient flow function output has the possibility of being produced later than expected. Specifically, when dealing with surge conditions, delays can reduce the efficiency of HFP. Further, it was identified that cooperation mechanisms and communication among the hospital and its external stakeholders do not appear to be efficient when dealing with disruptive events. Figure 3 demonstrates the assigned values for functional variability and their criticality scale by the experts as well as the number of DFs that their variability can be transferred to. These values (Green = No impact, Yellow = Moderate impact, Red = High impact) were identified based on the collective impact of functions outputs regarding to their timing and precision. Based on the collective

#	Function	Number of DFs	Timing	Precision	Criticality
1	Triage, Assessment and Streaming	4	On Time	Acceptable	Yellow
2	Early Treatment and Fast Track	1	On Time	Precise	Green
3	Acute Care	2	Too late	Precise	Yellow
4	Inpatient Ward Admission	2	Too late	Acceptable	Red
5	Discharge	0	Too late	Acceptable	Yellow
6	Bed Management	4	On Time	Acceptable	Yellow
7	Access to Patients Clinical History	4	On Time	Precise	Green
8	Performing Maintenance	5	On Time	Precise	Green
9	Maintaining Information/Communication System	18	On Time	Precise	Green
10	Maintaining Power Supply	14	On Time	Precise	Green
11	Number of Available Beds	9	On Time	Precise	Green
12	Maintaining Water Supply	5	On Time	Precise	Green
13	Maintaining Medical Gas Supply	4	On Time	Precise	Green
14	Maintaining Hospital Spatial Capacity	4	On Time	Precise	Green
15	Availability of Emergency Plans	11	On Time	Precise	Green
16	Performing Emergency Trainings and Drills	7	Too late	Acceptable	Red
17	Establish Disaster Cooperation Mechanism	5	Too late	Acceptable	Red
18	Report from External Agents	2	On Time	Acceptable	Yellow
19	Assess the Nature and Scope of the Event	3	On Time	Acceptable	Yellow
20	Sharing information, assessment and update	11	On Time	Precise	Green
21	Re-assessment and prioritisation of surge patient flow	7	On Time	Acceptable	Yellow
22	Direct Medical Surge Tactical Operations (Leadership)	6	On Time	Acceptable	Yellow
23	Procedures to execute the Surge Plans	10	On Time	Acceptable	Yellow
24	Activate Medical Surge Capacity	12	On Time	Acceptable	Yellow
25	Implement Surge Staffing Procedures	10	On Time	Acceptable	Yellow
26	Assessment, tracking, and deployment of extra assets, and resources	9	Too late	Acceptable	Red
27	Emergency Triage and Pre-Hospital Treatment	1	On Time	Acceptable	Yellow
28	Emergency Operation Centre Management	2	On Time	Acceptable	Yellow
29	Medical Supplies Management and Distribution and Logistics	1	Too late	Acceptable	Red

Fig. 3 Assigned values for functional variability and their criticality scale

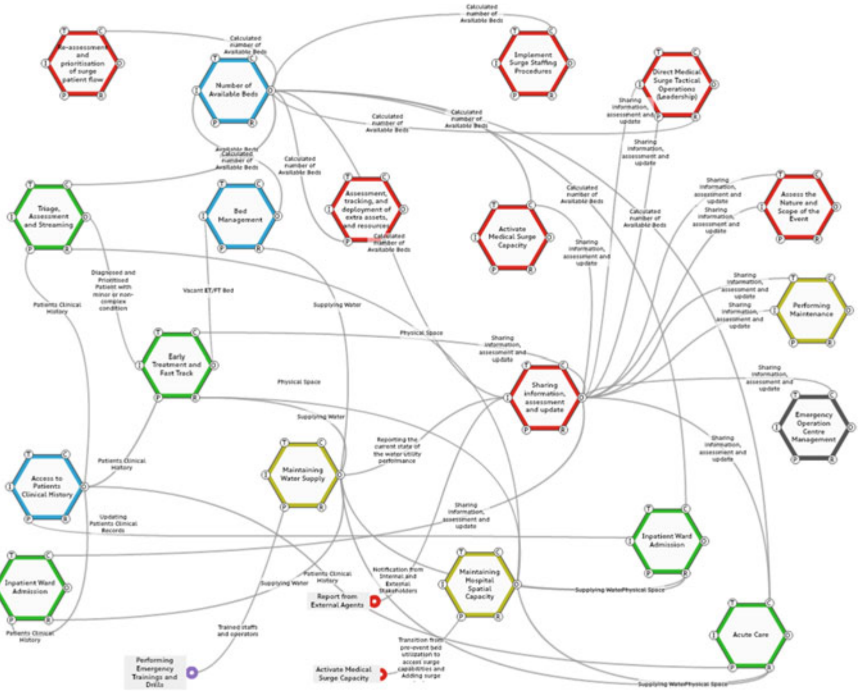

Fig. 4 Map of propagation of functional variabilities

impact of functional variabilities, it is evident that while selected functions were producing outputs with at least acceptable precision, the timing of generating outputs were the factor determining the criticality of functional variabilities.

Finally, by considering the values assigned in Fig. 2 and interactions among the UFs and DFs, Fig. 4 narrows the number of identified interactions to 83 links and demonstrates those interactions through which UF variabilities can resonate and affect the entire system. Therefore, functional variabilities can spread and amplify via these couplings. On the flip side, Fig. 4 presents those couplings that can dampen functional variabilities. It is worth mentioning that in both Figs. 4 and 5, not all interdependencies among functions are presented, and couplings that exert no influence on the DFs are not presented.

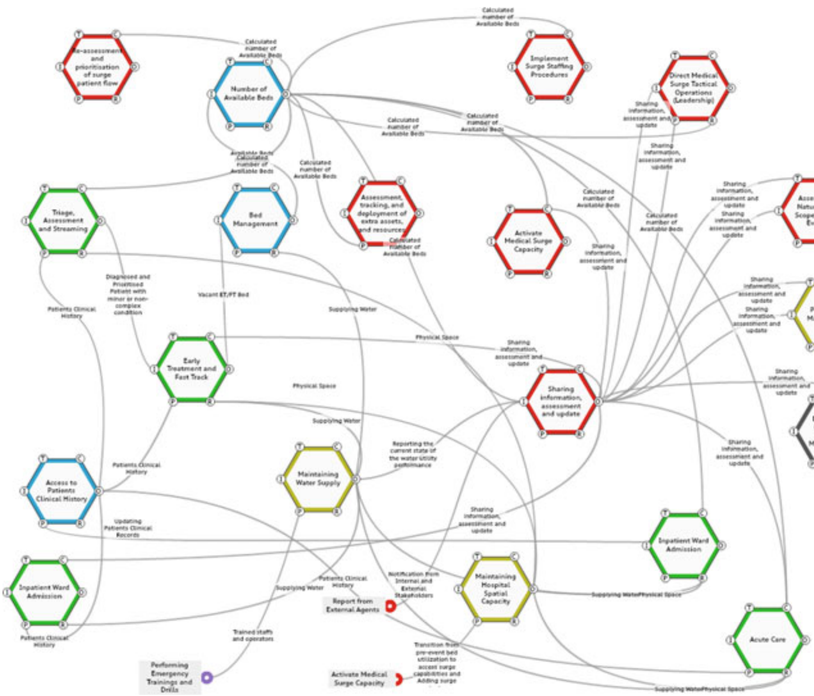

Fig. 5 Map of dampening of functional variabilities

4 Discussion

This paper aimed to understand HFP under surge protocols. This goal was achieved through the identification of functions performed, possible functional variability generated via performing those tasks, and the cascading effect of those variabilities through the system via couplings among functions. The results of the project provide a fresh perspective on how different dimensions of HFP can interact at a system level.

FRAM application to analyse the system, considering complexity theories and the socio-technical perspective, was proven to be helpful in achieving the objectives of the paper. The FRAM highlights the deviation between WAI and WAD in the context of HFP when dealing with surges. The findings of the study highlight the type of dynamic interactions among functions. The results indicate that propagating functional variabilities throughout the system can take a toll on the timing of the hospital's overall performance. Figure 3 shows those interactions that increase the possibility of transferring UF variabilities to their DFs. As explained by the FRAM principles, the overall system can adapt itself to noise passing through under normal conditions; however, in surge conditions and when the system is under the stress, the resonating impact of these variabilities can exert a noticeable impact on HFP.

Further, the findings of the current paper shed light on interactions among functions through which certain functional variabilities are dampened. Thus, Fig. 4 represents potential opportunities in the hospital system, by highlighting the system's potential and ability to deal with a portion of functional variability and functional resonance. Hence, FRAM has been proven to be an insightful technique to demonstrate the synergy among various dimensions of HFP and lay out areas of improvement by which the system can perform efficiently and enhance resilience.

The current study highlights the fact that technical functions often deliver outputs on time with the utmost precision regarding quality. However, with the in-built redundancies in hospital design, Fig. 4 identifies a low probability for variability being produced by the routine performance of such infrastructure. In contrast, it can be argued that availability of trained staff, vacant beds and resources are existing challenges. These challenges are amplified via lack of coordination mechanisms with internal and external stakeholders, leadership, and assessment, tracking and deployment of extra assets and resources. The cooperation among the leadership team, and the government, for facilitating and establishment of the communication capacity contributes to the effectiveness of Coordination of the Response Agents. It can be argued that by establishing cooperation and information sharing mechanisms among responding agents, as well as performing regular training and drills, the efficiency of inter-agency cooperation can be improved.

Further, it has been clarified that lack of efficiency and effectiveness of implementation of surge procedures and re-assessment and prioritisation of patient flow can create variability and amplify impacts on HFP. The lack of efficiency in reassessment and prioritisation of patient flow has been argued to prolong the length of stay in the hospital, even though the efficiency of ED throughput increases (Shimada et al. 2012). Morton et al. (2015) reviewed and highlighted the impact of the variability of this coupling as the potential increase in mortality rate (in severe cases), decrease in the ED and Acute Care wards throughput and consequently reducing the hospital surge capacity. In total, hospital's capability of providing available beds during surge, controls the allocation of resources throughout the process. These impacts can heavily affect the overall timing of performing tasks and, therefore, reduce the number of patients serviced.

In summary, this paper offers a unique insight into HFP for a hospital system dealing with adverse events and operating under a surge. The current modelling and analysis considered complexity theory and adopted a systemic approach to the hospital systems rather than a micro approach in which typical hospital functions are analysed at the organisation–human–technology interaction level. By approaching HFP at the system level, decision-/policy-makers may gain a realistic understanding of WAD and the potential inherit risks and opportunities existing in the system. Consequently, the findings support those of Clay-Williams et al. (2015), by demonstrating the potential of using FRAM to obtain insights into a hospital system for implementing, updating and revising the current guidelines, protocols and practices. Further, the system approach provides insights into interdepartmental interactions and the types of impacts these can impose on HFP. Therefore, the hospital will be able to decrease potential risks by either improving performance of certain functions or enhancing the buffering capacity of their DFs.

5 Conclusions

HFP during clinical surges is a complex issue, especially when aligned with an increase in healthcare demand due to disruptive events (natural and man-made). It requires involvement of different inter-organisational and external stakeholders to deliver critical healthcare services. This paper provides a comprehensive insight into this complex process using a FRAM analysis. The application of FRAM as an analysis technique clarified the deviation between WAI and WAD and highlighted the hidden obstacles and opportunities in hospital system performance.

The results of this paper identified certain couplings that have the potential to vary the output of their DFs and highlighted the DFs' potential to cope with certain types of variations in their receiving aspects. Based on these findings, it can be argued that success in the context of HFP should be defined in terms of the timing of performing each function. Therefore, decision-/policy-makers must focus on ways to make HFP practices during clinical surges more efficient and increase the buffering capacity of those functions that play a critical role in propagating functional variabilities throughout the system. Future studies need to identify the critical path among functions, via which functional variabilities can resonate, as well as investigate the impacts of technical, organisational and external influences on HFP.

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The Support of Continuous Information Flow Through Building Information Modeling (BIM)

Alireza Ahankoob, Behzad Abbasnejad and Peter S. P. Wong

Abstract The lack of mechanisms to manage construction project information using traditional documentation methods leads to information waste. Building information modeling (BIM), as one of the recent developments in the architect, engineering, and construction industry (AEC) has revolutionized the process of managing information among project stakeholders. BIM is advocated as an effective platform that digitizes and accommodates all essential project information that can be extracted, networked and shared among project stakeholders to foster effective decision making and construction operations. Despite the significant role of BIM in supporting lean construction principles, there is little evidence on how BIM leverages continuous information flow in construction projects. This study aims to find the mechanisms through which BIM facilitates continuous information flow. A desktop study on secondary data was conducted to identify those mechanisms. The results of the secondary data analysis suggest that the key aspects of BIM in storing and transferring project information such as effective exchange of information, early involvement of project stakeholders, information accuracy and real-time access to project information can enhance information flow in construction projects.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_11

Keywords Building information modeling · Construction projects · Information flow · Information waste

1 Introduction

The construction organizations have long been looking for strategic solutions to remain competitive in the market. Information management is one of those strategies that construction organizations commonly adopted to operate efficiently. The aim of information management is to ensure that only the reliable and valuable information is stored, shared, and used as not all the information transferred is valuable to the receiver (Graebsch et al. 2007). Fragmented communication among project stakeholders hinders the exchange of valuable information in project environment, leading to information waste. Waste is usually defined as an unnecessary activity that does not add value to customers' requirements (Worley and Doolen 2006). In the context of information management, Hicks (2007) defines waste as 'the additional actions and any activity that arise as a consequence of not providing the information consumer immediate access to an adequate amount of appropriate, accurate and up-to-date information'.

Previous research has shown that the application of lean concept in business processes significantly reduces waste. The philosophy of lean production focuses on continuous improvement concept to eliminate seven types of wastes in business processes including: overproduction, waiting, defect, transport, extra processing, inventory, and motion. While, the implementation of lean principles has proven to generate positive impacts on construction projects such as better cost performance (Thomas et al. 2003), the transient nature of project environment limits its application in managing information. Likewise, within the construction industry, information is primarily managed and transferred manually in document-based format as organizations suffer from the lack of integrated information system (IS) infrastructure. This type of managing project information leads to information waste in construction projects. Therefore, the need of an integrated approach to manage information based on lean thinking is vital in project environment. Building information modeling (BIM) as a new methodology of managing project information, has the potential to improve project stakeholders interaction (Chen and Jupp 2019). BIM serves as an information repository in construction projects. In this regard, Aranda-Mena et al. (2009) studied five Australian construction firms involved in architectural and engineering practices to recognize business drivers toward the uptake of BIM. They found that improved information flow was ranked as one of the top advantages of BIM across four of the five case studies. Despite the significant role of BIM as a project information repository (Ahankoob et al. 2019), there is limited evidence to conceptualize its potentials in supporting unified information flow. This paper aims to identify those potentials through a desktop study on secondary data, but first the sources of information waste in construction are reviewed to better understand how BIM fosters continuous flow of information.

2 Literature Review

2.1 Information Waste in Construction Projects

The dynamic nature of the construction industry requires construction organizations to actively address the existing complexities to remain competitive in the market. The process of managing information is one of those complexities that influences project performance. Tribelsky and Sacks (2011) state that poor management of information flow can lead to different types of waste in construction including: rework, waiting for information, over-design, and the extension of overall project duration. However, studies focusing on drivers of information waste in the construction context are scarce. There are some efforts in lean production literature that show the main sources of waste in information processing (Graebsch et al. 2007), but construction organizations represent different characteristics that limits the deployment of information management technologies applicable to the manufacturing. Therefore, a review on secondary data was implemented to extract the main areas of information waste in construction projects, which are described here (Fig. 1).

2.1.1 Poor Exchange of Information

The construction is a project-based industry where geographical distribution and organizational dispersion create barriers for effective exchange of information. These characteristics of the construction industry hinders the ability of construction organizations to effectively absorb and transfer information in project environment (Ahankoob et al. 2018). Traditional ways of communication even make the situation

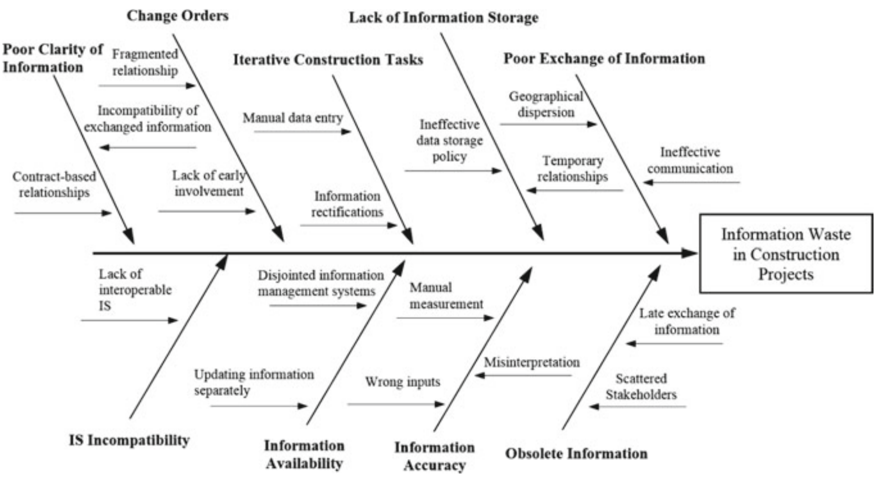

Fig. 1 Causes of information waste in construction projects. *Source* Author

worse where 2D documents form the basis of project stakeholders' communication, resulting in additional times and processes to flow information from one trade to another.

2.1.2 Lack of Information Storage

The temporary nature of construction projects and lack of long-term relationships between project stakeholders create barriers to store project information thoroughly. Innovative technology solutions are recognized as a significant ingredient in building a robust platform for accessing, storing and retrieving some of the essentials of organizational memory. However, despite the existence of innovative technologies construction organizations are still dependent on traditional means of information sharing. In this context, the results of Ahmad et al. (2017) study showed that most of the Jordanian contractors particularly small and medium companies had no effective management system to store electronic documents. Based on the data collected from the interview, paper-based filing system was the common way of storing files, which could lead to loss of information. Thus, lack of mechanisms to store projects' information lead to losing data and lessons learnt in upcoming project phases.

2.1.3 Change Orders

While the early involvement of project participants has been emphasized as a critical factor to make a clear vision of communal problems (Beach et al. 2005), clients and contractors are generally absent in the early decision making processes. Lack of early client and contractor involvement in design phase can lead to change orders in the construction phase. The fragmented relationship between designers and subcontractors also hinders the concurrent construction from the early stages.

2.1.4 Poor Clarity of Information

Clarity of information implies "the perceived level of lucidity and comprehensibility of information received from a sender" (Schnackenberg and Tomlinson 2016). In real-world there is a risk of confusion in interpreting a piece of information received by team members due to the incompatibility of exchanged information. For instance, in 2D traditional communication, the contractor might interpret a piece of information designed by architect based on its conception and not fully understand the designed purpose. This is because the senders fail to include additional information (e.g. shape, physical size and location of an object) in the transferred documents. This misunderstanding among team members can even be intensified by the contract-based relationship between project stakeholders (Issa and Mutis 2009), where they have less opportunity to communicate after the completion of a construction task.

2.1.5 Information Accuracy

Basically, construction documents should be transferred from one trade to another to form the final revision. Any misinterpretation and importing wrong inputs can reduce the accuracy of information received by other trades especially in large and complex projects. Likewise, in the traditional approach, a construction trade manually measures the number, volume and other numerical data of building components through different design sections, elevations and floor plans (Monteiro and Poças Martins 2013). It is therefore very prone to error and time-consuming to understand the construction plans and 2D documents (Sacks et al. 2004).

2.1.6 Information Availability

In construction projects, every discipline has its own information management system to store and retrieve information. As a result, project information is stored in disjointed information management systems, which creates barriers to effectively track information. On the other hand, construction information is mainly updated by a variety of actors separately. In the absence of an integrated project model, it will be difficult to access information.

2.1.7 Obsolete Information

In construction projects, there is a large flow of documentary information between stakeholders from planning to the handover phase (Peansupap and Walker 2005). The absence of a systematic approach to transfer project information timely generates significant delays in transferring information from one trade to another (Al Hattab and Hamzeh 2013). Further, as project stakeholders are scattered in different locations, access to up-to-date project information is difficult. Therefore, it is possible that the received information is obsolete.

2.1.8 Iterative Construction Tasks

Construction tasks, particularly those involved in the conceptual design are very iterative and require rectifications or feedbacks from other project team members (Al Hattab and Hamzeh 2013). The process of rectification requires some time to modify information. For example, in 2D paper-based communication, in the case of any change in the project information, designers and contractors must update all project information manually which is unreliable and time-consuming (McKinney and Fischer 1998). Document-based collaboration also involves extensive manual data entry through different information systems (IS). Repetitive manual data entry tasks and inputting data in segregated IS systems enlarge the number of errors diminishing the reliability of received information.

2.1.9 IS Incompatibility

Construction projects involve actors with diverse backgrounds, which create, extract and exchange information. Lack of incompatible IS in conventional drafting methods and paper-based communication increase the likelihood of missing information (Issa and Mutis 2009). Delivery of incomplete information requires a period of time to interpret information by a receiver. Subsequently, an additional time is needed to understand and interpret project information due to the lack of integrated IS systems.

The above arguments have summarized the drivers of information wastes in construction projects and based on evidence in the literature, it is suggested that BIM is able to minimize the influences of these drivers. Thus, a comprehensive review was conducted to explore how BIM can improve seamless information flow in construction projects.

3 Research Method

A desktop study on secondary sources was conducted to identify the main causes of information waste in construction projects. The databases and search engines included "American Society of Civil Engineers (ASCE) Library", "Web of Science", "Taylor & Francis". The phrases including: "Information Flow", "Lean Construction", "Information Waste in Construction", "Construction Information Management", "and Lean Information Flow" were used to find previous relevant articles. The results of the secondary sources review led to the identification of major causes of information waste in construction projects. Similar databases and article publishers were also used to review the literature on BIM to reveal its potential capabilities in fostering lean information flow in construction projects. The study focused on peer-reviewed articles published between 2007 and 2019 as the term BIM was not widely popular before this period (Lee et al. 2006). For this part, the terms "Building Information Modeling and Project Information", "BIM and Lean", "BIM and Information Management", and "Information Flow and BIM" were adopted. The review on BIM literature revealed some of the main mechanisms of BIM to reinforce lean information flow.

4 Results and Discussion

Based on the desktop analysis on secondary sources, the role of BIM and major mechanisms through which BIM reinforces continuous information flow is discussed in the following sections.

4.1 The Role of BIM to Support Continuous Information Flow

The potential of BIM to support lean principles has pushed it beyond information and communication technologies (Sacks et al. 2010). BIM has been defined in a variety of ways in different contexts. According to Vanlande et al. (2008), BIM is the process of generating, sorting, managing, exchanging, and sharing building information in an interoperable and reusable way. Succar (2009) defines BIM as "a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle". For the purpose of this study, BIM is considered as a medium of communication that forms project information richness. The potential of BIM to develop seamless information flow has been investigated by the work of other researchers. Russell et al. (2009) integrated linear scheduling with 3D model to create 4D snapshots. The main advantage of their research was to create a "two-way flow of data" (information flow) between construction and design stage in order to evaluate alternative construction processes. The collaborative framework of BIM developed by Wu and Xu (2014) shows that information flow in BIM is multi-directional from the perspective of construction supply chain. Similarly, Čuš-Babič et al. (2014) used BIM to integrate information flows throughout the construction industry supply chain from detailed design to construction stage. The result of these studies indicates that the flow of information in BIM follows a continuous pattern through whole project life cycle (Zhang et al. 2013). This paper aims to identify some of the main mechanisms of BIM that triggers the continuous flow of information in construction projects. These mechanisms are discussed below.

4.1.1 Effective Exchange of Information

BIM parametric models contain multidisciplinary information that is exchangeable during the whole project life cycle (Wu and Xu 2014). Eastman et al. (2011) classified data exchange in three formats: (1) direct links; (2) proprietary exchange format developed by a commercial organization to support interfaces between applications in that company; and (3) non-proprietary data model exchange to transfer information publicly within the building construction industry. In BIM, model elements are defined along with their attributes and their relations with other elements (Karan and Irizarry 2015), the model is therefore more than repository. This characteristic of BIM models enhances the consistent flow of project information from conceptual design phase to the operation. For example, by observing 26 design and construction firms, Taylor (2007) found that disparate design and construction firms were able to articulate their constructability knowledge in BIM more clearly than paper-based communication.

4.1.2 BIM Information Repository

The maintenance of information during the building life cycle is one of the fundamental objectives of BIM. BIM retains and represents data in a digital format which not only makes building geometric information accessible, but can also store project participants' comments and decision making during a project's life cycle (Sacks et al. 2010). Succar et al. (2012) identified three kinds of data stored in a building model, namely: structured data (data associated with intelligent objects), semi-structured data (including JSON: JavaScript Object Notation and XML data files), and unstructured data (Comprising documents, photographs and multimedia files). This type of classification considers a range of building information and more explicitly identifies the capability of BIM to retain a wide range of information including architectural, geometric, and technical information along with a virtual 3D model (Fadeyi 2017).

4.1.3 Early Involvement of Key Stakeholders

BIM enables multi-skilled teams to collaborate concurrently through a shared model from the conceptual to the operation phase instead of the sequential flow of information in traditional contracting (Becerik-Gerber et al. 2012). This is because project stakeholders have access to the all project life cycle information in the early phases of a construction project (Smith and Tardif 2009). For instance, key features of BIM such as 4D simulation, interoperability and information repository strengthens the concurrent collaboration of project stakeholders to effectively discuss constructability issues (Keskin et al. 2019). Sebastian (2010) examined the use of BIM in a pilot project of small-scale housing and found that the early involvement of key participants was reinforced through a model-based collaborative design. The early involvement of project stakeholders and client in BIM-based projects eliminates change orders and delays in later phases of the project due to the provision of poor information.

4.1.4 Enhanced Information Clarity

The integration of non-graphical and graphical data increases the clarity of information. In this context, Marzouk and Abdelaty (2014) point out to the extraction of meaningful information from BIM models due to the integration of the geometry parameters with other useful information such as quantity, schedules, cost and material characteristics in BIM model. As a result, in BIM-based project the information received from other stakeholders is not as vague as it was in traditional paper-based communication. The reduced number of requests for information (RFI) as a measure of improved quality of information (Azhar 2011; Dowsett and Harty 2013) are examples of the clarity of information in BIM-based projects.

4.1.5 Increased Information Accuracy

Eastman et al. (2011) refer to the enhanced accuracy as an advantage that benefits construction companies in the bidding process through reduction of uncertainty in material quantities. In this respect, the case-based study conducted by Kim (2012) at California State University indicated that apprentices produced more accurate estimation of material quantity take-off while using BIM automated quantity take-off. Likewise, BIM enables construction trades to probe project models more precisely (Olsen and Taylor 2017). Automated clash detection of BIM informs team members about parts of the project model that are in conflict or clashing with each other. Hanna et al. (2013) observed that 70% of electrical and mechanical trades who had used BIM visualization could significantly reduce design error conflicts.

4.1.6 Real-Time Access to Project Information

The combination of non-graphical and graphical data in BIM facilitates real-time access to project information. This capability of BIM fosters the pull flow of information between project stakeholders. In a case study of four building construction projects, Demian and Walters (2014) observed that the introduction of BIM-based system enhanced the exchange of more accurate, real-time, and appropriate information between project participants. Homayouni et al. (2010) observed that the real-time exchange of information between first, second and third tier parties (e.g. owner, consultant, contractor and sub trades) in network-based (i.e. cloud) BIM led to a better collaboration (Homayouni et al. 2010).

4.1.7 Elimination of Repetitive Tasks

BIM minimizes repetitive construction tasks by automating calculations and data exchange between various applications. In this regard, Peterson et al. (2011) used BIM in a construction engineering course and perceived that BIM-based system allowed reduced data entry which provided students with greater accuracy of cost estimation tasks. Likewise, Ji and Leite (2018) developed a rule-based 4D planning system to improve the efficiency and effectiveness of tower crane planning while aiming to eliminate repetitive tasks and manual input. Reduction of human involvement in data entry processes increases information quality in the design and construction phases.

4.1.8 The Storage of Up-to-Date Information

Keeping up-to-date project information is another capability of BIM. This capability of BIM is attributed to self-coordination of the information provided by parametric building modeling (Vanlande et al. 2008). BIM as an information repository supports the creation of consistent and up-to-date information from planning, design through fabrication, to construction stage, leading to transparent information flow within the supply chain (Čuš-Babič et al. 2014). In fact, a BIM model is delivered from designers to contractors and sub-contractors, thus, each discipline has the ability to update and merge its individual discipline-specific information to the model (Olcay 2010). The results of a case study in an industrialized construction project showed that up-to-date design data, along with reliable exchange of information in BIM provided a transparent relationship among project stakeholders (Čuš-Babič et al. 2014).

4.1.9 Compatibility of Information

It is necessary to transfer compatible information in order to perceive all the potential vales of BIM aforementioned. The emergence of BIM interoperability has facilitated the exchange of compatible information between project stakeholders (Grilo and Jardim-Goncalves 2010). Eastman et al. (2011) describes BIM interoperability as "the ability to exchange data between applications, which smooths workflows and sometimes facilitates their automation". Industry Foundation Class (IFC) as non-proprietary data model is considered as the main source of interoperability for BIM files (Redmond et al. 2012; Gui et al. 2019). Although, BIM applications still are not fully interoperable systems, the benefits of exchanging interoperable information in BIM-based projects has been underlined by previous research. For instance, Pinheiro et al. (2018) used IFC file format to transfer information between BIM and building energy performance simulation tools. They developed a model view definition (MVD) to define a subset of the IFC data, aiming to facilitate information exchange between different applications. Likewise, Nawari (2012) used interoperability in off-site fabrication to exchange trustworthy information such as material specification, quantities, delivery sequence between contractor, designer, fabricator and engineers.

5 Conclusions

Construction projects consist of multiple parties that interact only during project duration. It is also unlikely that every project participant works together collaboratively on a specific task at a certain time. Information decentralization intensifies this fragmentation which results in loss of project information. These discussions reveal that it is challenging to store, transfer and use information in a project environment. This difficulty in recording and transferring valuable information increases the risk of generating waste in the process of information management.

The currently ineffective interaction of project stakeholders calls for innovative solutions. The use of BIM as a medium of communication helps construction organizations to improve their business performance, by supporting the seamless flow of information through project life-cycle. Existing literature does not clearly identify how BIM reinforces continuous flow of information in construction projects. This paper addresses this gap by highlighting BIM mechanisms for unified information flow. Different information waste drivers and associated BIM mechanism through which information waste can be either removed or minimized were discussed through a desktop study on secondary sources. The shortcoming of this study is the practical observation of all these mechanisms in a case study. Future research is needed to practically test all these mechanisms through an observation. It is expected that this paper provides a platform for future studies to test more business concepts related to BIM.

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Minimizing Emissions and Cost Through Reducing Equipment Idle Time in Concreting Operations

Nur Kamaliah Mustaffa and Mohd Feisal Hafiz Abdul Aziz

Abstract Concreting operations commonly utilize a large range of equipment that generates a considerable amount of greenhouse gas (GHG) emissions. Equipment idle time is considered as a non-productive time that it increases the fuel use and emissions without any production. Reducing idle time in operation implies the opportunity to improve productivity, cost efficiency, and emissions reduction. Continuous efforts have been made to determine the efficient solutions in reducing emissions of construction operations. Existing publications on concreting operations have focused on cost and production, with little attention being given to emissions. In response to this need, this paper aims to examine the influence of equipment idle times towards emissions, costs and production performance. This paper investigates the link between idle time, equipment utilization, production, emissions, costs, and optimum equipment configurations. Case study data along with Monte Carlo simulation are used to develop a model for cyclical concreting operations. The results highlight that eliminating most of the truck waiting time translates to higher utilization of both trucks and loader, thus increasing the non-idle fuel use and consequently increases emissions.

Keywords Concreting operations · Cost per production · Emissions per production · Idling time · Non-idling time

1 Introduction

Production and cost, and more recently also emissions have become a central part in managing construction operations. Continuous efforts have been focused on providing tools for efficiently improving construction productivity and minimizing cost and emissions. Most of the current efforts in reducing cost and emissions in construction

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_12

operations have focused on technological strategies, with little attention given to change operational strategies on site (Ahn et al. 2010; Ahn and Lee 2013). Introducing new green technologies including engine retrofits and using cleaner fuels has the potential to reduce emissions; however, these new technologies may come with an additional cost (Ahn et al. 2010). Avetisyan et al. (2012) and Ahn et al. (2013) draw attention towards the possible measure in reducing construction emissions not only by adopting cleaner equipment and fuel but also by improving operational practice through the reduction of engine idling. Equipment idle time is considered as a non-productive time that it increases the fuel use and emissions without any production. Engine idling results in unnecessary fuel consumption, increasing total operation cost and potentially can shorten equipment life. The reduction of engine idling may offer a great opportunity to increase productivity and minimize cost and emissions in construction operations (Ahn and Lee 2013). Hence it becomes a priority to improve or change operational practice on site in order to reduce engine idling.

Construction operations commonly utilize a large range of equipment that generates a considerable amount of greenhouses gas (GHG) emissions. According to EPA (2009), reducing 10% idling of the off-road diesel equipment will result in lower GHG emissions, which provide a sector-wide saving of approximately 1.8 billion lbs of CO_2 per year. Considering the significance of minimizing the equipment idle time that would result in a reduction of emissions, there is an identified need to study the influence of construction equipment idling on unit emissions and unit costs. The need for construction equipment idle time estimation has been highlighted in a number of recent studies (Frey et al. 2008; Lewis et al. 2012; Akhavian and Behzadan 2013; Ahn and Lee 2013; Ahn et al. 2013). However, most of the focus has been given on estimating idling in earthmoving operations and does not consider other construction operations. In response to this need, this paper aims to examine the influence of equipment idle times towards emissions, costs and production performance in concreting operations. In concreting operations, a queue of trucks may occur while trucks wait at the loading or unloading points which may result in an increase of unloading server and truck idle time on site. It is important to note that equipment idle time is interrelated with equipment utilization (percentage of time working), fuel use (and hence emissions), costs and operation production. Therefore, this paper aims to explore the link between idle time, equipment utilization, production, cost, and emissions.

The queue analysis approach using a Monte Carlo simulation is used in this chapter to develop a model for cyclical concreting operations. The case study involves concreting operations on a residential construction site, with concrete trucks cycling between batching plant and construction site.

This paper has been organized in the following way. First, the background of the study and the simulation approach employed in this study are presented, followed by a case study using field data. The next section discusses the influence of equipment idling on production, emissions, and cost. The final section presents the conclusions.

2 Background of Studies

The construction industry has suffered from low productivity due to many factors including labor and equipment operations which are caused by managerial practice in a construction project. Low productivity levels have been a constant issue in construction which results in time overrun and consequently cost escalation in total project performance. There are a growing and continuous interest in productivity studies worldwide, however, many studies have focused on the importance of labor productivity (Yi and Chan 2013; Nasirzadeh and Nojedehi 2013; Jarkas and Bitar 2011). Recent attention has shifted to also include a minimum emissions criterion in the analysis of construction productivity to reduce the environmental impact of construction operations. As construction equipment is one of the most crucial and critical resources for a construction project, the systematic management and analysis of a construction equipment operation are also essential for productivity improvement.

There are a number of published studies that highlight the important consideration of construction equipment idling in cost estimation, fuel use and consequently emissions estimation. Specifically, the underlying methods used are mostly in developing data-driven modelling and simulation (Frey et al. 2008; Akhavian and Behzadan 2013; Ahn and Lee 2013). Assessing emissions by obtaining practical emissions data related to specific activity modes is an effective mean for estimating the amount of time that construction equipment spends idling since it distinguishes the difference between productive and non-productive time (Lewis 2009). Lewis et al. (2012) further draw attention towards developing the significant measure on estimating emissions by developing a model to determine the fuel use and emissions rate for different activity modes such as equipment idling and non-idling. Peña-Mora et al. (2009) present a framework for managing emissions in construction operations. The emissions estimation framework proposed integrates different methods to be used including adopting simulation modelling, portable emissions measurement system (PEMS), a global positioning system (GPS), wireless network and geographic information system (GIS). Akhavian and Behzadan (2013) propose a simulation-based evaluation framework for real-time monitoring of construction equipment idle times. This study integrates the use of a distributed sensor network with simulation modelling to evaluate the effect of various operational strategies on equipment idling and emissions. In addition, Ahn et al. (2013) adopted automated measurement to measure the working and idling modes of construction equipment. Although all such work highlighted the impact of engine idling on fuel use and emissions, however, the focus of all these publications is limited to earthmoving and does not consider concreting equipment. To the best of authors' knowledge, the only significant study, related to emissions associated with concreting equipment can be found in Frey and Kim (2009). Therefore, this paper aims to examine the influence of equipment idling on emissions and cost in concreting operations.

3 Modelling Concreting Operations

The typical concreting operation involves a cyclical process of truck hauling of concrete between the batching plant and unloading point at a construction site. The number of fleet trucks dispatched to the site is based on the required volume of a concrete requested by the contractor. The queue of trucks may occur while waiting at the loading or unloading points.

For the purpose of this study, a field study involving placement of slab concrete structures using placement method of the pump was considered. The case studies involve trucks cycling between a batching plant and a residential development construction site.

3.1 Field Study

A fleet of seven trucks, each of 10 m^3 capacity were used to deliver concrete for pouring a 250 m^3 slab structure. The batching plant was located around 3 km from the construction site. A trailer-mounted concrete pump, with a pumping rate capability of 85 m^3/h, was employed in the operation.

The total operation of trucks going repeatedly between a concrete batching plant and the site were recorded both manually and by video over an extensive period of times. The average truck cycle component times of queue waiting times and maneuver times at both the batching plant and site, loading times, unloading times, wash out, and travel times were obtained. The case study was supplemented with data on fuel use, owning and operating costs, capacities, distances, equipment engine power (HP), engine load and engine. Table 1 shows the result of the average truck cycle component times.

Table 1 Field-observed truck cycle component times

	Field study
Truck cycle component	Time (min)
Queue-at-load	19.712
Maneuver at batching point	1.525
Load	9.921
Loaded haul	9.347
Queue-at-unload	38.504
Maneuver at site	1.402
Unload	15.523
Wash out at the site	1.996
Return	9.124

3.2 Underlying Model

The underlying model used in the paper's analysis for concreting operations is based on Carmichael and Mustaffa (2018). Monte Carlo simulation is performed to analyze the production, equipment utilization, unit emissions, and unit cost. The pump is considered as a single server case. Trucks are viewed as customers. Figure 1 shows a schematic of such an operation.

The Monte Carlo simulation program for concreting operations performs in the following steps:

1. The model starts with field studies at construction sites. The components of truck cycle times are observed over many cycles during field measurements using manual recording and video footage.
2. The observed component of truck cycle times is then reduced into the definite set of operation parameters.
3. The control policy for each loading policy in the developed model is defined.
4. The statistical goodness of fit is conducted by over-plotting the best-fit distribution on the same diagram with the cumulative frequency plot obtained from field data. This gives the visual comparison of the goodness of fit for the particular distribution. The family of Erlang distributions is chosen to model cycle times as it forms good fits to field observation (Carmichael 1987).
5. Upon selecting the truck fleet sizes configurations, the particular distribution in terms of relevant probability density function for the component cycle times such as service times, S and backcycle time, B is input.
6. For each truck arrivals, the random numbers are generated through sampling the relevant probability density functions (Hillier and Lieberman 1990).
7. The output statistics for any required variables is simulated using Monte Carlo program.

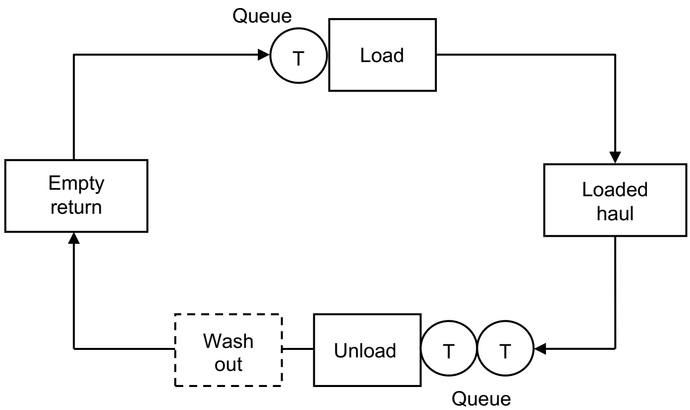

Fig. 1 Schematic of concreting operation. Truck denoted as T

8. The optimization process starts by calculating the server utilization, truck utilization, waiting times, production, cost and emissions for the configured fleet using Eqs. (1)–(10) as follows.

3.3 Production

For a single pump operation, the number of truck cycles (NC) is given as,

$$\text{Number of truck cycles, } \mathrm{NC} = \zeta - (\mathrm{K} + 1) \tag{1}$$

where ζ the total number of truck cycles and K is the truck fleet size.

Thus, the total duration is defined as,

$$\text{Total duration, } \mathrm{TD} = \mathrm{CUM}(\zeta) + \mathrm{B}(\zeta) - \mathrm{CUM}(\mathrm{K} + 1) \tag{2}$$

CUM(ζ) is the cumulative time for the total number of truck cycles and B(ζ) is the backcycle time for the total number of truck cycles.

The total production is given by,

$$\text{Total production, TP} = \sum_{\mathrm{NC}} \mathrm{PROD(n)} = (\zeta - \mathrm{K} - 1)\mathrm{CAP} \tag{3}$$

where PROD(n) = CAP is the capacity of a truck.

The total production/unit time is given by,

$$\text{Total production/unit time} = \frac{\mathrm{TP}}{\mathrm{TD}} \tag{4}$$

The server (pump utilization (the proportion of time that the server is busy)), η, is calculated from,

$$\text{Server utilization, } \eta = \frac{\sum_{\mathrm{NC}} \mathrm{S(n)}}{\mathrm{TD}} \tag{5}$$

where S(n) is the service time.

The truck utilization, u, is the proportion of time that trucks are either in service traveling with respect to total truck cycle time. It excludes truck waiting time. It is calculated from,

$$\text{Truck utilization, } \mathrm{u} = \frac{\sum_{\mathrm{NC}} \mathrm{B(n)} + \sum_{\mathrm{NC}} \mathrm{S(n)}}{\mathrm{K} \times \mathrm{TD}} \tag{6}$$

3.4 Emissions per Production

The total emissions per unit time are calculated from,

$$\text{Total emissions/unit time} = N_{P/C}\eta + I_{P/C}(1 - \eta) + K(N_T(\mu\eta/K\lambda) + I_T(1 - \mu\eta/K\lambda)) \quad (7)$$

And,

$$\text{Unit emissions} = \text{Total emissions per unit time/Total production per unit time} \quad (8)$$

where η and $1-\eta$ are the proportion of time that the pump is idling and the proportion of time non-idling, respectively, while $\mu\eta/K\lambda$ and $(1 - \mu\eta/K\lambda)$ are the proportion of time that the trucks are idling and the proportion of time non-idling, respectively. The approach of Frey and Kim (2009) is employed to determine the fraction of emission for idling (I_T) and non-idling (N_T) of the trucks. $I_{P/C}$ and $N_{P/C}$ are idling and non-idling emissions of the pump, respectively; and these are obtained from the equipment manufacturer and the approach of Hasan (2013). The emissions factor provided by DCCEE (2017) is used to determine the total carbon dioxide equivalent (CO_2-e) emissions.

3.5 Cost per Production

For any single pump-trucks operation, the cost per production is,

$$\text{Total cost/unit time} = C_{P/C} + KC_T \quad (9)$$

where $C_{P/C}$ is denoted as the owning and operating cost per unit time of the pump and C_T is the owning and operating cost per unit time of truck. Then, cost/production or unit cost becomes,

$$\text{Cost/production} = \text{Total cost per unit time/Total production per unit time} \quad (10)$$

9. For such truck fleet sizes configuration, minimum unit emissions and minimum unit cost and the optimum of truck fleet sizes are determined by plotting the outputs in graphical forms.

4 Results and Discussion

Based on the outlined analysis method and observed field data of the previous sections, production, waiting times, unit emissions, unit costs and optimal fleet sizes for placement method of pump can be established.

Figure 2 shows the production (expressed as m^3/h) and truck waiting time plotted against truck fleet size for concreting operations. Inevitably, concrete placement using a pump, through a higher placing rate and a lower service time, generates a significantly higher production.

In placing concrete using the pump, the production reaches a maximum value of approximately five trucks. The capability of the pump to supply a large volume of concrete at a higher rate contributes to a significant reduction in service time. Therefore, with less time required to complete the placing process compared to the other placement method such as crane, the pump can serve more trucks before it reaches the maximum production. It also can be observed in Fig. 2, as the production reached maximum values at the matching point, the truck waiting times increased over the fleet sizes. However, it should be noted that the increasing truck fleet sizes beyond the matching point will not increase the production, but will significantly increase the waiting time of trucks at the site.

Figure 3 demonstrates the idle and non-idle times of the truck and pump as a server. As can be observed in the same figure, the increase of the fleet size causes the slopes of server non-idle time to increase and their idle time to decrease. This behavior is different from the proportion of truck cycle. The truck idle times are observed to be constant at small fleet sizes and increase after the matched point, while the truck non-idle time decreases. Hence, this implies that there is a trade-off between truck and server proportion work-cycle.

Harmonizing pump server and the truck choice is acknowledged to be necessary for maximum production, thus minimizing emissions and cost per production. Based on the observed field data in Fig. 4, it is discovered that unit emissions and unit costs with the truck fleet size varied. For placing method of using pump, it is seen

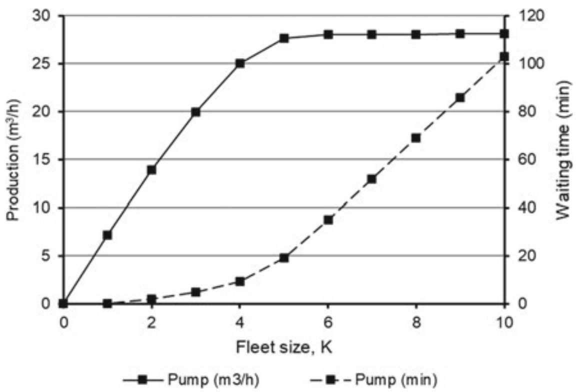

Fig. 2 Production and truck waiting time versus truck fleet size for placement method of pump

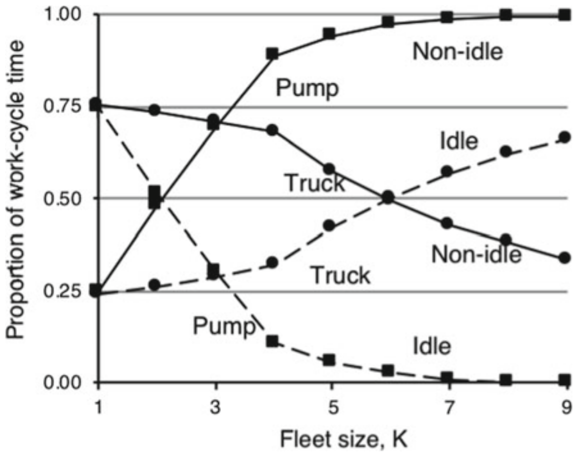

Fig. 3 Idle and non-idle times of the truck and pump

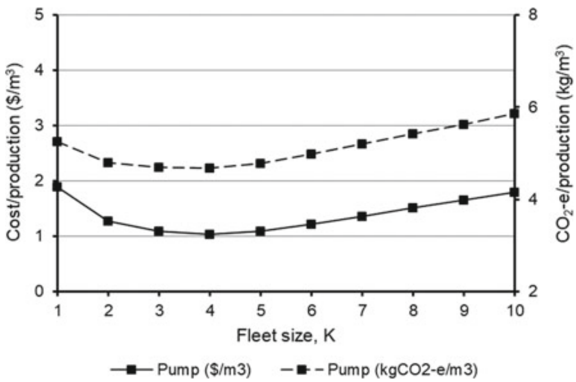

Fig. 4 Unit emissions and unit costs versus truck fleet size for concreting operations

that for minimum unit emissions and minimum unit costs, the optimum truck fleet sizes coincide. However, it can be observed that the curves are reasonably flat near the optima. The utilization of truck fleet sizes greater than those optima will only increase unit emissions and unit costs. The coincidence of optima results for both unit emissions and unit costs in the concrete placing is consistent with the studies of Ahn et al. (2009) and Carmichael et al. (2012, 2014) in earthmoving operations.

The equipment waiting time is considered as idling and non-productive in concreting operations. Waiting time can be described as the time between a truck arriving at the load point and the time truck starts maneuvering to load. This unnecessary idling is believed to affect the equipment performance, fuel use, production, unit emissions and unit costs of the operation. Figure 5 shows that the unit emissions and unit costs increase as the truck waiting time increases. Initially, the unit emissions are observed to decrease with the increase of truck waiting time from 0 to 2.5 min. However, unit emissions start to increase when the waiting time is greater than 2.5 min. Similar behavior is observed to occur for unit cost. The increased truck waiting time translates

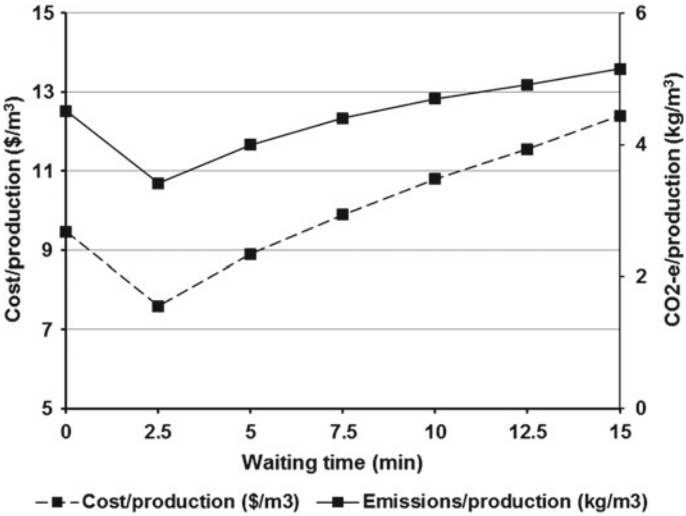

Fig. 5 Unit emissions and unit costs versus waiting time for concrete operations

to the increase in total fuel use, with a consequent increase in the emissions (Lewis et al. 2012) and costs (Ercelebi and Bascetin 2009). Although, reducing equipment waiting time is crucial for efficient operations, however, the findings of this study reveal that eliminating most truck waiting time also results in the increase of unit emissions. Eliminating truck waiting time translates to higher utilization of both trucks and loader, thus increasing the non-idle fuel use and consequently increases emissions.

5 Conclusion

In this paper, the influence of equipment waiting time and equipment utilization on the performance of production, unit emissions and unit costs in concreting operations are examined using Monte Carlo simulation analysis. Reducing truck idle time and increasing equipment utilization might be anticipated to increase production and reduce emissions and costs. However, the results demonstrate that eliminating most of the truck waiting time translates to higher utilization of both trucks and loader, thus increasing the non-idle fuel use and consequently increases emissions. The results of the case study analyses demonstrate that the optimum truck fleet size for unit emissions coincides with that for the unit cost for placing method of pump used in concreting operations.

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Comparative Analysis of Mega Road Construction Projects in Term of Innovation

Una Obiose Kriston Nwajei and Bo Terje Kalsaas

Abstract *Purpose* This paper examines, using critical realism, the causes and mechanisms of innovation in three civil road construction projects. Its focus is to examine how value can be created within the design process through innovation. Emphasis is placed on Best Value Procurement (BVP) as a procurement strategy where the preferred contractor is considered the expert, as it is the first case of its use in Norwegian road construction projects. Data was collected through surveys and interviews. Findings indicate that procurement using early involvement is innovative in the design process yet must be adapted, to allow for early planning of innovative ideas that help, to foster innovative solutions. However, there are also some contributing causes towards a lack of innovation due to the strategic choices within the projects, such as how the project will be delivered in terms of, the commercial incentives within the contract.

Keywords BVP · Incentives · Innovation · Mechanisms · Value creation

1 Introduction

The construction and building industry are changing through many initiatives by governmental departments in Norway. Its focus is to strengthen the public sectors ability to implement change and to become more efficient. As a result, Difi (a Norwegian state department with responsibility for public procurement, management and digitisation of the public sector) has invested in a method called Best Value Procurement (BVP) to bring a significant improvement to public sector procurement. BVP is a method developed by Dean Kashiwagi at Arizona State University in 1994 and was first implemented in 2005 by the Directorate for public works and water management in the Netherlands, called rijkswaterstaat, tested and adopted BVP in 2008

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_13

(Storteboom et al. 2017). BVP has five phases: preparation, tender, evaluation, pre-award/clarification, and execution (Kashiwagi 2011; Van de Rijt and Santema 2012). A six-page document and interviews of key personnel are performed in the evaluation stage examining past performance information, project capability, highlighted client's risks in the project and additional values that can contribute to the project goals. The pre-award/clarification stage is where the contractor can concretely make it clear the scope of the work for the project including the expected timetable, important milestones, risk assessment plan and define how they will, satisfy and exceed all the requirements of the contract. If the contractor's offer is accepted, then a contract is signed, however, if the contractor's offer is rejected, then the procurement process will starts over again. In 2016 Difi carried out an initiative to pilot ten BVP projects in Norway in order to highlight the strengths and weaknesses in the method.

A state-owned limited liability company under the Ministry of Transport and Communications called Nye Veier (NV) (translation: New Roads AS), decided to use BVP as their main procurement strategy and two projects, E18 Rugtvedt-Dørdal and E6 Arnkvern-Moelv, were pilots projects for Difi. NV were tasked to construct, operate and maintain the main roads in Norway. Their main goals were to ensure faster construction and an equal quality standard of 4-lane motorways with the aim of transforming the construction industry of which innovation is a part. In addition, societal value is very important in their business model. This reform from the government resulted in the existing, Norwegian governmental agency, responsible for the public roads in Norway, Statens Vegvesen (SVV) (translation: State Highway Authority), giving a part of its portfolio of road construction projects, to NV. SVV intended to build these projects using a Design-Bid-Build (DBB) execution approach. However, NV would instead use a Design-Build (DB) strategy, in other words, a contract whereby the supplier is responsible for integrated detailed design and construction. NV was motivated by their change to the DB-strategy by experiences from Sweden which road authorities build cheaper roads by using DB, according to an unpublished consultant report.

NV is responsible for operation and maintenance of their road sections. Public procurement in Norway must adhere to EU-regulations stipulating open and fair competition.

Also, the construction industry has over time been characterised as having low levels of innovation (Koskela and Vrijhoef 2000). The 2017 Norwegian bibliometric data for the construction industry shows that Research and Development (R&D) investment in innovation by companies is low. The problem is not that there is no innovation; the statistics clearly show increased rates of R&D from 30.43 million USD in 2016 to 39.81 million USD in 2017, a rise of 30.8%. The fact is the industry is spending more money than it ever had compared to 2007; however, this figure is significantly smaller compared to other sectors. Innovation activity in the construction industry from 2014–2016 in Norway, measured by the number of innovative or innovation projects, have been below average, compared to all industries. However, the fact remains that innovation in the construction industry, regardless of how it is measured, is being adopted and being created regardless of its comparatively low level compared to other industries (SSB 2019). The goal of this research is to examine if BVP is an enabler for innovation in NV's road construction projects.

2 Theoretical Framework

Innovation originated in the late middle ages where the English language began to replace the Latin verb "innovare" with innovate or innovation: meaning "the action or process of innovating" or as "a new method, idea, product". In line with the Latin definition, the perspective of Tidd et al. (2005) is that innovation is a process, position and a paradigm, all involving a change in what an organisation produces.

However, the term innovation has different meanings depending on a person's perspective. For example, the Norwegian Central Statistics Bureau (SSB), define four types of innovation: Product innovation where a new or significantly improved good or service is introduced; process innovation—the implementation of an improved production or delivery method; organisational innovation, similar to process innovation—the implementation of a new organisational method in the firm's business practices, workplace or organization; and, marketing innovation where a new marketing method is introduced to change product design, placement, promotion or pricing. Whereas Slaughter (1998), viewed innovation on a scale, at one end, incremental innovation consisting of small changes to a specific element or component. Next modular innovation where it has limited impact on other components or systems, then there is architectural innovation which has a small change within a concept or components. Afterwards comes systems innovation being a link between multiple innovations which are integrated together requiring significant changes to components and systems. Finally, radical innovation, which comprises of a breakthrough in science or technology causes major changes to the industry.

Schumpeter in 1942, regarded innovation as discontinuities, either rendering obsolete competence or building on existing know-how through technology advancements. He suggested a distinction between invention (generating new ideas) and innovation (applying new ideas) (Tidd et al. 2005; Winch 1998). Von Stamm (2008) definition of innovation, bears a resemblance to Schumpeter, as he describes innovation as creativity plus successful implementation, further stating that often, innovation requires creativity (coming up with ideas) plus putting those ideas into practice (idea, selection development commercialisation and creativity). Christiansen (1997) in Von Stamm (2008), seem to build on Schumpeter's work, states that innovation can be defined as a technology, product or process, that sneaks up on a business and impends to displace it.

As mentioned earlier, incremental and radical innovations are not the only form of innovation; innovation models have tried to capture the broader perspective. For example, Miller et al. (1995) argue that certain models exist of industries pertaining to complex system industries, which as a result changes their dynamics of innovation and affects the different types of actors in the innovation network especially their distinctive roles in the innovation process (actor-system network). The network of actors play an important role in understanding who is the key initiators of innovation in a project; however, Eric Von Hippel in Von Stamm (2008) argues that users, are also an important source of innovation, and are perhaps the ones who have the main stimulus. Ive in 1996 argued that "construction innovation depends upon the coincidence of the means, motive and opportunity to innovate" (Winch 1998, p. 274). Projects participants (trade contractors) often have limited incentive to be innovative when they are selected in a competitive environment where price is an important factor in order to achieve the contract (Winch 1998). In 1993, Slaughter had argued that innovation occurred, often by the people working on site, which was (and still is) not always recognisable. Innovations take time and money and the pressures during construction due to these factors often result in the production of an "adequate" solution so that construction progress could continue, instead of the "best" solution. Winch (1998, p. 274) points out that "If incentive structures did not favour innovation, then innovation is unlikely to take place" (p. 274). The only way to encourage innovation was to incentivise and motivate actors in a direction that favours innovation.

On the other hand, focusing more on managers, who were the innovators, had the problem of turning these innovative "ideas into good currency". How to incentivise and motivate agents (contracted for work) is a challenge, according to the principal-agent theory (Eisenhardt 1989). For example, Information may be misleading, between the owner and the agent before and after contract signing, for opportunistic gain. However, Buckley and Enderwick (1989) point out that that from a contractor's perspective it is his "desire to find a competitive price that is consistent with an acceptable rate of return given the risk and inherent uncertainties in the construction process". Winch (1998) suggested that construction is made up of a complex system which requires management of four processes, in order for successful innovation to occur: the firm level consisting of two processes—both an adoption and implementation dynamic (the ability to adopt new ideas)—then at the project level, two processes, where problem-solving and a learning dynamic occur (where there is the ability to learn and re-apply this learning to future projects, in a qualified form). The two forms are stimulated by a learning organisation. This is also supported by Bygballe and Ingemansson (2014), who argues that "explorative and exploitative type of learning, is a prerequisite of the innovation process." Von Stamm (2008) outlook on innovation suggests that even if an organisation tries to be innovative, they need to allow for creativity, an example of this can be seen in Kalsaas (2013) which addresses collaborative innovation regarding drilling performance in the oil industry. Creativity can be stimulated through training and creation of the right environment; however, environmental components can also sometimes hinder creativity. Encouragement of information flow, freedom to conduct one's work, and having available resources—all these can foster creativity. On the other hand, workloads might be positive, in providing creative challenges, but might also produce negative pressures leading to a blinkered outlook. Furthermore, organisational culture, such as conservatism and internal problems tend to be also negative elements influencing the creative environment.

In the end, creativity relies a lot on intrinsic motivation, which can be inspired but not enforced. If an organisation wants to be innovative, they must employ people to think and behave differently, which requires time. Correspondingly Nam and Tatum (1997), argue that innovation will be slow unless there are innovate leaders in projects, denoted "champions". In construction, the role of the champion tends to be split between the principal constructor and the architect/engineer, whose roles are the fulcrum for innovation. While this may be true, Kalsaas (2013) suggests that this role arises from the customer-supplier interaction. Bowley, on the other hand, suggests that innovation can and is often found by "ersatz"-substitution when all other solutions are unavailable. Whereas Bonke suggests that even though one is innovative, it can be stifled either through the exploitation trap (for example locked into a particular technology) or through the exploration trap (whereby technology is reinvented in a circular rather than a progressive manner) (Winch 1998). Research shows that early involvement has various impacts on the design and construction in a project. Examples can be seen in Song, Mohamed, and AbouRizk (2009), who examined the impact of early involvement in design on the construction schedule performance and Wondimu et al. (2016) who studied early contractor involvement (ECI) in public procurement projects and its effect on consistent product and process designing.

3 Analytical Model

Innovation can have a wide variety of meanings; however, in this paper, innovation is defined from the theory as product, process and organisational innovation. We have created an analytical model in Table 1 which will be applied to analyse the research question: is BVP an enabler for innovation? Five variables were chosen which address contracting, fixed price, time compression, early involvement and the client goals on innovation. The client's contracting strategy is to have strong impact on innovation as it is here that the commercial incentives for the parties are decided. In summary the analytical model, see Table 1, shows that there are excellent conditions for innovation if commercial incentives are aligned, the contractors are paid for creating value, time is available for creativity, learning and innovation, contractors are involved early; and that the client has clear goals on innovation which are proactively followed up.

In procurement during the bidding phase, the providers are open to all types of innovation due to the relatively strong incentive that arises from the possibility of being awarded a contract. It is the contract that is the mechanism that drives all participants to look for opportunities to innovate. An example is the bidder suggests innovations for the project. If a signed contract has a fixed price, then it has been used to shift the risks from the owner to the contractor. When the contract is signed it gives a limited incentive to focus on product innovation because the focus has now shifted to lowering costs in order to make as much profit as possible. However, this mechanism to potentially lower costs means that it gives a relatively strong incentive

Table 1 Relationship between type of innovation, variables and mechanisms in projects

Innovation	Variables				
	Bidding phase contracting	Fixed price	Time compression	Early involvement	Client goal innovation
Product	Relative strong (contract—commercial incentives)	Limited (potential lower costs)	Limited (time pressure)	Relative strong (joint problem solving)	Relative strong (focus, reporting)
Process	Relative strong (contract—commercial incentives)	Relative strong (potential lower costs)	Relative strong (time pressure)	Relative strong (joint problem solving)	Relative strong (focus, reporting)
Organisation	Relative strong (contract—commercial incentives)	Relative strong (potential lower costs)	Relative strong (time pressure)	Relative strong (collaboration)	Relative strong (focus, reporting)

to seek out, both process and organisational innovation, in order to become as efficient as possible in the project. An example could be using Lean methodology.

A contractual delivery date can limit the amount of time in a project, then the incentive to innovate is limited because those delivering the project have no time for product innovation and project modifications require approval. However, a pressured timeframe is a mechanism that also gives a relatively strong incentive to seek out both process and organisational innovation in order to organise and run the projects as efficiently as possible. Early involvement into the design process is another variable in a project, where there is a relative strong incentive to focus on both product and process innovation to solve problems in order to achieve improved constructability. The mechanism here is joint problem solving, innovations to help solve problems that would be encountered later in the project. There is also a relatively strong incentive to pursue organisational innovations by collaboration to increase organizational effectiveness.

The client is a variable that plays a vital role in innovation. Firstly, if they set a goal in the project to be innovative, this is expected to create a relatively strong incentive, especially in the bidding process, to potential participants in execution to focus on pursuing all types of innovation. However, this incentive decreases when the contract is signed and becomes less effective when combined with fixed price remuneration and time compression. Secondly, if the client, after the contract is signed, pushes for innovation in the project this strengthens the message for project participants to be innovative. The mechanism for both instances is the level of proactiveness from the client, which can either create or reinforce the incentive for innovation in the project.

4 Method

The research reported on in this paper is based on a mix-methods approach leaning to Yin's (1994) approach and critical realism from Sayer (1992), in theoretically informed case studies. Data was collected from three master student projects.[1] A total of 136 survey respondents responded from the three projects, where 57, 49 and 30 responses were collected from case studies 1, 2 and 3, respectively. Also, 29 semi-structured interviews were conducted within the 3 projects where 9, 11 and 9 participated from case studies 1, 2 and 3, respectively. Interview data was analysed using a method for analysing qualitative research called the framework analysis method, to find the themes for analysis (Gale et al. 2013). The respondents in the study included respondents from the Owner, Main Contractor, Design Consultants and Sub-contracted; Engineering, Construction and Electrical consultants' firms.

5 The Cases

Case study 1 concerns the E18 Tvedestrand connection to Arendal route based in the southern part of Norway. This project started as two projects, which were merged into one project to allow the contractor to utilise the 10 million cubic meters of overburden collected throughout the different stages of the road construction, see also (Kalsaas et al. 2018). The awarding criterion is shown in Table 2. This was NV first, and largest DB contract which was completed July 2019 (3 months ahead of contracted schedule).

Case study 2 concerns the E18 Rugtvedt-Dørdal project located in the south-eastern part of Norway. The project used the BVP procurement process and had an optional maintenance contract which could be awarded in order to compensate for the negative aspects that can occur in a DB by incentivizing the main contractor to think about quality and customer value (Kalsaas et al. 2018). The project is due to be completed in December 2019.

Case study 3 concerns the E6 Arnkvern-Moelv project, a 24 km stretch of road based in the eastern part of Norway. The project used the BVP procurement process and had the possible awarding of an optional operational and maintenance contract, for 20 years. The project is due to be completed in June 2020. Data was collected at different times in the projects with Case 3's data being collected when participants had the least experience working together, case 2 had more experience than case 3 whereas Case 1 data was collected when participants had the longest working experience together, in relation to all cases.

[1]Andersen and Vee (2018), Engelien and Ronæs (2018) and unpublished work from Willemsen, Axel (2018).

Table 2 Summarised overview of the three case studies

	Case study 1 E18 Tvedestrand-Arendal	Case study 2 E18 Rugtvedt-Dørdal	Case study 3 E6 Arnkvern-Moelv
Procurement procedure	Traditional DB contract. process with negotiations	BVP	BVP
Awarding criteria	Organisation 5% HSE 2% Implementation 5% Technical solution 2% Environmental consideration 3% Price 83%	Performance justification 25% Clients risk 15% Additional values 10% Interviews 25% Price 25%	Performance justification 25% Clients risk 15% Additional values 10% Interviews 25% Price 25%
Contract value (ex VAT)	3.076 billion (NOK) or 310 million (EUR)	1.8 billion (NOK) or 186 million (EUR)	2.15 billion (NOK) or 222 million (EUR)
Compensation	DB fixed price	DB fixed price	DB fixed price
Is there an optional contract	No	Yes, 20 maintenance years	Yes, operational and maintenance 20 years
Deliverable	25 km four-lane highway, 27 bridges, 4 twin bored tunnels, 2 road junctions, 9 culverts	16.5 km four-lane highway, several crossing and 27 bridges	24 km four-lane highway, 2 railway bridges, two short tunnels
Area plan	Inherited two finished plans	Inherited finished plan	Inherited finished plan

6 Findings and Discussion

The theory and analytical model presented above will provide the framework for the discussion of the empirical evidence. Findings from the surveys, see Table 3, indicated positive attitudes to innovation in all three mega-project case studies. The results show that Case 2, E18 Rugtvedt-Dørdal, were more positive to their project being characterised by new solutions and innovation compared to the other cases. Highest scores were found in case 2 E18 Rugtvedt-Dørdal compared with the lowest scores in case study 3 E6 Arnvern-Moelv.

It is interesting to notify from Table 3 that the traditional procured DB-project (case 1) received a better score than one the BVP projects (case 3) regarding innovation. Below we discuss briefly findings from the interviews case by case.

Case 1

Findings, Case study 1 E18 Tvedestrand-Arendal match expectations from the theory. The delivery model was a Design-Build (DB), and the contractor were procured using traditional procurement. However, as this is a contract where the main contractor is set to deliver the project for a fixed sum, their incentive to innovate was limited

Table 3 Attitudes from the survey

	Case study 1 E18 Tvedestrand-Arendal (%)	Case study 2 E18 Rugtvedt-Dørdal (%)	Case study 3 E6 Arnkvern-Moelv (%)
Completely agree	21	23	20
Somewhat agree	47	55	36
Neutral—no difference from previous projects	24	16	30
Somewhat disagree	4	2	7
Completely disagree	2	0	7
No opinion	2	4	0

in line with the analytical model in Table 1. When looking at the overall responses, participants had different interpretations of what innovation was in the project. Some stated that there was no innovation, while others agreed that, the project had product innovation through the use of an initiative of a model-based approval process using BIM, to remove paper drawing from the construction process; this is perhaps not that new to the industry, but again new to this project type.

There were some that stated that there was process and organisational innovation through the use of a DB instead of a DBB, nevertheless, some of these respondents, especially from the main contractor and consultants, discussed how the execution model DB reduces the time to evaluate solutions due to simultaneous design and construction. This is also consistent with the analytical model in Table 1 that time compression gives limited incentive for product innovation; often resulting is an adequate solution instead of the best possible solution. However, time pressure is also a mechanism that gives a relative strong incentive for process innovation. Yet from the owner's perspective, the project was a reworked areal design, and it was down to the main contractor, to be innovative.

Case 2

The findings, from Case 2, E18 Rugtvedt-Dørdal indicates that the project had an initiative planned to increase quality considerations, through the possible awarding of an operation and maintenance contract to the main contractor. The delivery model was a Design-Build (DB) and procurement of project contractor was done using BVP method, the first of its kind in Norway. The findings indicate that some stated that there was no innovation in the project, while a vast majority were extremely favourable to the project being characterised by innovation. Product innovations were stated as being through BIM, and Virtual reality whereas process and organizational innovation were through new ways of working such as DB, instead of DBB, early involvement from the main contractor and designers with the municipality on detailed area planning and the use of BVP.

Positive attitudes to innovation were attributed to the main contractor and designers use of time within the BVP procurement process. The main contractor's assumption that they would win the contract early since they were in the concretisation phase allowed them to start the project early and gave them extra time in planning of the project. This would be a plausible explanation as to the lack of references to limited time compared to the other case studies; however, the time pressure, together with the early start gave the participants a relatively strong incentive to collaborate and solve problems in line with the analytical model in Table 1. However, the consultant and designer organisations had prior experience of area planning and were able to reuse this knowledge again in this project.

The owner had a set goal for innovation and is mentioned as pushing for innovative thinking only at a certain time in the project. Examples were given by the designers and main contractor of their plight towards innovative ideas in dealing with lighting the main highways. These findings are, in line with the analytical model that strong incentives, for product and process innovation, occur through early involvement and the client's goal. However, since there was still time compression, with the use of DB, and a fixed price contract, these limit the amount of time to be innovative. Also, the owner's goal can be assumed, in the bidding phase before contract signing, to give a relatively strong incentive for innovation; however, after contract signing coupled with the use of fixed price, this incentive would decline. The incentive could be even stronger if bidders were required to answer how they intended to handle innovation in the project using the two-page document for additional values listed in the BVP process. This would give a relatively strong focus on innovation but also some form of measurement in relation to the client's goal. The awarding of the optional maintenance contract is an important incentive that looks to increase quality in the project; however, this incentive, if coupled with other reinforcing incentives, could give an even stronger incentive for product innovations. Nonetheless, there were those who experienced a lack of innovation in the project, because of the amount of regulations and the very detailed requirements present in the handbooks in the project.

Case 3

The findings from Case 3 E6 Arnkvern-Moelv, are from a project using Design-Build (DB) and the BVP method. Also, the owner had an offer of an optional 20-year operational and maintenance contract. The results showed that there was a mix of attitudes to innovation in the project. The project claimed to be innovative through, engineering and automation, BIM, environmental awards and the reuse of detailed plans. There were those who experienced a lack of innovation because of the very detailed requirements present in the handbooks and the difficulty getting in touch with decision makers in the project. There was also a conflict between the consultants and the main contractor because of claimed lack of proactiveness from the main contractor's part in the project, which resulted in the design managers for both parties being replaced. Discussions also revealed that time pressure, from the DB process, and the fixed price contract were the main causes that limited innovation in this project.

According to data, time pressure led to well-known solutions to being chosen in the project. The owner, similar to case 2, believed that the main contractor was responsible for innovation in the project, since it was a DB contract.

7 Conclusion

The paper analyses if BVP is a driver for innovation in three of NV's mega road projects. The quantitative and qualitative analysis found inconclusive evidence to suggest that best value as a procurement strategy was a driver for innovation in two of the case studies. Use of the analytical model showed that in cases 1 and 3, there were limited incentives to innovative, even though case 1 used traditional procurement and case 3 used BVP. Both cases were based on the project's strategy to use DB, a fixed price contract and the client assuming a lesser role in innovating. In addition, case 3 did have internal conflicts between the main contractor and designers, which is a contextual issue. However, in case 2 the project was more innovative due to an early start using the BVP method, initially caused by the time pressure in the project however innovative actions were based on prior experience (innovative leaders) and the owner pushing more for innovation in the project. It could be argued that BVP was an enabler.

There was a broad plan from owner to be innovative however there was no conscious plan as the project's delivery strategy give different incentives which both hindered and promoted innovation in the projects. It was also clear that the owner regards the main contractor as the main innovator in the projects, not themselves. Findings also identified contextual conditions in all three case studies which influenced the levels of innovation in the projects such as the number of mandatory handbooks, regulatory regulations and the ease in obtaining approval from decision makers.

Innovation can be improved, within a project's delivery model, such as sharing risk and reward by extending it to the main contractor and designers so that those in a position to innovate are rewarded for taking such risks (Kalsaas et al. 2018). Procurement is another example which can include innovation, e.g. BVP awarding criteria, the two-page criteria on additional values, could be adapted so that bidders were required to answer how they intended to handle innovation in the project. Innovation can be improved, not just based on a projects delivery model but by being aware of other contextual factors in projects such as having enough time, money, participant who can share information and work together as well as learning organisations.

The findings from the case studies were consistent, reliable and repeatable while external validity was analytically generalizable based on the analytical model, which provided an explanatory framework with wide applicability, not just to NV but to others who are interested in innovation in complex projects. In addition, the analytical model created identified the relationships between the types of innovation, variables and mechanisms in projects. However, innovative leaders might be a factor which is missing from the analytical model.

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Investigating the Use of Electronic Documents in the Jordanian Construction Projects

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Abstract Construction processes normally require large exchange of information among project parties on a daily basis. The wide development in Information and Communication Technology (ICT) in recent decades has helped to provide easy processing of data during the life-cycle of construction projects. However, traditional manual methods of filing are still common in the construction industry. The aim of this study is to investigate the use of different electronic documents in the construction projects. A quantitative survey was conducted with 91 respondents from the construction projects' engineers and practitioners. Also, the questionnaire survey investigates if there is an Electronic Document Management System (EDMS) applied in construction projects. Finally, the types of electronic files and the extent of using electronic-based documents were investigated. The results of this study help to understand the context of the documents in the construction projects that may be useful to seek opportunities for improvement, and provide effective solutions for EDMS application.

Keywords Construction projects · Document management system · Information and communication technology · Questionnaire survey

1 Introduction

Construction projects normally require intensive exchange of data, especially among its contract parties on a daily basis (Maqsood et al. 2004). Although there is a great potential in the construction industry to adopt electronic business (Anumba and

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_14

Ruikar 2002; Mohammed and Stewart 2003), there are still many barriers for its adoption in a broad way (Ahmad et al. 2015, 2017; Jordanian Construction Contractors Association 2018).

DMS refers to the repository of work documents that enables end-users to retrieve required information. Some literature has combined the meanings of the term document management with other concepts such as communication, knowledge management, and information system (Aurelia and Ana 2008). Also, previous literature used different names of DMS, such as project web, project extranet, and project information management system (Björk 2003). EDMS is a software application dedicated to facilitating the management of documents by enabling secure storage, search and retrieval of documents in electronic format (Laserfiche 2007).

Many organizations have claimed saving time and efforts, increasing productivity and profitability, and improving coordination and collaboration among end-users by implementing effective EDMS (Laserfiche 2007; Al Qady and Kandil 2014a, b; Hjelt and Björk 2006; Rujirayanyong and Shi 2006). Hjelt and Björk (2006) argued that the major reason for applying EDMS is no longer technical or cost-related, but are rather related to psychology and business models. However, some factors in the construction projects may prevent the successful application of EDMS such as the complexity, the diversity of work performers, the non-repetitive nature of processes, the time and cost pressure, difficulty of systems' integration and the need to make changes to the routine procedures of work (Björk 2003; Carrillo et al. 2004; Ahmad and An 2008; Egbu 2004; Egbu and Botterill 2002; Alaghbandrad et al. 2012).

2 Literature Review

A research by Oladapo (2007) studied the conditions of ICT use in the Nigerian construction industry to evaluate its impact on the industry and the challenges to its adoption. The study categorized the factors affecting the level of ICT use into internal and external factors to the industry. The results of a questionnaire survey from 136 respondents, comprising contractors, consultants and academic researchers, showed that some of the internal factors such as type of business (contracting, consulting or academic), management awareness of the ICT benefits, and years of experience of managers on computer use were significantly correlated with the level of ICT use in the construction industry. Nevertheless, none of the external factors, such as client demands, technological demands, influence of competition, availability and affordability of hardware/software, and availability of power were significantly correlated with the level of ICT use. Also, the results showed that the highest uses of ICT in the industry are word processing, Internet communications, costing, and work scheduling. The challenges with the most effect on the use of ICT are insufficient/irregular power supply, expensive ICT hardware and software, low job order for firms, worrying from viruses and high rate of obsolescence of ICT software and hardware.

A study conducted by Bäckblom et al. (2003) examined the usage of EDMS in the Finnish construction industry. The researchers collected their data through telephone interviews with key personnel from 100 randomly chosen construction projects. The results of their study showed that about one third of large projects and only a few small projects have already adopted EDMS technology. The results also showed that the use of EDMS is yet incomplete in coverage and only a few individuals in the project can use the system efficiently due to psychological nature and insufficient training of end-users.

Moreover, a paper by Björk (2003) has surveyed and investigated individual research efforts in EDMS by examining the required specifications, frequency of use, measuring of benefits, barriers to wide-spread adoption, problems of application, scope for standardization, and evolving of the market of such systems. The results indicated that the use of project webs is becoming more common, especially in large projects. Also, the results showed that there is still a lack of reliable measurements to evaluate the overall cost saving and quality improvements for applying EDMS. The author concluded from many reported case studies that the barrier to wide adoption of EDMS is no longer the cost, but rather the willingness to use new EDMS technology by the organizational management and all project stakeholders. On the technical side, EDMS offered by vendors are almost similar in features, and their prices are not exceedingly high for development and services.

3 Methodology

The aim of this study is to investigate the extent of the use of electronic documents, the existence of EDMS, and the types of electronic documents used in the site of construction projects. A quantitative survey was designed and organized into three sections. The first section collects information about the questionnaires' respondents. The second section asks the respondents to provide their opinions about the documents' organization and types. Finally, the third section asks respondents to provide useful feedback in the form of suggestions and recommendations for successful implementation and application of EDMS. Google forms application was used to distribute and fill the questionnaires and a total of 91 respondents from the construction projects' engineers and practitioners have completed the questionnaire survey. The following sections summarize the main results of the questionnaire.

4 Characteristics of Respondents

The final number of responses, after excluding the questionnaires with many empty answers or repetitive respondents, equals 91 questionnaires. In the first part of the questionnaire the respondents were asked to provide information describing themselves and their organizations. Table 1 summarizes the results of part 1 in the questionnaire.

Table 1 Characteristics of the questionnaire respondents

Criteria	Categories	Number of respondents	Percentage of respondents
Types of respondents' organizations	Contractor	41	45.1
	Consultant	16	17.6
	Public or government representative	24	26.4
	Private client representative	10	11.0
	Total	91	100.0
Roles of respondents in their organizations	General or regional manager	8	8.8
	Project manager	19	20.9
	Site engineer	32	35.2
	Trainee engineer	12	13.2
	Other	20	22.0
	Total	91	100.0
Respondents' experience	<5 years	31	34.8
	5–9 years	13	14.6
	10–14 years	8	9.0
	15–19 years	10	11.2
	>20 years	27	30.3
	Total	89	100.0
Project financial size	<1 M $	20	22.0
	1–5 M $	32	35.2
	5–10 M $	7	7.7
	10–50 M $	10	11.0
	50–100 M $	8	8.8
	>100 M $	5	5.5
	No response	9	9.9
	Total	91	100.0
Last project finish date	Not finished yet	56	61.5
	<1 year	18	19.8
	1–2 years	7	7.7
	>2 years	4	4.4
	No response	6	6.6
	Total	91	100.0

Table 1 shows that the highest percentage of the respondents are working with contracting companies. Also, the largest percentage of the respondents are working as site engineers, which makes the results highly representative for the documents management in the sites of construction projects. The results showed that respondents are very well distributed among the categories of years of experience. The majority of the respondents (about 57%) are involved in projects with a financial size less than five million US dollars. At the time of conducting the questionnaire survey, most of the respondents were still involved in the execution of construction projects, or at least have their projects recently finished.

5 Use of Electronic Documents

The second section of the questionnaire investigates the use of electronic documents in the sites of construction projects. Firstly, the respondents were asked to evaluate the extent of use of electronic-based documents compared to paper-based documents. Figure 1 shows the results of the evaluation to these questions.

The results showed that the paper-based documents are still more commonly used than the electronic documents. According to comments from expert respondents the electronic-based files and documents are more commonly used in the organizations' management offices than in the construction site projects.

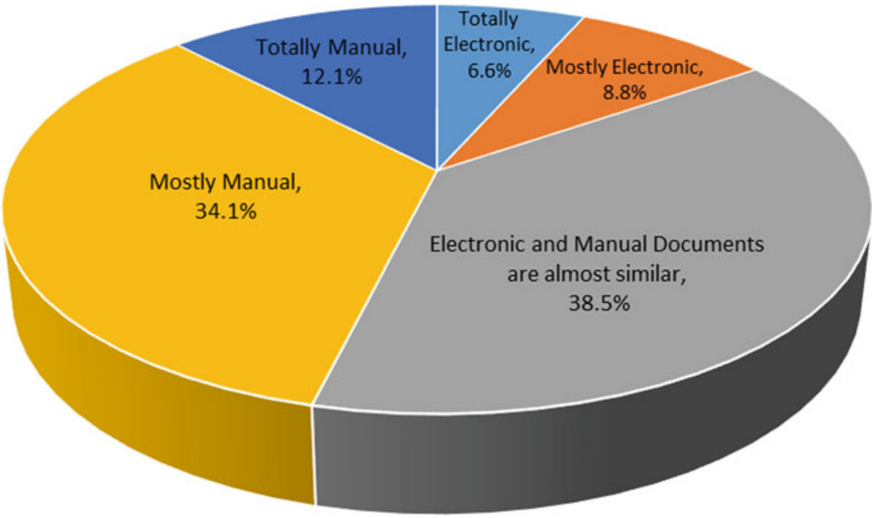

Fig. 1 Evaluation of the extent of use of electronic and paper-based documents in the sites of the construction projects

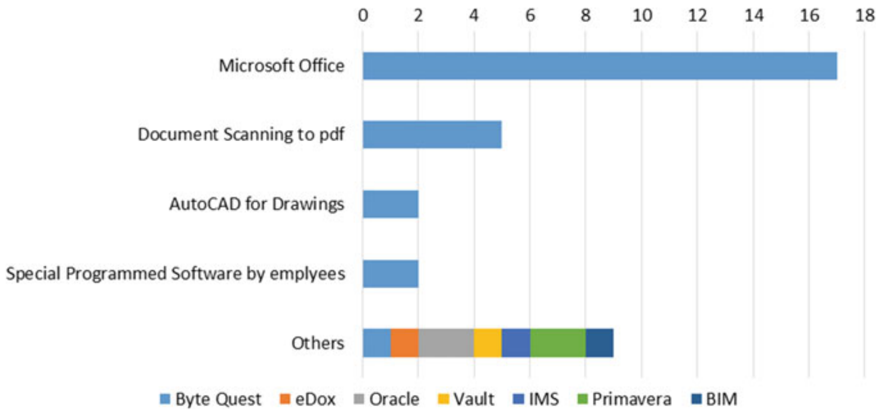

Fig. 2 The main electronic systems used for document control and management in the construction projects

Then the respondents were asked to name or describe the main electronic system used to control and manage the documents in the construction projects they are involved in. Answers were received only from 35 out of the 91 respondents. The results showed that according to the respondents' opinions, the Microsoft Office packages are the most common tools used for managing and controlling documents in the construction projects. Figure 2 represents the answers collected. Eleven out of the 35 respondents have experienced a specialized programmed software used as EDMS in their construction projects.

6 Feedback Section

The final section of the questionnaire survey asked the respondents to provide their feedback in the form of recommendations or suggestions that can be useful for successful installation, development and/or application of EDMS in the construction projects. A good number, 41 out of the 91 respondents, have provided useful comments in the feedback section. Summary of the respondents' feedback is provided in Table 2.

The results of the feedback section showed high interest from the respondents to apply EDMS in the construction projects to improve the work performance. For successful implementation and application of EDMS in the construction projects, the respondents provided recommendations to encourage training and e-learning, and to focus on appointing employees qualified for effective use of EDMS. However, some of the respondents feel that applying EDMS in the construction projects is a difficult or impossible aim in the existing conditions.

Table 2 Summary of the respondents' feedback

No.	Category of feedback	Description	Repetitions
1	Usefulness and importance of the application of EDMS in the construction projects	Improve work performance	3
		Stop losing important information	1
		Improve information searching and retrieval	1
		Reduce storage area	1
		Help to achieve financial benefits	1
2	Recommendations to motivate and improve the implementation of EDMS	Training and E-learning	5
		Appoint qualified employees and engineers for EDMS	5
		Define regulations that motivate or enforce EDMS application	4
		Encourage young employees and engineers to play important role in EDMS application and decision making	4
		Improve awareness about EDMS importance	1
		Feasibility study	1
		Transfer success stories from private to public sector	1
		Apply user friendly systems	1
		Combine required tasks in one platform	1
		Use effective categorization of information	1
		Include the use of EDMS in the education system at early stages	1
3	Challenges for EDMS application	Think that applying EDMS in the construction projects is not easy or impossible in the existing conditions	7
		Public organizations are more unwilling to apply EDMS in the construction projects	4
		Management and decision makers are not interested or unwilling to apply EDMS	3
		Unwilling to change the routine ways of doing work	3
		Some people think the application of EDMS is against their benefits	2

(continued)

Table 2 (continued)

No.	Category of feedback	Description	Repetitions
		Every organization have different way for organizing and managing their documents	1
		Benefits and feasibility of applying EDMS are not easy to prove	1
		Decision makers think the useful and effective software programs are not available	1
		Expected high cost of EDMS	1
		Information security risks	1

7 Conclusions

This study evaluated the usage of electronic documents in construction projects by a sample of engineers and practitioners involved in the construction projects. The survey was successfully completed by 91 engineers working with contractors, consultants, public organizations and private organizations. It examined the extent of use and types of electronic documents used in the construction projects, and collected useful feedback from the respondents. Some of the main findings are as follows:

- The results showed a higher percentage for using manual documents than electronic documents. However, the authors think that the extent of use of electronic documents is satisfactory for a developing country like Jordan.
- The most used tools for document management according to the engineers involved in the construction projects are the Microsoft packages, but also the results showed a good extent of the use of specialized EDMS packages.
- The feedback section showed that some of the questionnaires' respondents are confident that the application of EDMS in the construction projects is useful mainly in terms of improving work performance, in addition to preventing the loss of data, improving information retrieval, reducing required storage area and even help achieving financial benefits.
- The respondents provided recommendations to improve the application of EDMS in the construction projects, including: provision of effective training and e-learning contents, recruiting and appointing qualified employees in electronic programs, defining and enforcing regulations for EDMS application in the construction projects, and encouraging young engineers to take part in the decision-making process.
- A number of the survey respondents think that the application of EDMS in the construction projects is very difficult in the existing conditions, and that it is even more difficult in public organizations and projects.

Even though previous literature has examined the use of electronic documents and EDMS in construction projects, there is a lack of effective application of EDMS in Jordanian construction projects. Further investigation is required concerning this issue in order to enhance the awareness of the practitioners and engineers regarding the importance of EDMS, and motivate its successful implementation in the construction projects. It is anticipated that this study can guide decision makers to adopt procedures that motivate the use of EDMS and avoid challenges to its application. Future plans of this study can aim at designing a model for successful development and implementation of EDMS for construction projects that can integrate the business operations of the different parties involved in the project. It is useful to develop and re-conduct this study every few years to detect any development in the use of electronic documents and EDMS in the field of construction project management.

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Improving Collaboration in Construction Projects in Developing Countries: The Case of Kurdistan Region of Iraq

Hazhar Faris, David Hutchinson and Mark Gaterell

Abstract The construction sector is criticised for being fragmented and for having a large number of problems between stakeholders such as adversarial relationships, lack of trust and ineffective communication. These issues emerge especially in developing countries. Collaboration has been introduced as a solution to such issues. However, delivering an effective process of collaboration is a challenge with a wide range of factors involved. This paper identifies and sorts the critical factors that affect collaboration in the construction sector and recommends ways to adapt such factors in the sector. Through a comprehensive review of the literature, two groups of critical success factors have been identified to improve such practices, hard factors and soft factors. This study contributes to the scarce literature about collaboration in the construction industry in the Kurdistan and identifies factors of collaboration that construction projects need to adopt in order to improve their performance.

Keywords Collaboration · Critical factors · Construction · Developing countries · Kurdistan-Iraq

1 Introduction

Adversarial relationships and a lack of collaboration are familiar challenges in the construction industry. Many researchers have insisted the construction industry needs to improve collaboration between involved stakeholders to enhance the performance of projects (Grilo et al. 2013; Morrell 2015; Shelbourn et al. 2007). The construction industry has seen three different delivery approaches: traditional construction

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_15

management (TCM), project management (PM) and partnering. In the traditional approach, parties compete to win bids and relationships are defined based on strict contracts. TCM has resulted in many adversarial relationships in the construction sector. The PM model was developed to overcome challenges facing construction projects; however, it also faced many difficulties in the industry. Then, partnering was introduced to the construction sector by Latham (1994) and aimed at solving the problem of fragmentation of the sector. Partnering improved project delivery methods; however, relationships are far from collaborative and the construction sector still needs to take serious actions to solve this problem.

Although construction projects face many challenges globally, these obstacles are increased in the case of developing countries (Ofori 2000). This is because these countries have more severe social, cultural and economic situations (Elkhalifa 2016). Similarly, in the Kurdistan region of Iraq, construction projects are confronted with a wide range of problems such as a clear lack of collaboration between involved parties (RTI International 2008). This article aims to address this issue by identifying the critical factors needed to improve collaboration in construction projects in developing countries and especially in Iraqi Kurdistan.

2 Literature Review

Globally, the construction industry is a main contributor to economic growth and to development of nations; this contribution increases in the case of developing countries (Ofori 2007). Lopes et al. (2002) investigated the role of construction in developing countries and argued that there is a significant relationship between the amount of construction going on and economic growth for countries still at the developing stage. In Iraqi Kurdistan, despite the construction sector being essential to the growth of the region, construction faces many obstacles such as organizational issues, adversarial relationships and a clear lack of collaboration (Mustafa 2017). Shawkat et al. (2018) agreed that several barriers are confronting construction industry in the Kurdistan region including deficiencies in the construction process, considerable shortage of skilled professionals, socio-cultural, technical and management factors. According to Zebari and Ibrahim (2016), the construction process in the Kurdistan is highly uncommunicative, and involved stakeholders are not collaborating, this lack of interaction between participants has resulted in underperformance of industry products. The authors added that there is a clear lack of collaboration between construction and design teams.

Additionally, the sector is growing for many reasons such as the growth in foreign investment in the region as illustrated by the World Bank (2015). Actually, Barnard (2013) expected more developments and progress in the Kurdistan region. Consequently, the need for improving relationships and collaboration between the stakeholders involved in the project lifecycle is increasing. Researchers have agreed that collaboration is important for improving construction practices and that it has many benefits for the industry (Kożuch and Sienkiewicz-Małyjurek 2016; Meng

2013; Shelbourn et al. 2007). Despite its benefits, delivering effective collaboration in the construction industry is still a challenge, a range of factors need to be considered as a means for achieving collaborative environments (Koraltan and Dikbas 2002; Shelbourn et al. 2007). Therefore, this research reviews the literature to identify the most critical factors needed to deliver effective collaboration.

3 Research Methodology

A considerable amount of literature exists on the factors to deliver collaboration and ensuring better relationships within construction projects. In this research, a comprehensive review has been undertaken to identify critical success factors of collaboration. The process of identifying factors of collaboration, partnering and alliancing from the previous literature has been used by other researchers such as (Chan et al. 2003; Nyström 2005; Yeung et al. 2007). The authors have reviewed the most relevant literature from 2000 to 2018. To identify a sample of papers to be reviewed, the first step was to search for keywords in titles and abstracts of the articles. As the past literature has used different words to describe collaborative relationships, such as partnering, strategic partnering, alliancing, teamwork, collaboration and so on. Similarly, studies describing factors of collaboration have used different terms such as critical factors, attributes, attitudes, components and so on. In this research, a combination of words from both aspects of collaboration and factors has been used to identify related studies. Then, related articles were scanned qualitatively to identify most-closely related studies. Similar approaches were also used by Kożuch and Sienkiewicz-Małyjurek (2016) and Wu et al. (2008) in collaboration research. This process resulted in 35 articles being considered for this research which are listed in Table 1.

The most commonly mentioned factors in the articles were identified. Later, to determine whether similar factors are needed in the Kurdistan region, those factors were compared to the literature of Kurdistan construction and similar challenges were found (Abramzon et al. 2016; Mustafa 2017; RTI International 2008; Shawkat et al. 2018; Zebari and Ibrahim 2016). Additionally, some factors were merged into one item, and the greater group was kept. For example, the literature has linked the early involvement of participants and contracts and sometimes has used them for the same purpose. The early involvement of participants depends on the type of contract, as explained by Hughes et al. (2012). Since early involvements have been mentioned more frequently than contracts; that former factor has been kept. The final factors identified from the literature are shown in Table 2 with their definition outlined below.

Table 1 Reviewed papers to identify factors of collaboration

Ref. No.	Author(s)	Year	Ref. No.	Authors	Year	Ref. No.	Author(s)	Year
1	Akintoye et al.	2000	13	Lu and Yan	2007	25	Patel et al.	2012
2	Black et al.	2000	14	Shelbourn et al.	2007	26	Akintan and Morledge	2013
3	Bresnen and Marshall	2000	15	Yeung et al.	2007	27	Meng	2013
4	Bresnen and Marshall	2000b	16	Dikmen et al.	2008	28	Rahman et al.	2014
5	Cheng et al.	2000	17	Erdogan et al.	2008	29	Azhar et al.	2014
6	Bayramoglu	2001	18	Koutsikouri et al.	2008	30	Gassel et al.	2014
7	Cheng and Li	2001	19	Wu et al.	2008	31	Bidabadi et al.	2015
8	Cheng and Li	2002	20	Eriksson	2010	32	Bidabadi et al.	2016
9	Koraltan and Dikbas	2002	21	Xue et al.	2010	33	Kozuch and Sienkiewicz-Małyjurek	2016
10	Chan et al.	2004	22	Bemelmans et al.	2012	34	Koolwijk et al.	2018
11	Vaaland	2004	23	Hughes et al.	2012	35	Nursin et al.	2018
12	Nystrom	2005	24	Meng	2012			

4 Critical Factors of Collaboration

4.1 Trust

For collaboration to be effective, parties need to build trust (Meng 2013). This is because if the level of trust is low, parties tend to act against each other and it is not possible to work collaboratively. Construction organisations need to improve the level of trust between their practitioners by using new ways of working (Wu et al. 2008). It is very important in construction projects that stakeholders take time out from routine activities to increase the level of social interaction in order to build mutual trust and respect (Shelbourn et al. 2007).

Table 2 Factors of collaboration and references mentioned

Rank	Critical factors	Frequency	No. of papers (from Table 1) mentioned the factor
1	Trust	31	([1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [12], [13], [14], [15], [16], [17], [18], [19], [21], [22], [23], [24], [25], [26], [27], [28], [29], [31], [33], [34], [35])
2	Communication	26	([2], [4], [5], [6], [7], [8], [9], [10], [14], [15], [16], [18], [19], [21], [22], [23], [24], [25], [27], [28], [30], [31], [32], [33], [34], [35])
3	Conflict resolution	21	([5], [6], [7], [8], [9], [10], [11], [12], [13], [15], [16], [17], [19], [21], [23], [24], [25], [27], [28], [29], [35])
3	Mutual goals	20	([1], [4], [5], [9], [10], [12], [13], [14], [15], [18], [19], [21], [22], [23], [24], [25], [27], [28], [29], [33])
5	Top management support	20	([1], [2], [5], [7], [8], [10], [12], [13], [15], [16], [20], [19], [21], [22], [25], [28], [29], [31], [32], [34])
6	Commitment	19	([1], [2], [3], [5], [7], [8], [10], [13], [14], [15], [16], [19], [22], [25], [28], [31], [32], [33], [34])
6	Gain-pain sharing	18	([1], [2], [3], [6], [9], [13], [14], [15], [19], [20], [21], [22], [23], [24], [27], [28], [29], [34])
8	Culture	16	([1], [2], [4], [5], [9], [13], [14], [16], [18], [21], [22], [25], [29], [31], [33], [35])
9	Resource sharing	14	([5], [7], [8], [10], [12], [13], [14], [15], [17], [19], [25], [26], [28], [33])
10	Early involvement	14	([4], [5], [6], [10], [12], [14], [15], [20], [21], [23], [25], [29], [31], [34])
11	Clear roles	13	([2[, [4], [10], [14], [16], [18], [23], [25], [27], [28], [31], [32], [33])

4.2 Communication

Construction organisations need effective communication skills to exchange visions and ideas and to reduce misunderstandings and produce effective working environments (Cheng et al. 2000). Clear communication channels create formal and informal ways to exchange information, increase shared awareness and obtain shared benefit (Patel et al. 2012). To attain a steady process, design and construction teams need to have clear communication channels to increase shared awareness and avoid technical issues.

4.3 Mutual Goals

Establishing mutual goals is a major contributor to the success of projects and is regarded as a prerequisite of success for collaboration (Bresnen and Marshall 2000a). Construction teams need to agree on mutual goals at the highest levels of management and transfer those goals to the lower levels to ensure all involved parties work toward a common target.

4.4 Conflict Resolution

Disputes are present in all construction projects depending on size, duration and complexity of contracts. However, Xue et al. (2010) indicated that a proper strategy of conflict resolution provides stability and prevents many issues related to adversarial relationships in traditional contracting approaches. Practitioners need to solve disputes at the lowest level possible before rapid escalation to legal authorities (Bayramoglu 2001). If a conflict reaches a point that requires a court to solve it, it may cause all parties to lose time and incur a cost.

4.5 Top Management Support

Nyström (2005) identified top management support as the main prerequisite for developing a collaborative approach in the construction industry. Therefore, in order to achieve targets set for parties working at different levels in construction projects, top management needs to show full support. Support from management is essential to develop and maintain relationships at a high level and to avoid disputes (Dikmen et al. 2008).

4.6 Commitment

A core item required for the success of collaboration is commitment by the involved parties; commitment and motivation are required to reinforce relationships in construction projects (Bresnen and Marshall 2000b). Success of collaboration in construction projects is highly influenced by the commitment of parties in providing shared resources and working toward common objectives.

4.7 Gain-Pain Sharing

Another crucial factor for a collaboration to succeed is a gain-pain sharing system between parties. It can be argued that the absence of a proper means of gain-pain sharing is responsible for restraining resources and information, which results in a lack of collaboration. The importance of risk sharing increases in the case of larger projects. As explained by Lu and Yan (2007), in complex projects with a high degree of uncertainty it is essential to share risks and rewards in a systematic way to gain effective collaboration.

4.8 Culture

Project and organisational management trends are moving toward more decentralised, flexible and collaborative organisations. However, the success of this step toward collaboration is associated with understanding the crucial role of cultural changes within this process (Black et al. 2000). Culture could indicate methods of communication and engagement of the members in projects.

4.9 Resource Sharing

Resource sharing increases trust and respect between parties and helps to produce collaborative environments. Sharing resources increases the willingness to work collaboratively and facilitates the development of relationships in an efficient way (Rahman et al. 2014).

4.10 Early Involvement of Key Participants

Traditional ways of project delivery have restricted involvement of some key participants at early stages. These approaches have resulted in adversarial relationships and underperformance in construction projects. The early involvement of participants increases the level of understanding, thus reducing disputes and improving team performance. Collaborative teams need to be built on the early involvement of key members so as to move away from a conservative construction culture and improve the performance of industry products (Hughes et al. 2012).

4.11 Clear Roles

For a collaboration to be successful, roles need to be clearly defined and individual responsibilities need to be coordinated toward achieving the project target (Patel et al. 2012). The complexity that exists in construction projects makes it difficult to clarify the responsibilities of each individual. However, Black et al. (2000) indicated that a clear understanding of responsibilities is required if collaborative working is to succeed, and that this requires the effort of all project stakeholders.

5 Discussion

5.1 Analysis of the Study Results

After reviewing the literature, 11 critical factors were identified and explained. In order to clarify the confusion that exists in the literature about collaboration factors, these factors are classified into two categories: hard factors and soft factors. Hard factors are tangible items and tools that mainly depend on contractual agreements (Yeung et al. 2007) whereas soft factors are items that depend on the behaviour of participants and organisations' personnel (Shelbourn et al. 2007). Soft factors need to be developed throughout the lifecycle of a project. Soft factors identified in the literature include trust, communication, mutual goals, and culture. These factors are necessary for any kind of project to increase interaction and understanding between parties. Focusing on soft issues is necessary to achieve effective collaboration. However, soft factors alone are not sufficient to deliver a successful process of collaboration; hard factors and systems need to be in place to complete the process. Hard factors determined in this study include conflict resolution systems, top management support, gain-pain sharing systems, resource sharing, clear roles, and the early involvement of key participants. Figure 1 indicates the most critical factors grouped into hard and soft factors of collaboration.

Nyström (2005) classified factors of partnering into general prerequisites and components. Prerequisites are factors that need to be provided before the formation of a collaboration process while components are factors established and developed during the process of collaboration. Looking at the factors found in this research, prerequisites for a collaboration process are top management support, early involvement of key participants and resource sharing. These factors are necessary to establish a collaborative working environment between construction parties, without providing prerequisites it is not possible to build a collaborative environment. Other factors identified in this research can be described as items to be developed during the collaboration working process which are trust, communication, mutual goals, conflict resolution, commitment, gain-pain sharing, culture and clear roles.

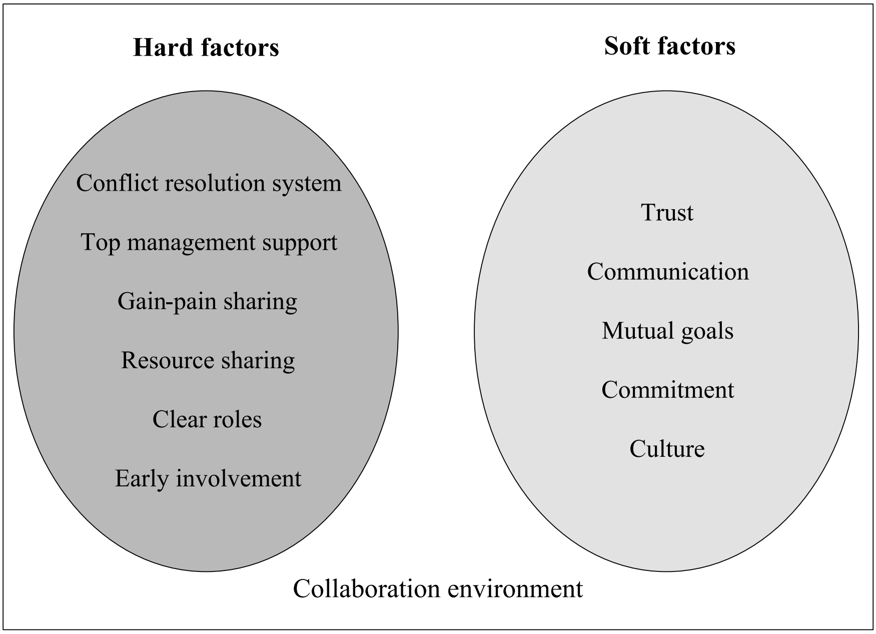

Fig. 1 Two groups of collaboration factors

The findings of this research are consistent with those of Chan et al. (2004) and Cheng and Li (2001), both of whom looked at critical success factors for partnering in the construction industry. Compared to those studies, it can be noted that the role of both trust and communication factors has increased. Obviously, the importance of communication has increased with the implementation of complex designs and the use of advanced technologies in construction projects. To simplify complex designs and to enable effective collaboration, clear communication channels need to be established (Koutsikouri et al. 2008). Similarly, the importance of trust has increased; in this research mutual trust was identified as the most critical factor. Other factors found in the literature included the evaluation of the process, contract types, technology, sharing information, respect and experience.

5.2 The Implications for Construction Projects in the Kurdistan Region and Further Study

The construction sector in Iraqi Kurdistan consists of public and private sectors. Implementing collaboration in the public sector could face more challenges than the private sector. In the public sector, government rules place many policies that do not encourage collaboration such as awarding contracts based on lowest-bid basis and restrictions on early involvement of contractors. Construction is a conservative sector with a wide range of adversarial relationships. In order to implement collaborative approaches governments need to enforce new rules, for example, at bid awarding stage they could restrict cost considerations to focus on lifecycle cost rather than lowest-bid. To enable collaboration in a conservative construction sector, Koraltan and Dikbas (2002) recommended that contracts be awarded on the most economically advantageous offer instead of the lowest initial bid. In many cases, the lowest initial bids are not the most advantageous option if lifecycle cost is considered. Collaboration has many benefits regarding cost reduction.

Implementing collaborative approaches in the public sector obliges construction organisations to work under, and get used to, the new approaches. This change can make organisations realise the benefits of collaboration and increase interest in adopting new approaches in the private sector. The Kurdistan Regional Government (KRG) could help in improving collaboration and in using public funds efficiently by assessing bids based on other criteria rather than just lowest-bid and bringing in contractors at an early stage (Bekr 2015). Additionally, in the Kurdistan region, there are a significant number of international companies with considerable experience in collaborative approaches and new ways of working. The KRG could form partnerships with such companies and benefit from their experience in legislating and implementing new rules for the construction sector. Since construction practitioners in both private and public sectors are not familiar with collaborative approaches, significant effort needs to be expended in order to increase the level of awareness toward collaboration. At this stage, universities, research centres and government departments can have a crucial role. These organisations could help by organising introductory seminars and workshops about collaboration in the construction industry. These presentations could have a significant impact to increase awareness and to reduce resistance to change in construction practices (Arayici et al. 2011).

As little literature exists on collaboration in construction projects in Kurdistan region, further research is essential. KRG needs to collaborate with a research institution in the region to investigate practical ways to implement collaboration in the construction sector. Construction industries faces similar problems in other developing countries. Therefore, the identified factors and suggested methods of implementation could be usefully applied in other countries.

6 Conclusion

Collaborative construction practices are still far from effective in developing countries in general, and in the Kurdistan region in particular. To develop a successful collaboration, a wide range of factors should be considered. Since many attributes and factors have been linked to improving collaboration in the construction industry, confusion exists in identifying the most critical factors required to deliver effective collaboration. This paper identified 11 factors as essential for achieving effective collaboration in the construction sector. These factors were divided into two groups:

hard and soft factors. Soft factors consist of trust, communication, mutual goals, commitment and culture. The necessary hard factors include conflict resolution systems, top management support, gain-pain sharing, resource sharing, clear roles and the early involvement of key participants.

It is recommended that KRG demand new rules to be applied in public projects. New policies at the bid awarding stage are essential to ensure that contracts are not awarded based only on the lowest initial bid. KRG also needs to encourage early involvement of contractors through imposing new regulations. Additionally, the study suggests that KRG could form partnerships with international construction companies that have experience in collaborative working and benefit from their experience in legislating and implementing new rules. Furthermore, the regional government needs to collaborate with a research institution in the region to investigate practical ways to implement collaboration in the construction sector.

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Comparative Analysis of Methodologies for Calculating the Economic Life of Construction Equipment

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Abstract The most profitable period of owning and operating a machine is during its economic life. To find the "sweet spot", i.e. the time in the life cycle of the machine where owning and operating costs reach the minimum point, is a complicated task. It is evident that, in order to conclude with the best decision of either to keep or replace piece of equipment, repair-related cost information is indispensable, as it reflects machine's DNA. Construction companies are currently facing an imbalance between the huge amount of owning and operating and maintenance (O&M) data that they have and the lack of solid organizational structures in order to make the best use of this knowledge. Thus, there is a dynamic that remains unused. This research highlights the advantages and disadvantages of methodologies for calculating the economic life of construction equipment and proposes a conceptual model that determines the replacement period using owning and O&M costs.

Keywords Construction equipment · Economic life · Optimization methods · Replacement · Residual value

1 Introduction

In the construction industry, several attempts have been implemented to improve construction equipment's productivity. The main objective of these attempts has been to improve profitability (Edwards et al. 2003). Such initiatives are inextricably linked to the use of construction equipment, without which the efficient and cost-effective

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_16

delivery of construction projects could not be realized. However, the construction equipment should be properly maintained so as to minimize incidences of breakdowns. Breakdown may cause important losses in machine utilization (Edwards et al. 2005). Apart from this, the performance (i.e. productivity) of construction equipment is gradually decreasing over time, while new equipment with comparatively higher performance is emerging (Naskoudakis and Petroutsatou 2016). The cost to operate and maintain construction equipment outweighs the profit of its use as time passes, and there is a point where replacing it is the only solution. The replacement decision is not an easy task to perform as it should take into account several parameters affecting the investment in the machinery. The factors that affect the economic life of equipment are discussed in the literature review. The purpose of this study is to present a methodology of replacing construction equipment based on factors identified in the literature and incorporating them in the proposed conceptual model.

According to Vorster (2009), for every machine, there is an economic ownership period or "sweet spot" when the sum of hourly and operating costs is minimized, due to the fact that the machine has worked long enough to reduce owning costs, but not long enough to experience unnecessary and usually high repair costs. Hourly cost calculations are very sensitive to estimates. Additionally, the age of a machine, as well its utilization, are key estimates in the owning and operating cost calculation, which in turn determines any proper decision making for equipment replacement.

2 Theory and Hypotheses

Gillespie and Hyde (2004), in their final report for the Virginia Department of Transportation, used historical records from a loader with a backhoe, in order to identify the best minimization method of the life cycle cost, as the key to getting the most out of the equipment budget. They applied their methodology on the basis that the optimal equipment replacement strategy is to keep and operate a piece of equipment as long as the expected marginal cost of operating it is less than or equal to the expected average total cost of a new piece over its lifetime. Their research indicated that an analysis using fuel cost, as the measure of service, produces findings that are interesting and plausible, but not very precise. To confirm the findings, they proposed further analysis using hours of service. This requires a more in-depth study of the recorded hours-of-use data and the downtime data, suggesting that these data should include the number of hours of availability (or, conversely, the number of hours of downtime), the dates it goes out of service for repairs and the dates it returns to service, and finally its residual value.

Nunnally (2006) noted that in order to estimate any equipment's hourly production, it is necessary to estimate many factors, such as fuel consumption and tire life. The best basis for estimating such factors is the use of historical data and if such data are not available, consulting the equipment manufacturer for recommendations could be another option. They also pointed out that replacement decisions require a precise investment amount for a particular year.

Vorster (2009) concentrated on the estimation of the residual market value (RMV) of equipment, by taking mostly into account the equipment's manufacturing year and the total working hours. He overlooked the O&M characteristics of the future equipment, which will replace the current.

Fan and Jin (2011) noticed that for a specific type of a dump truck there is a discrepancy between the manufacturer's recommended life and the actual life in a contractor's fleet. So, they published their study on the factors affecting the economic life of heavy construction equipment and how the combination of the influencing factors reduce or increase the equipment life span. Their study described seven affecting factors: (i) age of the equipment, (ii) manufacturer, (iii) operating division of the contractor, (iv) class of the equipment, (v) annual preventive maintenance cost, (vi) annual traveling distance and (vii) annual accumulated fuel cost. Their results proved that the annual accumulated fuel cost is the most important impact factor.

Gransberg (2015) in his final report for the Minnesota Department of Transportation, also argued that the fuel price is probably the most critical input when determining the economic life of the equipment, as a significant cost item of the O&M costs. He reached this conclusion, by comparing a deterministic and a stochastic model of a dump truck and proved that allowing fuel process to range probabilistically in the analysis provides a mean to quantify the certainty of the equipment replacement decision.

All of them agreed that equipment's historical data are necessary to form a predictive model and that there are critical factors that affect equipment's economic life, with fuel cost being the most crucial. Their focus is on estimating the Total Replacement Cost (TRC) or the Optimum Replacement Period (ORP) of the equipment that is in use. The company's profit originates from the equipment's productivity and from its residual value. A common characteristic of all these research approaches is that they did not consider any future investment on new equipment. In reality, the old equipment will be replaced by a new one, so it is required to obtain its O&M data and its RMV. This study focuses on this need.

Xirokostas (1999) highlighted this dynamic. His approach was based on the operating and maintenance characteristics of the equipment that will replace the current and how new equipment's RMV will evolve. So, for accomplishing his calculations he used values such as Estimated Residual Market Value (ERMV), O&M costs and acquisition cost for the new equipment; he sourced data for new equipment from original manufacturers or from the market. In order to estimate the minimum TRC and consequently the optimum replacement period for the new equipment, there are seven different methods of replacement (Table 1).

3 Methodology

This research introduces a conceptual model of Xirokostas's approach and applies a 2-step sensitivity analysis as described below.

Table 1 Equipment's replacement methods (Xirokostas 1999)

	Methods of replacement
1	Equipment of the same type
2	Improved equipment
3	Equipment, which follows a linear technological improvement
4	Equipment, which follows a continuous technological improvement of constant rate
5	Equipment, which follows a rapid linear technological improvement
6	Equipment, which follows a rapid, but continuous technological improvement of constant rate
7	Equipment, which follows a general form of continuous technological improvement

Original Equipment Manufacturers (OEMs) agree that machinery has a technological evolution over time at a constant rate. Furthermore, the decrease in residual value and the increase in O&M costs follow a rate according to the use of the machinery and its age. The impact factors taken into account are presented in Table 2.

The optimization process defines the optimum replacement time when the TRC (C_n) is minimized. C_n is given by the following mathematical equation:

$$C_n = C_n(s) + C_n(u) \tag{1}$$

where

$$C_n(s) = \frac{1}{1 - (a\rho_s)^n} \cdot (I - a^n \cdot S_n)$$

for every $\rho_s = 1 - m_s$

Table 2 Construction equipment's impact factors

	Impact factor	Description
1	Interest rate (i)	The cost of capital invested in equipment
2	RMV the 1st year (S_1)	The residual market value of the new equipment, the first year of operation
3	RMV decrease per year	The decrease in equipment's residual market value each year
4	RMV decrease rate (m_s)	The % rate that the equipment's residual market value decreases each year
5	O&M cost the 1st year (u_1)	The operation and maintenance cost the 1st year
6	O&M cost increase rate (m_u)	The % rate that the equipment's O&M cost increases each year

and

$$C_n(u) = \frac{1}{1 - (a\rho_u)^n} \cdot \sum_{j=1}^{n} a^j \cdot u_j$$

for every $\rho_u = 1 - m_u$
where

$C_n(s)$	cost due to RMV decrease
$C_n(u)$	cost due to O&M
n	time period in years of use of the machine
i	interest rate
$\alpha = \frac{1}{1+i}$	present worth compound amount factor
I	cost of purchasing the new machine
S_n	RMV of the new machine for each year
u_j	O&M costs for each year of operation
m_s	decrease rate of RMV
m_u	decrease rate of O&M costs.

The RMV data are provided by the OEMs and the data on O&M costs are provided by the company's historical data log of the same or similar type of equipment. As it could be realized, both the two clauses of the mathematical equation are dependent on *i,* the interest rate that a company wants to apply, in order to calculate the cost of capital invested on a machine. This is not a simple issue to answer, mostly because of the capital-intensive nature of equipment operations. Usually, this information is dictated by the financial department of the company, taking into account a number of factors, including: (i) the availability and expected return from alternate investment opportunities, (ii) the availability and cost of capital of the company, and (iii) the relative risk involved in the investment, on the basis that equipment is a depreciating asset working in a volatile and competitive environment. Equation (1) is applied to an earthmoving dozer. The cost estimations of the dozer, combined with the company's data are presented in Table 3. Figure 1 shows the formulas applied on an excel sheet and the results generated.

The solution to the aforementioned deterministic approach revealed that the optimum replacement period for the new equipment is after 10 years of owning the equipment. By that time TRC reaches its minimum, which is 718.300€. Another indicator of the optimal replacement time is the year in which the equipment's RMV is still greater than its O&M cost. Currently, the solution showed that this condition occurs again approximately after 10 years of operation. The table also shows that if the company decides to keep the equipment longer, after 14 years of operation, the equipment will be totally depreciated. Another significant point (decisive point) is when RMV and O&M cost coincide (Fig. 2).

Table 3 RMV and O&M cost estimations

Parameters		Value
Purchase price	I	240.000€
RMV the 1st year (manufacturer)	S_1	115.000€
Annual RMV decrease (manufacturer)		9.500€
RMV decrease rate (manufacturer)	m_s	3%
O&M cost for the 1st year (company)	u_j	8.000€
O&M cost increase for the next 5 years (company)		1.500€
O&M cost increase after 6 years until the end of its life (company)		2.500€
O&M increase rate (company)	m_u	5%
Interest rate (company)	i	3%

n/j	$(\alpha\rho_u)^n$	$1-(\alpha\rho_u)^n$	$(\alpha\rho_s)^n$	$1-(\alpha\rho_s)^n$	a^n	S_n	a^nS_n	u_j	a^ju_j	$\sum_{j=1}^{n} a^ju_j$	$I-a^nS_n$	$\frac{(12)}{(5)}$	$\frac{(11)}{(3)}$	$C_n = (13) + (14)$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	0,922	0,078	0,942	0,058	0,971	115	111,65	8	7,77	7,77	128,35	2.203,333	100,00	2.303,33
2	0,851	0,149	0,887	0,113	0,943	105,5	99,44	9,5	8,95	16,72	140,56	1.242,633	111,99	1.354,63
3	0,785	0,215	0,835	0,165	0,915	96	87,85	11	10,07	26,79	152,15	923,359	124,38	1.047,74
4	0,724	0,276	0,787	0,213	0,888	86,5	76,85	12,5	11,11	37,89	163,15	764,404	137,14	901,54
5	0,667	0,333	0,741	0,259	0,863	77	66,42	14	12,08	49,97	173,58	669,547	150,27	819,82
6	0,616	0,384	0,698	0,302	0,837	67,5	56,53	15,5	12,98	62,95	183,47	606,714	163,78	770,49
7	0,568	0,432	0,657	0,343	0,813	58	47,16	18	14,64	77,59	192,84	562,159	179,52	741,68
8	0,524	0,476	0,619	0,381	0,789	48,5	38,29	20,5	16,18	93,77	201,71	529,008	196,88	725,88
9	0,483	0,517	0,583	0,417	0,766	39	29,89	23	17,63	111,40	210,11	503,442	215,48	718,93
10	0,446	0,554	0,549	0,451	0,744	29,5	21,95	25,5	18,97	130,37	218,05	483,172	235,12	718,30
11	0,411	0,589	0,517	0,483	0,722	20	14,45	28	20,23	150,60	225,55	466,738	255,65	722,39
12	0,379	0,621	0,487	0,513	0,701	10,5	7,36	30,5	21,39	171,99	232,64	453,169	276,96	730,13
13	0,350	0,650	0,458	0,542	0,681	1	0,68	33	22,47	194,46	239,32	441,792	298,97	740,76
14	0,322	0,678	0,432	0,568	0,661	-8,5	-5,62	35,5	23,47	217,93	245,62	432,126	321,63	753,76
15	0,297	0,703	0,406	0,594	0,642	-18	-11,55	38	24,39	242,32	251,55	423,819	344,88	768,70

i = 0,03

Fig. 1 Calculation table

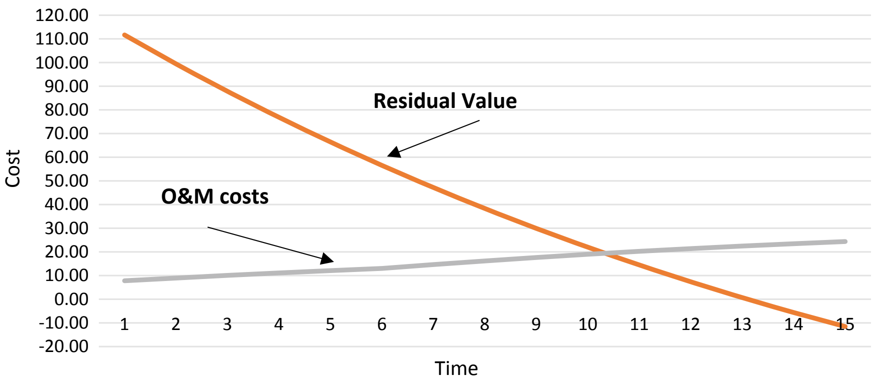

Fig. 2 Residual value and O&M costs

4 Sensitivity Analysis

The sensitivity analysis tests the behavior of minimum TRC, in changes of O&M costs for the 1st year, RMV the 1st year, m_u, and m_s with the interest rate fixed. The value of these factors is changing by 10%. Figure 3 depicts the tornado diagram for the above factors, expressed in percentage of increase or decrease of TRC.

The aim of the analysis is generally to identify if RMV is more sensitive than the equipment's O&M to TRC. Table 4 presents the analysis's results, which show that TRC is more sensitive to RMV than O&M variations.

According to Vorster (2009), the RMV of a machine when sold at any point in its life is an unknown that depends on many factors. Make, model, type and age when sold are the underlying determinants while other factors such as the condition of the machine and the amount of life left on major wear items affect individual transactions.

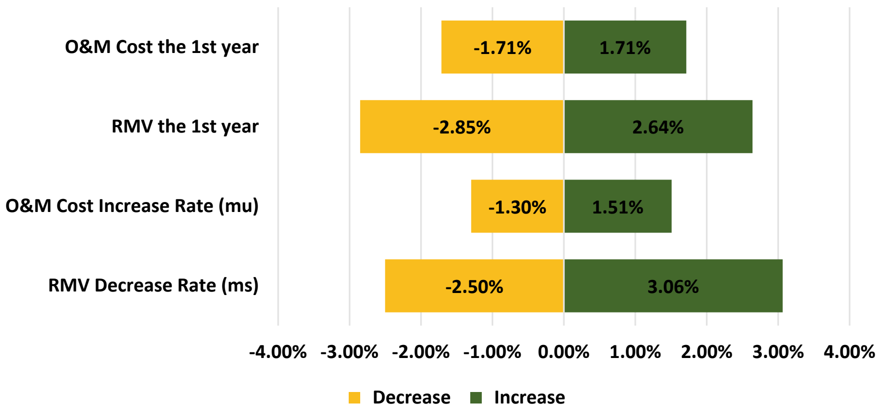

Fig. 3 % variations of TRC

Table 4 Sensitivity analysis results

Factors	10% factor decrease		10% factor increase	
	% of TRC variation (%)	TRC variation (€)	% of TRC variation (%)	TRC variation (€)
RMV decrease rate (m_s)	−2.50	−17.979	+3.06	+21.998
O&M cost increase rate (m_u)	−1.30	−9.326	+1.51	+10.832
RMV the 1st year	−2.85	−20.488	+2.64	+18.961
O&M cost the 1st year	−1.71	−12.307	+1.71	+12.307

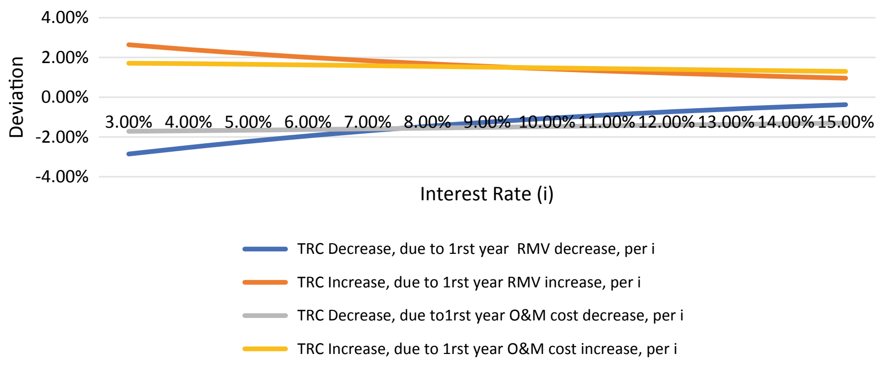

Fig. 4 Trend lines of TRC sensitivity in RMV and O&M cost for the 1st year, per interest rate (i)

The state of the economy, the amount of work in the area and the machine's ability to meet current environmental standards also have a major impact. This research exploits the equipment's historical data and OEMs' estimations for RMV and O&M cost.

The prevailing determinants of RMV value are the market itself. On the other hand, O&M costs can more easily be estimated if the company keeps good track records for its equipment (Peurifoy et al. 2011).

The next step in the sensitivity analysis is to investigate the changes in TRC to interest rate variations. The range of the interest rate is selected to be from 3 until 15%. The variation of factors in Table 4 remains the same at 10%.

Figure 4 shows the trend lines. From the figure, it is observed that the trend line for TRC decrease, due to 1st year's RMV decrease intersects the trend line for TRC decrease, due to 1st year's O&M cost decrease at 7.5% of *i*, above which TRC is more sensitive to RMV. The trend lines that present the increase variations intersect at 9.5%. So, the values of *i* between 7.5 and 9.5% make TRC more sensitive to RMV variations. This could be of importance for a company when it wants to minimize the risk involved in RMV estimations. The same happens when m_s and m_u are analyzed. Figure 5 depicts the corresponding trends. The values of *i* range between 4 and 7.5%, presenting an "interest rate window", in which the company should invest in the specific equipment.

5 Discussion and Implications

The investment in machinery is an important capital asset for every construction company. Through a comparative analysis of the methods that calculate the period after which the machinery should be sold, this study proposes a conceptual model that estimates the time of replacement. The 2-step sensitivity analysis, that is performed,

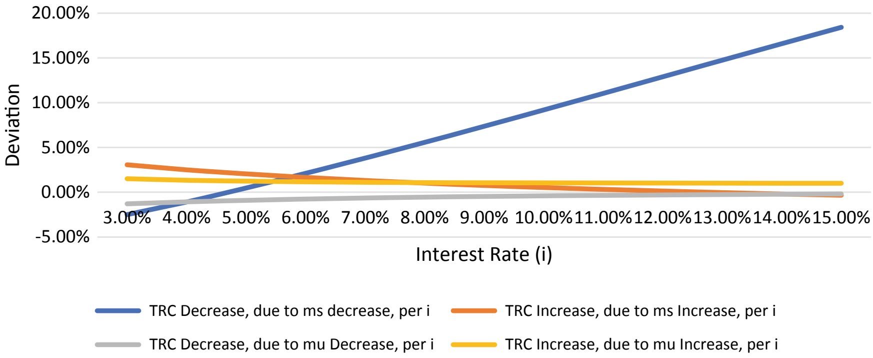

Fig. 5 Trend lines of TRC sensitivity in RMV and O&M change rates, per interest rate (i)

highlights some interest areas for further investigation of the factors that impact the economic life of the machinery.

These factors are RMV and O&M costs that determine the replacement period. TRC proved to be more sensitive to RMV. The risk is highly interrelated to the estimations that are made concerning the values of RMV. The results determined ranges of values of i for minimizing the risk in estimations of RMV. The values of i between 7.5 and 9.5% make TRC more sensitive to RMV variations. The values of i range between 4 and 7.5%, presenting an "interest rate window", in which the company should invest with the minimum risk undertaken in its estimations.

6 Conclusion and Further Research

This research introduces a conceptual model for the optimization of construction equipment's economic life and applies a 2-step sensitivity analysis. According to the methodology, economic life coincides with the optimum period for equipment's replacement.

There are several factors affecting the equipment's economic life that have been recorded in literature. For the proposed model, the factors taken into account are the interest rate of money invested in the machinery, the residual value and the O&M costs. TRC is more sensitive to RMV than O&M variations.

Furthermore, a 2-step sensitivity analysis is performed in order to investigate the behavior of minimum TRC, in changes of O&M costs for the 1st year, RMV the 1st year, m_u, and m_s keeping the interest rate fixed. Then, the ranges of i are determined where TRC are more sensitive to RMV. Out of these intervals, the owner could minimize the risk of not estimating accurately the RMV.

The practical limitation of this study is that the proposed methodology should be applied to a number of machines of the same type to reach more concrete results.

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Extracting Construction Knowledge from Project Schedules Using Natural Language Processing

Xiaojing Zhao, Ker-Wei Yeoh and David Kim Huat Chua

Abstract A sound and good quality schedule is critical to the success of a construction project. However, the little time available for proper project scheduling in the planning and design stage often impairs the quality of a schedule. Few efforts have been made to evaluate and maintain the schedule quality in the construction stage. Usually project teams need to put intensive manual efforts to conduct schedule quality diagnosis which is time-consuming and subjective to a large extent. One major challenge of diagnosing schedule quality is understanding the activity characteristics and construction logic. The multi-partite nature of construction projects (i.e. schedulers and project teams) further exacerbates the difficulty of diagnosis. This paper thus proposes a novel semantic-based logic reasoning and representation methodology to extract construction methods from the schedule to ensure a consistent project schedule. The intellectual contributions of this paper are twofold. First, this paper develops an ontology of tasks with hierarchies from the schedule to automatically extract the construction methods and activities. Second, this paper presents a novel dependency-based information representation schema for representing the logics between tasks and key constraints to facilitate the complete automation in construction logic reasoning from the schedule. To test the proposed system, this

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_17

paper evaluates the average rate of recall and precision achieved by the system for extracting construction activities and logics in the schedule within one month and compared the results with the rate achieved by manual check. The developed system provides both academics and practitioners a method to detect the deficiencies of project schedules and assists project planners to produce and maintain good quality schedules starting from project initiation until its completion.

Keywords Automatic reasoning · Construction project · Construction knowledge · Ontology learning · Schedule quality

1 Introduction

A good project schedule adequately reflects the project scope and defines how and when the project team will deliver the products (PMI 2007). A project schedule with high quality helps improve the planning and control of construction activities and enhances the construction productivity (Bragadin and Kähkönen 2016). Construction activities are subject to many uncertainties, which may lead to multiple schedule disruptions during project execution. Schedule delays may cause a multitude of negative effects on the project. Creating a high quality schedule is a highly complicated task especially in large scale construction projects, as large scale projects are usually characterized of inherent complexity, greater uncertainty and heterogeneous entities with diverse interactions. Despite the importance of project schedules, only a few research efforts have been put forward to examine the quality of schedules.

A number of studies have examined the requirements and performance indicators of schedule quality. U.S. Defense Contract Management Agency (DCMA) (2012) proposed 14 assessment measures for schedule quality control that included logic, leads, lags, relationship types, and critical path check etc. The "cost estimating and assessment guide" report published by United States Government Accountability Office (GAO) provided a best practices checklist for practitioners to manage project cost and schedule (GAO 2009). The schedule quality can be also controlled by the scheduling process (e.g. PMI 2013; Douglas 2006). The process of scheduling should include activity definition, duration estimation, sequencing, resource estimation, schedule development and control (Bragadin, and Kähkönen 2016). A scheduling method prescribes a set of techniques, procedures and rules used by project schedulers (PMI 2007). The scheduling maturity model developed by Association for Project Management and overall quality indicators by PMI can be used to measure the quality of schedule development process (PMI 2013; Douglas 2006).

However, research on schedule quality is still limited. Previous efforts mainly examined the schedule quality from two approaches, i.e. schedule planning, as well as schedule control and evaluation. For schedule planning approach, industrial institutions, such as PMI and DCMA, created standards to define the schedule quality and its development process, and recommended skills and competences required by companies to achieve schedule quality. However, measures to evaluate the schedule at this stage are limited. For schedule control and evaluation approaches, most studies (e.g. APM 2012) examined the compliance of project schedule with predefined schedule assessment criteria based on project schedulers' judgement. Current methods and techniques for schedule checking might be inaccurate and inefficient for large schedules.

This paper develops an automatic project schedule checking (APSC) system to extract construction methods from the project schedule using natural language processing, with the ultimate aim of checking the completeness and accuracy of a construction project schedule. First, an accuracy check and rectification module was developed to check for spelling errors and informal or inconsistent abbreviations in the project schedule; Second, a construction method extraction module was developed by extracting syntactic and semantic features from the schedule. Third, a web-based ontology was developed to represent the properties and hierarchical structure of construction schedules. The developed ontology serves as a means of construction schedule knowledge sharing and reuse. In comparison with traditional schedule checking methods, the APSC system developed in this paper is expected to improve the schedule quality by reducing errors during the schedule checking process.

2 Research Background and Knowledge Gaps

This section reviewed literature on: (1) the principles and assessment methods of schedule quality; (2) natural language processing (NLP); and (3) Ontology development.

2.1 Assessment of Project Schedule: Principles and Methods

Many studies on project schedule examined the quality of project schedule from the perspective of contract management and compliance. Russell and Udaipurwala (2000) identified a series of indicators for schedule quality under four groupings: accuracy and completeness; consistency with other planning documents; good practice/workability; benchmarks for control. A good construction project schedule should comply with contract and planning documents, DCMA (2012) formalized 14 check points for schedule health assessment which include logic check, relationship type, float, resources, critical path check and baseline execution index etc. In addition, some schedule protocols provide additional checks for project schedule quality such as merge points, diverge points, redundant relationships, and out-of-sequence progress. Farzad Moosavi and Moselhi (2014) summarized 48 schedule assessment criteria from different perspectives, including contractual obligation compliance, completeness, the reasonableness of job logic and realist of activity duration. The top ten amongst includes scheduling process, milestones, procurement, Work Breakdown Structure (WBS) and submittal activities etc.

Aside from contract management and compliance, research and industrial practices attempted to control schedule quality during the scheduling process. Various industrial standards and benchmarking schemes have been provided as references for schedulers. PMI (2006) provided practical standards for industry-specific WBS to support the generation of project schedule. PMI (2007) provided a 'schedule model' that represents how and when the team should deliver the pre-defined project scope. American Association of Cost Engineers (AACE) International developed planning and scheduling guidelines for training and professional development (Douglas 2006). The guidelines recommended the roles/responsibilities and skills/knowledge of a scheduling professional in three sections: project planning, schedule development, and schedule management. GAO (2009) developed ten best practices to maintain an integrated network schedule and ten indicators to assess schedule health. NSAI (2009) described the business requirement specification and specification mapping in project schedule and cost performance management. A number of studies also used the above criteria to examine the quality of schedule. Farzad Moosavi and Moselhi (2014) assessed the schedules against industry benchmarks and job logic of three case building projects. Bragadin and Kähkönen (2016) identified five schedule health indicators (i.e. general requirements, process requirements, schedule mechanics requirements, cost and resources requirements, and control process requirements) and evaluated the overall schedule health through a weighting process.

2.2 Application of NLP in Information Extraction

2.2.1 Syntactic Information Representation

NLP algorithms were designed to retrieve information from plain text. One common tool used in NLP is Stanford Parser (De Marneffe et al. 2006). It is a probabilistic natural language parser that exploits the grammatical structure of sentences to enable Parts-of-Speech (POS) tagging, chunking, parsing and Stanford dependencies. POS tagging is the process of labelling words or phrases in a text based on the context and definition of words. The results of POS explain how a word is used in a sentence. Words are classified as nouns, pronouns, adjectives, verbs, preposition, conjunctions, etc. (Toutanova et al. 2003).

Chunking is another widely used NLP technique which separates a sentence into phrases (e.g., noun groups, verb groups) rather than single words (Klein and Manning 2003). Libraries such as Spacy and TextBlob can be used to generate phrase out of text.

Parsing analyzes the grammatical structure of a sentence and identifies phrases and their recursive structure. The parse tree illustrates the syntactic relation among the sentence words. Constituency-based parse tree and dependency-based parse tree are the two types of parse trees that are commonly used.

The constituency-based parse trees contain two kinds of nodes: terminal and non-terminal. All interior nodes are non-terminal nodes (e.g., noun/verb phrase) and all leaf nodes are terminal nodes (e.g., noun/verb). The dependency-based parse trees only contain terminal nodes (e.g., noun/verb). A dependency-based parse tree has fewer nodes in a given sentence than a constituency-based parse tree.

2.2.2 Semantic Information Representation

The semantic representation is commonly adopted to leverage domain knowledge in the reasoning process in order to address the complex relations involved in a certain domain. This is vital for construction schedule checking since the descriptions of construction activities and tasks is contextual. The semantic representation facilitates computer interpretability, which is essential to facilitate automatic testing and verification of construction schedules.

The Stanford dependencies provide a simple and uniform representation of semantic relations between words. Dependency representations contain around 50 grammatical relations. A grammatical relation holds between the governor (regent/head) and the dependent. For instance, in the statement "The message is sent by the server", the relation is agent while the dependent is server (De Marneffe et al. 2006). This typed dependency means that server performs the action represented by the passive verb sent.

Another technique to detect semantic relations is Semantic Role Labeling (SRL), also called semantic parsing (Gildea and Jurafsky 2002). SRL identifies semantic arguments associated with verbs (predicates) in a sentence and their specific roles. For instance, given a sentence "Install sprinkler pipes", the verb "install" is identified as the predicate, while the message "sprinkler pipes" is identified as the theme. The output is a constituent parse tree that can be transformed into a dependency graph (Björkelund et al. 2009).

In construction applications, Yurchyshyna and Zarli adopted semantic annotation and context-based scheduling to formalize construction conformance requirement in order to realize effective code checking (Yurchyshyna and Zarli 2009). Al Qady and Kandil (2010) utilized shallow parsing to extract semantic knowledge and concept relations from construction contract documents. Two measures, recall and precision, were used to measure the efficiency of Information Retrieval algorithms. Arellano et al. (2015) integrated NLP techniques and application specific ontologies to analyze the requirement specification.

2.2.3 Ontology Development

An ontology is defined as an explicit representation of concepts and their relationships in a certain domain. Ontology is commonly developed to provide an information structure and a common understanding for knowledge sharing (Gruber 1995). A number of recent studies used NLP techniques and ontology to extract the knowledge from web pages, and have shown a greater performance in extracting the information. In the construction domain. Creation of OWL ontology not only supports the semantic annotation of text, but facilitates the querying and manipulation of ontology (Zhou and El-Gohary 2017). This study therefore built up a knowledge base for construction schedules, defined all the classes and subclasses with their object properties and relations.

2.3 Knowledge Gap

Despite the achievements mentioned above, most studies on schedule quality assessment manually checked the quality based on predefined criteria and experts' judgement. The schedule management involves daily tasks, duration, location information, resources used and quantities, constraints and milestones. Checking the large amount of records and construction documents manually takes a lot of time and effort. The performance of manual schedule quality check could be subjective and prone to inaccuracy. A few studies recommended the utilization of BIM to automate the generation and update the construction schedule. However, little effort has been done to examine the accuracy and completeness of the project schedule in the project planning stage.

The application of NLP techniques is a promising option that can streamline information extraction and reasoning from construction documents, thereby enabling automatic extraction of construction methods and dependency logic among construction tasks. However, the application of NLP in construction schedule is still in its infancy, and a system is needed to extract the construction knowledge and encode its description and their dependencies.

3 Proposed Approach for Construction Knowledge Extraction from Project Schedule

The system architecture of the proposed approach is summarized in Fig. 1. Our approach supports the extraction of both syntactic and semantic structures from the activity descriptions in the project schedule. The proposed system contains three main components: Schedule accuracy check module, Construction method extraction module, and Construction schedule representation module.

3.1 Schedule Accuracy Check

The project schedule document was first pre-processed. This pre-processing phase is called text normalization, which includes the removal of unnecessary marks, punctuations, white spaces, special symbols and stop words. Stop words refer to the words that do not carry important meaning such as “the”, “a”, “on” and “all”. In addition, all the letters were converted to lower case. After pre-processing, the text was tokenized

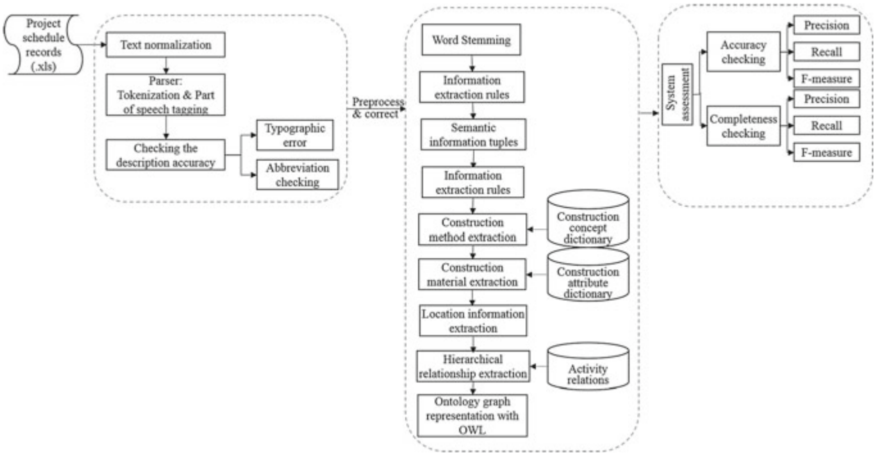

Fig. 1 The architecture of the proposed APSC system

into sentence, and further parsing and morphological analysis were carried out to bring it into singular form.

The document was then stemmed to reduce words to their root form (e.g., formworks-formwork; painting-paint). Porter stemming algorithm (Porter 1980, 2001) and Paice/Husk stemming algorithm (Zamora 2019) are the two major methods to obtain the word stem. Porter stemmer was applied in this study. It is assumed that there is no stem dictionary and an explicit list of suffixes was given as a criterion to reduce a word to its valid stem.

Three types of errors typically exist in the project schedule, namely, typographic error, cognitive error, and unstandardized abbreviations/descriptions. Typographic errors refer to mistyped words and the correct spellings of the words is known (e.g. peparation-preparation; scuper-scupper). These errors occur when the correct spelling of the word is known but the word is mistyped. Cognitive errors occur when the correct spellings of the word are unknown. The pronunciation of misspelled word is similar to that of the intended correct word. In the case of cognitive errors, the pronunciation of misspelled word is the same or similar to the pronunciation of the intended correct word. The unstandardized abbreviations refer to the abbreviations that are commonly used by construction schedule but cannot be recognized in NLP (e.g. MEZZ; SCDF).

In order to check and modify inaccurate spell error in the activity description, the dictionary lookup and n-gram analysis were used. The error rectification was realized through comparison between misspelled string with the dictionary of words. The word with minimum edit distance was chosen as the correct alternative. These methods can be thought of as calculating a distance between the misspelled word and each word in the dictionary or index (Mishra and Kaur 2013). The shorter the distance the higher the dictionary word is ranked. The interactive spell checking was used to check whether each word is in dictionary and suggested corrections were recommended.

3.2 Construction Method Extraction

Construction methods describe the procedures and techniques that are used in the construction process. In this paper, a construction method is defined as a series of sequential construction activities. A description of construction activity usually consists of construction action, materials or elements, and location information. In a project schedule, a description of construction method is also linked to its duration, start and end date. In order to extract the valid concepts of construction methods from corpus, POS tagging such as noun phrase (NP), verb phrase (VP) and adjective phrase (AP) was first assigned to each word of the rectified schedule text based on its context and definition. A rule-based shallow parser was then used to break the sentence into clauses, and the words in each clause were further tagged into NPs, VPs and APs etc. and its roles (e.g. SUBJ, DOBJ and ACTIVE_VERB). In order to extract the key phases of construction method, the extracted template was set as

JJ-NN, NN-NN (NNP-NNP) and JJ-NN-NN, e.g. "Install-slab-bottom-rebar" (NNP-NN-NN-NN) and "HCS-installation" (NNP-NN). The NLTK package was used to generate POS tagger.

Named Entity Recognition (NER) tool was used to find named entities in text and classify them into pre-defined categories. The extracted phrases formed the activities in construction methods with the help of dictionary. First, construction activities were extracted from the text. Each formed action was extracted based on construction action dictionary. Construction material/elements extractor was designed to identify the material/element (subject or object) related to each action is divided into two categories. After the extraction of construction activities, the hierarchical relationship between activities is further inferred by two different methods: 1. Inherently nested relationships between activities, and 2. Hierarchical relationships defined by start and end dates.

3.3 Construction Schedule Representation Module

The paper presents the construction methods identified from project schedule in RDF/OWL format. A schedule ontology was developed with Protégé software. Figure 2 represents the construction activities in the schedule ontology and a screenshot of the ontology implemented in the software. Developed by the Stanford center for biomedical informatics research, Protégé provides an open-source platform for ontology development to represent the domain knowledge base. As showed in Fig. 2, a construction activity has data type properties that define its action, material/element, location, duration, lag, and predecessor. The hasElement object property relates activities to building material/elements. The dependencies between an activity and other activities are described by its lag and predecessor. The dependency between the concerned activity and predecessor includes finish to finish, finish to start, start to finish, and start to start. The hasLag property describes the number of lag days between two activities. In a construction schedule, an activity may represent the construction of one element or several elements.

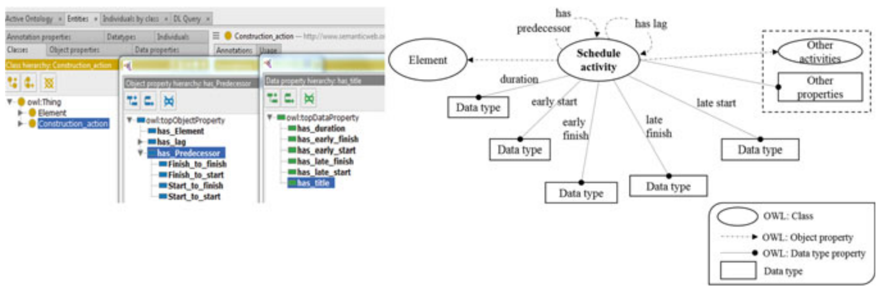

Fig. 2 The ontology of project schedule

4 Implementation of the Proposed System

The proposed system has been implemented using JAVA platform. The Java API for Stanford parser is integrated with the rest of the modules written in Java. Finally, an ontology in OWL format supported by Protégé represents the knowledge base of project schedule.

4.1 Schedule Accuracy and Rectification

The accuracy check results produced by the system for a case project schedule (including activity description) are presented in Fig. 3. The input text is part of activity description in the project schedule. The results of spelling checking not only extracted the spelling errors in the activity description, such as 'scuper', but also the informal/inconsistent abbreviations used by various parties such as 'LT' and 'HT'. After automatic extraction and ratification process, the tree structure generated from shallow parsing in Fig. 4 shows the identified noun phrases of construction methods in the schedule.

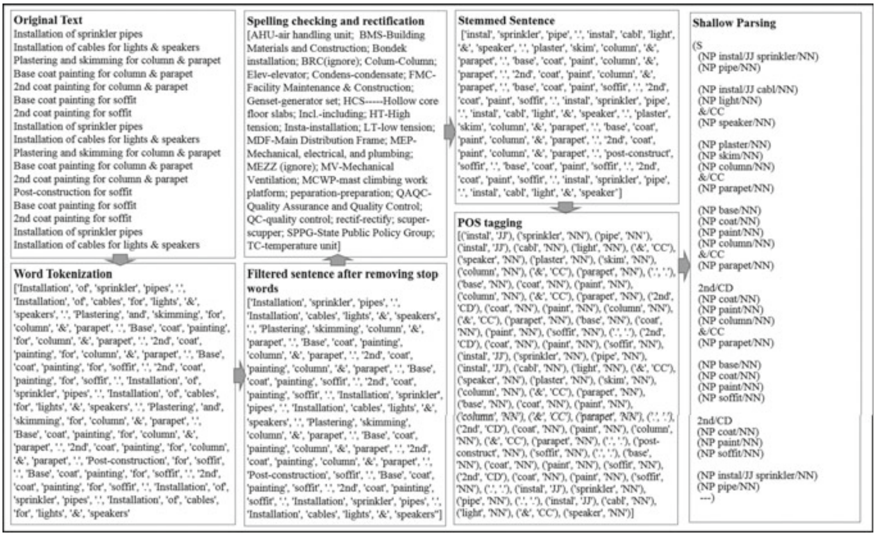

Fig. 3 An illustration of inputs and outputs of main NLP steps

Fig. 4 Output from the chunking of schedule description

4.2 Schedule Knowledge Base in OWL Format

The class tree of construction methods generated from given input is then exported on an ontology editor (Fig. 5). An ontology of project schedule in web-based format integrates the NLP results and systems requirements and helps organize the semantic features of project schedule in the hierarchy structure. The developed ontology serves as a proof of construction methods and stores the hierarchy and data in a relational database.

4.3 Validation

For the validation of the developed system, a master plan of a warehouse building project in Singapore is used. The building consists of five storeys with different elements on each floor. Considering this research domain is still a nascent area, the validation is limited to the performance of the system in extracting construction methods from the schedule.

The activity descriptions in project master plan were processed using the NLP framework described in research methodology. The evaluation results of schedule accuracy and completeness are summarized in Table 1. Three simple indicators were used to measure the performance of the system. The performance was evaluated using precision, recall, and F-measure, which combines precision and recall into one measure. Precision rate (P) measures the percentage of correctly extracted activities relative to the total number of activities extracted. Recall rate (R) measures the percentage of correctly extracted activities relative to the total number of activities existing in the source text. F-measure is calculated using Eq. (1) (Toutanova et al. 2003):

$$F = \frac{\left(\alpha^2 + 1\right) P R}{\alpha^2 P + R} \tag{1}$$

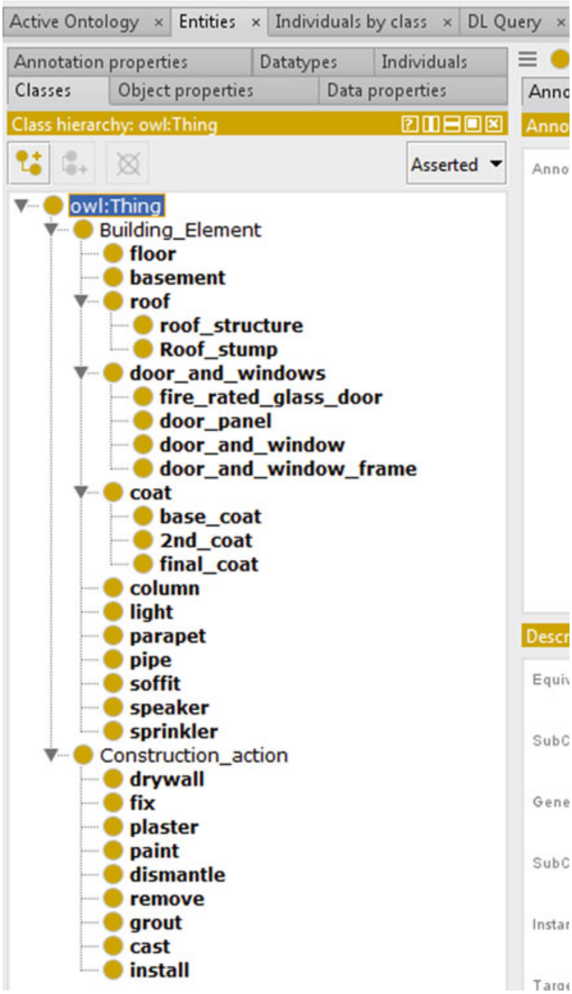

Fig. 5 Partial view of the construction schedule ontology

which α assigns relative weights to P and R value. $\alpha = 1$ in this study. The recall rate of the APSC system in activity extraction outperformed that in accuracy checking, while the precision rate of the APSC system in accuracy checking outperformed that in activity extraction. The results reflect the trade-off between recall and precision.

Table 1 Results of the development system in extracting construction methods from project schedule

Extraction completeness assessment		Accuracy assessment	
Total No. of activities	127	Total No. of inaccurate descriptions/words	53
Total No. of extracted activities	122	Total No. of inaccurate descriptions extracted	50
No. of correctly extracted activities	111	No. of inaccurate descriptions correctly extracted	48
P measure	92.1%	P measure	96.0%
R measure	90.9%	R measure	90.6%
F measure	91.5%	F measure	94.3%

5 Conclusions

This paper presents an APSC system for automatically extracting construction methods from project schedules to support the automated schedule quality assessment in construction. The combination of NLP techniques and defined OWL-based ontology models were used to extract both semantic features and syntactic features of construction activities. The developed system contributes to the body of knowledge in four main ways. First, the system allows for detecting and rectifying the inaccuracies in project schedule automatically, which avoids both errors and labor inputs resulting from manual schedule check. Second, the system allows for extracting the domain-specific information of construction methods from complex sentence structures, which save the computational efforts resulting from processing irrelevant text in project schedule. Third, the proposed OWL-based ontology allows for capturing the dependency relations among construction activities. The experimental results show that the proposed system is effective and efficient in evaluating the quality of construction project schedule. Two limitations exist in the study. First, the proposed system addressed most semantic ambiguities, however a number of semantic interpretation issues (e.g. POS tagging ‘construct, NN’) still require the human judgement. Future research is needed to realize the fully-automated way of semantic ambiguity and interpretation issues. Second, the proposed system is developed based on the schedule of building projects, additional effort may be required to extend the ontology for applying the system in a different domain such as infrastructure project.

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How Sustainability in Healthcare Sector Challenges Guidelines and Code Development: A Framework for Design of Sustainable Hospital Buildings

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Abstract It is nowadays an accepted fact that built environment is one of the major anthropogenic exploiters of nature as building consume a great amount of resources in the form of energy, materials and water which ultimately causes GHG emissions, resource depletion and waste generation. The concept of sustainability in building sector has not only put forth a challenge for builders but also the governing bodies that deals with the development of codes, guidelines and building standards. There is now a need to accrue all these standards and technology at one place in a framework which may help as a reference approach to design a wholly sustainable building. This study is based on review of literature where data from published articles, books and official websites of code developing authorities has been collected and investigated particular to the design of sustainable healthcare facilities. The output of this study is a comprehensive yet simple framework for the design of wholly sustainable hospital building which covers all aspects of sustainability and it may give designers and learners a portrayal of the process of designing a sustainable hospital building. This research aggregates all the available standards and guidelines for green and sustainable building design which is a good addition to literature and serve as compact reference for designers/constructors who are willing to adopt sustainable design and construction.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_18

Keywords Sustainability · Healthcare · Green building guidelines · Life cycle sustainability assessment

1 Introduction

The climate change and environmental impacts of human activities has become a heated debate at national and international forums (Bigelow and Zhang 2018; Chan 2018; United Nation Environment 2007; Hussain et al. 2018). The most important of all environmental concerns is to dispense the energy demand at global scale (Armendariz-Lopez et al. 2018). Buildings are one of the top environmental exploiters (Maslesa et al. 2018) because of consuming 17% global fresh water, 40% material and energy and 25% of total wood harvest per year (Boudhankar 2017). The consumption of resources and generation of waste is associated to each life cycle stage of building from its construction, operation and demolition. Possibly the best solution to conserve resources and decrease harmful environmental impact is '*sustainability*' which is a science, and a way of thinking and living. The idea of sustainable or green building has gained popularity in recent years. The degree of ecological balance maintained by the building classify it as green or sustainable. However, some literature treats these terms as synonymous. The difference between conventional and green or sustainable buildings is the financial, social and environmental benefits achieved by resource conservation and pollution reduction during building construction and operation phases (Boudhankar 2017).

Environmental impacts attributed to buildings also depend on the type of service provided by these structures. For instance, energy consumption of commercial buildings is higher than that of residential buildings and similarly production of waste and pollution by buildings also varies by their types. Healthcare buildings are considered among the highest resource consuming and waste generating structures (Energy 2010; Administration 2015), and produce significant hazardous and non-hazardous wastes (Pasqualini Blass et al. 2017). It has also been observed in developing countries that healthcare sector is confronting major challenges of cost, poor service quality, limited resources and crucial policies by government (Pasqualini Blass et al. 2017). Therefore, the reduction of hospital building resource consumption and waste generation must be catered at early design stage. But it is not simple as with ever advancing medical technologies and requirements of communities and societies, hospital designs need to support the concept of social, economic and environmental sustainability (Vittori 2013). ASHRAE defines green or sustainable hospital design according to minimization of harmful effects of building on surrounding nature, resources and processes. This means human activities should go hand in hand with nature and natural processes instead of crippling the planet's habitability (ASHRAE 2006).

The new wave of sustainable construction practice started in the 21st century as a challenge for industrialists and policy makers. It required the invention of new technologies, materials, policies and guidelines. Leaders of building industry were fully acquainted with the importance of sustainability in this sector and efforts were made to practically adopt it. Ratings systems such as US Green Building Council's Leadership in Energy and Environmental Design (LEED) emerged to measure the impact of buildings on sustainability. However, the healthcare industry did not attain focus in the early developments but since recently this sector is point of convergence of rating systems and specialized systems have been developed to exclusively deal with healthcare sustainability. One such initiative is the Green Guide for Health Care (Green Guide), a project of the Center for Maximum Potential Building Systems and Health Care Without Harm, which developed and pilot tested a range of sustainable building strategies unique to healthcare.

The architectural design and planning of healthcare facilities was influenced greatly by social, economic and technological advancements (Olenderek and Borowczyk 2016). A variety of research has been done on sustainable architecture, planning and design of hospital buildings which not only focuses on construction but operation and maintenance phases as well. For example, possibilities of floor-plan (Shekhawat 2017), gratuity of evidence-based healthcare design (Verderber et al. 2014), environment and behavior interest in healthcare design (Zhou 2014), contemplative architecture (Bermudez et al. 2017), sense of home (Eijkelenboom et al. 2017), influence of public opinion on architecture (Bianco 2018) implementation of healthcare internet of things, services, and people (HIoTSP) framework using wearable sensor technology (Khowaja et al. 2018), Cyber-Healthcare framework and its implementation (Bagula et al. 2018), variable acoustics within a big range (Cairoli 2018) healthcare distributed services promoting openness, interoperability, reusability and scalability (Calvillo et al. 2013), influence of architectural design features on human experience (Ergan et al. 2018), transforming hospitals to modern hospitals (Haghighathoseini et al. 2018), seismic resilience enhancement of hospitals (Khanmohammadi et al. 2018), technological sustainable subculture (Mavromatidis 2018), and ergonomics in the design process of hospital buildings (Villeneuve et al. 2007) have been investigated. Too many options and pathways leading to sustainability in healthcare are available now including hospital management strategies. This variety, however positively reinforcing for sustainability, has created several decision dilemmas for project teams. The designers and architects must carefully choose among these strategies for an efficient healthcare system. To help them to find a needle in a haystack, this paper presents a framework of design process of a sustainable hospital building. Different standards, building codes, guidelines and published literature have been reviewed to provide a simple methodology for where to begin the design of sustainable hospital, what makes it green and what processes are involved for final sustainability achievement.

2 Methodology

This is a review study of published literature, building design guidelines, codes and standards to provide a simple and elaborate path to engineers, consultants and architects for the design of a sustainable hospital. Stevanovic et al. in their recent article about hospital building sustainability have stated that appropriate methods are required for architects to evaluate hospital sustainability at early design stage because hospitals are complex structures and assessing their sustainability is very challenging (Stevanovic et al. 2017). In this paper a simple framework has been developed to clarify the process of sustainability achievement at design phase of hospital building. Author has studied about internationally recognized organizations which provides building standards, codes, guidelines and certifications either at material level or at building level as a whole. The findings of this study have been presented in two sections below. In first section, a brief introduction of organizations has been provided, which are studied by the author to achieve the goal of this study. The software tools which are very helpful especially in achieving sustainability at design stage have also been discussed. The main finding of this paper is the framework of procedure to design sustainable hospital which explains how things are connected and roles of different organizations to help in the design of sustainable hospital.

3 Building Codes and Guidelines Developers

In this section, a brief introduction of international organizations developing building guidelines, standards and codes applicable universally, have been presented. It also includes some commentary on the famous green building rating systems and software tools used worldwide for efficient and advance architectural, structural and technological design and planning of edifices.

3.1 ASTM International

The American Society for Testing and Materials (ASTM) is an organization which develops and publishes technical standards for a variety of materials, products, services and systems based on the guiding principles of World Trade Organization. These standards are published each year as a set of 80 volumes and broadly categorized into six groups: Standard Specification, Standard Practice Guide, Standard Classification, Terminology Standard and Standard Test Method. These standards include details about specification and testing of all construction materials including metals, rubber, adhesives, plastic, aggregate, cement and many more. ASTM international also provides standards for environmental technology, medical devices and services (ASTM 2019).

3.2 ISO

International Organization for Standardization (ISO) provides world-class specifications for products, services and systems to ensure quality, safety and efficiency. It is instrumental in facilitating international trade. ISO has published 22,215 international standards and related documents, covering almost every industry, from technology, to food, safety to agriculture and healthcare. ISO standards impact everyone, everywhere. ISO also provides standards which are applicable in sustainable construction such as standard for life cycle assessment and environmental product declaration of construction materials (ISO 2019).

3.3 ASHRAE

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) publishes standards for efficient indoor environment. It also promotes research to develop advance and innovative technologies for better indoor environmental technology used for heating, ventilation and air conditioning (ASHRAE 2019).

3.4 ASHE

American Society of Healthcare Engineering (ASHE) is a professional membership group of AHA (American Hospital Association) which provides education, professional development, networking, regulatory guidance and advocacy representation for its members. The members are involved in creating and providing healthcare facilities, and consist of engineers, architects, healthcare facility managers, infection control specialists and many others. ASHE membership is diverse with a common goal: to create and maintain a safe healing environment along with optimizing healthcare facilities (AHA 2019).

3.5 ANSI

American National Standards Institute (ANSI) is a nonprofit organization which represents USA in ISO to create universally recognized and accepted guidelines in almost every industry. It promotes conformity standards to ensure that all manufacturers produce compatible products with same standards and scale to make it easy for consumers internationally. ANSI has brought conformity to all industries worldwide even including safety signage which remains everywhere in the world (ANSI 2019).

3.6 EPA

US Environmental Protection Agency (EPA) strives for reservation and protection of environment to improve human health by indulging in research associated to pollution, its impacts and management. It provides regulations for the manufacturing, distribution and processing of various chemicals and pollutants. It also determines tolerance levels of chemical and other pollutants in food and water for humans and animals. Moreover, it issues regulation for carbon emissions from automobiles, power plants and other climate change contributors (EPA 2019).

3.7 ASME

American Society of Mechanical Engineers (ASME) is a leading international organization which promotes new research and practice in mechanical and multidisciplinary engineering and develops codes, guidelines, standards and conformity assessment programs (ASME 2019).

3.8 FGI

Facility Guidelines Institute (FGI) is a nonprofit organization that works to develop guidance for the planning, design and construction of hospitals, outpatient facilities, residential healthcare and support facilities. For 2018 edition of guidelines, FGI developed three books: a volume for hospitals, a new volume for outpatient facilities and the volume for residential healthcare and support facilities. Each provides basic information on planning, design, construction, commissioning and minimum design requirements for particular facility types. FGI requirements were updated to keep up with changes in healthcare delivery and allow flexibility in design to support development of facilities that will meet the needs of owners and their communities over the long term (FGI 2019).

3.9 GGHH

Global Green and Healthy Hospitals (GGHH) is a network of healthcare facilities, health systems, hospitals and health organizations at global level. This network is indulged in upgrading public and environmental health by reducing healthcare footprint on environment. It connects its members to designers and experts from around the world to educate them and help them achieve their sustainability goals for healthcare facilities (GGHH 2019).

3.10 US VHA

US Department of Veterans Affairs (VA) Health Administration or Veterans Health Administration (VHA) is the largest integrated healthcare system all over the US. VHA has been developing clinical practice guidelines to promote evidence-based best practice in collaboration with Department of Defense (DoD) and foremost expert organizations (GGHH 2019).

3.11 Green Building Rating Systems

Green building rating systems have gained popularity worldwide for the development of green buildings started from UK and US as BREEAM and LEED respectively. Now, many countries even from the developing world have introduced their own rating systems for their local conditions and environment to rate green buildings in terms of site sustainability, energy and water consumption, indoor air quality, material choice, waste reduction and innovation for better environmental performance. The sole purpose of these systems is to reduce environmental impacts of buildings (Shan and Hwang 2018) and overall sustainability of building (Ullah et al. 2019). A number of rating systems from around the world which are very famous and are frequently mentioned in literature are Leadership in Energy and Environmental Design (LEED)—(US), Leadership in Energy and Environmental Design (Canada), Green Star—(Australia), Building Research Environment Assessment Method Consultancy (BREEAM)—(UK), Building Environment Assessment Method (HK-BEAM)—(Hong Kong), Comprehensive Assessment System for Building Environment Efficiency (CASBEE)—(Japan), The Green Globe Rating System—(US), Ecology, Energy Saving, Waste Reduction and Health (EEWH)—(Taiwan), BCA Green Mark—(Singapore) and Australia Greenhouse Building Rating (AGBR) etc. Few ratings systems not only certify buildings in their own countries but also provide green building certification at international level for example LEED, Green Star and BREEAM.

3.12 Software Tools for Green and Sustainable Construction

A huge number of software tools are available to design and simulate different design aspects of green buildings including HVAC system, lightening, day light and glare effects, acoustics, fluid flow dynamics, dynamic thermal simulation, etc. the most popular and frequently mentioned tools in literature and also available worldwide (either free or as educational license to be used by students for research) are Design Builder, Energy Plus, eQuest, Autodesk Revit, Autodesk Insight360, National Energy Audit Tool (NEAT), Autodesk Green Building Studio, Trane Acoustics Program

(TAP), TRANSOL—Solar Thermal Energy, Life Cycle Analysis Tool, SimaPro, Climate Consultant, Athena Calc., Power Calc., etc. SimaPro is the most commonly used software for assessment of sustainability of products and services; its free educational license is available for non-OECD countries.

4 Framework of Sustainable Healthcare Design Process

At its core, a hospital is a construction project and therefore unique in terms of its location, and cultural and environmental conditions. In case of healthcare facilities and hospital construction, not only local conditions impact the design but the demand and variety of required health services also take part in how a hospital system should be designed and planned. Large hospitals are very complex structures and so is meeting their sustainable building requirements. Figure 1 shows a framework for design of sustainable hospital from conceptualization to final life cycle sustainability assessment. It represents the most important facts, codes, guidelines and standards which are employed to make healthcare building sustainable on top of considering modern architecture. This framework categorizes design process into four stages namely selection of critical design aspects, mandatory requirements, performance options and prescriptive options. All these stages of design are interconnected to each other. The first step is selection of building design aspects which are critical to sustainability achievement. Second stage is to fulfill mandatory design requirements or in other words code compliance which should be fulfilled. The next two stages tend to achieve sustainability in design. The detail of each has been mentioned in following sections.

4.1 Selection of Building Design Aspects

To design an efficient building, the main aspects of building must be kept in mind during the design and execution phase. A comprehensive study of literature, green building guidelines, standards and codes was carried out to identify the main features and aspects of an efficient building. If these aspects are designed carefully keeping in mind their environmental impacts, the resulted building will be a green structure. Applying life cycle approach and considering social impact of building will help to achieve a sustainable building. After a comprehensive study of green building guidelines and literature, the basic design aspects have been identified and the mandatory, prescriptive and performance path according to best codes and guidelines have been selected as shown in Fig. 1. These design aspects which are critical for sustainability are Building site, Energy use, Indoor environmental quality, Materials and resources, Airborne emissions, effluent, and pollutant controls, Water supply, and Waste. The

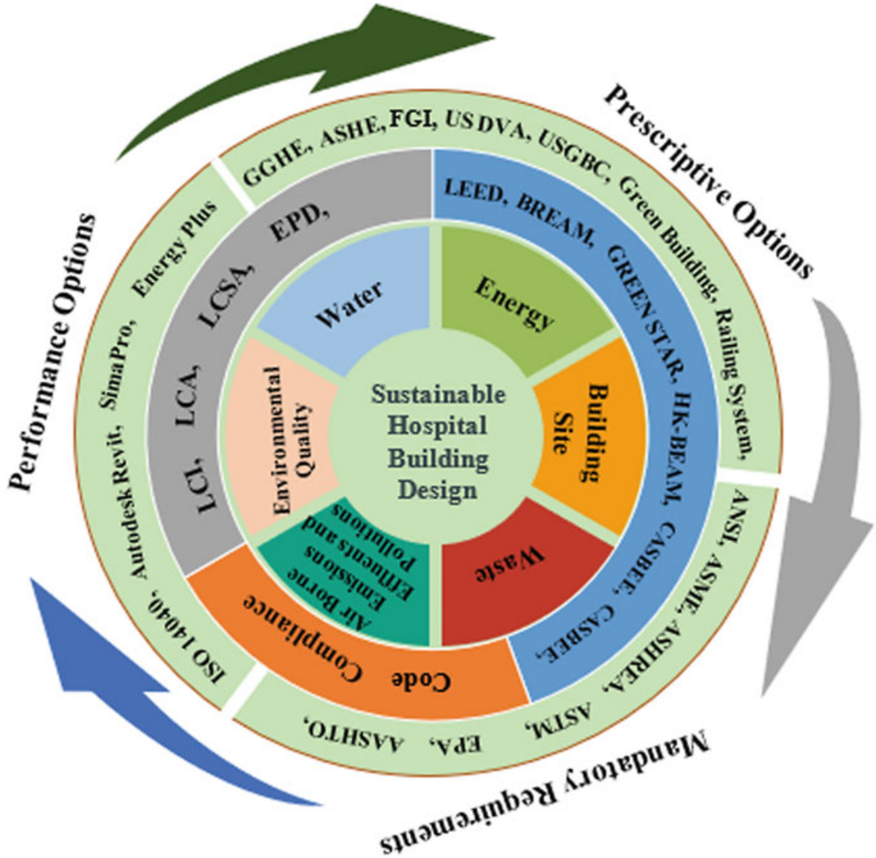

Fig. 1 Framework of sustainable healthcare design procedure

building energy use can be in the form of electricity, thermal and gas. Here electricity use will be applied consistently as an example to elaborate Fig. 1 in further stages of design procedure.

4.2 *Mandatory Requirements*

Mandatory requirements include all the necessary architectural and structural design, environmental protection and economical aspects of building. Once meeting the mandatory requirements, it needs to go for performance and prescriptive path to make the building sustainable. These guidelines are necessary for code compliance. These codes and guidelines are provided by ASTM, ANSI, ASHRAE, ASME, EPA, IES, and ISO. For example, the most important in any building is the efficient use of electricity which reduces the operational cost of building and environmental impact. The mandatory requirement for electricity use reduction is to provide measurement and verification plan, use of energy efficient electric appliances, efficient HVAC design. For example, ANSI/ASHRAE/IES Standard 90.1: *Energy Standard for Buildings Except Low-Rise Residential Buildings* to should be used for exterior lighting system of building.

4.3 Performance Options

A benchmark for performance of building is established while initiating the building design and these performance goals are achieved by comparison. It allows flexibility and innovation in design to achieve desired performance goals by considering the needs of healthcare organizations. For this purpose, simulation software tools are used to observe building performance under different circumstances. Building energy simulation or energy modeling by using software tools e.g. Energy Plus, eQuest, Autodesk Insight360 etc. can provide heating and cooling load of HVAC, exterior and interior lighting load. Due to flexibility of this option, designer may use innovative techniques developed by researchers and engineers worldwide, for example, Ullah et al. has proved in his study that the use of rat-trap bond in simple brick masonry wall in hot climate areas can reduce the electricity demand up to 60% as compared to conventional brick bond (Ullah et al. 2018). The most important aspect is assessment of building life cycle sustainability which demands a healthcare building to be sustainable economically, socially and environmentally. For an ideal sustainable hospital building, the social sustainability is very important and different guidelines are available to provide best possible healing environment inside the healthcare facilities. Life cycle assessment (LCA) is defined as sum of life cycle costing (LCC), social life cycle assessment (SLCA) and life cycle impact assessment (LCIA). Life cycle assessments are carried out based on standards procedure provided by ISO 14040. Eco-invent provides the largest life cycle inventory database worldwide which can be used to calculate LCA by software tools e.g. SimaPro, Open LCA, GaBi etc.

4.4 Prescriptive Options

The objective of this path is similar to performance path but instead of finding out ways to achieve desired performance goals, already established prescriptive measures are used to reach same design objectives. This style has lesser flexibility as designer has to comply with specific prescribed options. Organizations such as GGHH, ISO, ASHE, ASHRAE, US DVA, FGI and green building rating systems provide guidelines and techniques to achieve sustainability in healthcare sector. For example, ASHRAE provides roofing guidelines that include insulation and the solar reflectance index (SRI) of roofing material which will reduce the requirement of building energy. ISO: 14025 is environmental product declaration guideline to compare and choose greener and environmentally friendly product. Green building rating systems e.g. LEED, CASBEE, BREEAM, HK-BEAM etc. provide specific guidelines and a path to achieve green building certification.

5 Conclusions

Healthcare facilities have significant resource consumption and waste generation potential. Health service is one of the basic human needs and at the time of providing a better healthcare to human beings, robustness of natural environment should not be compromised. In this paper, the importance of sustainability in healthcare services has been emphasized and a framework has been provided to demonstrate the sustainable hospital design process. There are not only international but also national green building standards, guidelines and rating systems that have been developed worldwide. Besides green building rating system, certain software tools have also been developed to help designers to design sustainably and visualize the performance of building prior to its actual construction in the form of building simulation which provides a pretty good idea of how building will perform during its operational life. The framework provided in this study begins with the selection of building design aspects which are crucial to sustainability. A huge number of buildings codes, standards and guidelines required to comply with where some fundamental standards and specifications are mandatory and must be conformed in the design. The sustainability performance requisite of healthcare building is achieved by performance and prescriptive design options, and life cycle sustainability assessment which includes assessment of buildings impact on economy, society and environment. To achieve sustainability at global scale, it is suggested that the choice of builder/owner to go green or construct conventional building should be demoted by development of distinctive and comprehensive sustainable building codes, standard and guidelines available as a single set of guidelines to follow and construct sustainable structure only.

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Costs and Benefits of Green Retrofits: A Case of Industrial Manufacturing Buildings in Sri Lanka

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Abstract Unless the rate of green retrofitting of conventional buildings is amplified, built environment will have a huge responsibility in dealing with global warming, reducing resource consumption and greenhouse gas emissions. The contradictory views on initial costs and paybacks have discouraged industries investing on green retrofits, and building owners are reluctant to pay for green retrofits. In this context, the current study analyses the costs and benefits of green retrofits in industrial manufacturing buildings in Sri Lanka towards identifying the most appropriate retrofit options. The study used a mixed method approach to collect data through semi-structured interviews and documents of green certified industrial manufacturing buildings. Accordingly, four buildings were selected for the study, and the green retrofits applied in those buildings were identified through interviewing one professional from each building. Subsequently, the quantitative data on construction costs and economic savings were collected from two cases and analyzed using net present value and simple payback period. The analyses show that the use of green retrofits related to sustainable sites, water efficiency and material and resources are at a lower level, whereas green retrofits related to energy and indoor environmental quality are given the priority in existing industrial manufacturing buildings in Sri Lanka. Moreover, findings indicate the financial viability of the implemented retrofits in terms of sustainable features, such as energy and indoor environmental quality with positive net present values and simple payback period of less than 5 years. Considering the lifetime financial returns of those retrofits, each retrofit indicates significant benefits compared to initial investment. The outcome of the study would improve the application of green retrofits in existing buildings and thereby uplift the sustainable built environment by reducing greenhouse gas emissions and depletion of natural resources.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_19

Keywords Costs and benefits · Green retrofits · Industrial manufacturing buildings · Sustainable built environment · Sri Lanka

1 Introduction

The building owners globally have pledged to ensure environmental, social and economic sustainability since the impact of built environment on the greenhouse gas emissions and depletion of natural resources is staggering (Liang et al. 2016). However, replacing an existing building with a new green building would take more than 65 years to regain the energy savings intended to achieve through demolishing, and this is counter-productive to the idea of sustainability (Township's Boards of Historical and Architecture Review 2008). Therefore, policy makers have acknowledged the need for more retrofitting projects in the company's vision and environmental policy, as a way of attaining sustainability in the existing built environment (Wilkinson et al. 2009). Green retrofits enable upgrading of existing buildings in terms of energy and environmental performance, reduce water use reduction, improvement of comfort and quality of space with regard to natural lighting, air quality and noise, in a way that is financially beneficial to the owner (USGBC 2003).

Although there are a wide range of retrofit technologies readily available, identifying the most cost-effective retrofit for a particular project is still a major challenge. According to McDonald et al. (2008), the first costs for green space may be reasonable for a new construction but any improvements to existing space require capital expenditure. Similarly, Davies and Osmani (2011) indicated that the building owners are unwilling to pay for retrofits due to high initial cost. In fact, Rehm and Ade (2013) found that, green retrofits such as installation of high-performance cladding systems, implementation of rainwater harvesting systems and use of energy-efficient mechanical equipment are very expensive. Mostly, both owner and occupier are particularly motivated by the energy efficient retrofitting due to lower operation costs and the high return on investment (McGraw-Hill Construction 2009). Similarly, Gucyeter and Gunaydin (2012) pointed that the occupiers are interested in energy cost savings. Zhai et al. (2014) also indicated that the owners and occupiers are willing to invest on green retrofitting due to reduced construction costs compared to new construction.

Considering these views, the analysis of costs and benefits including initial investment costs and savings throughout the lifecycle is crucial to improve the implementation of retrofits. In the context of Sri Lanka, a limited number of buildings have been certified for incorporation of green features. In fact, Weerasinghe and Ramachandra (2018) indicated that 47 buildings have been green certified to date, of which only 7 industrial manufacturing buildings are existing buildings which were converted to green. The clients of the manufacturing sector are motivated to adopt green features in the buildings due to pressure from international clients to comply with energy and environmental regulations (Weerasinghe and Ramachandra 2018). Therefore, the current study enables the identification of the most appropriate retrofit options based on the analysis of costs and benefits of green retrofits in industrial manufacturing buildings in Sri Lanka.

2 Literature Review

2.1 Application of Green Retrofits

The available literature related to green retrofits was reviewed in order to identify the green retrofits that are implemented commonly in existing buildings. Table 1 presents the green retrofits implemented respective to each sustainable feature: sustainable sites (SS), energy and atmosphere (EA), water efficiency (WE), material and resources (MR), and indoor environmental quality (IEQ) based on LEED rating system.

As shown in Table 1, the identified green retrofits were arranged based on the number of sources which indicate the application of green retrofit technologies. According to existing literature, there are a wide range of technologies available for each sustainable focus area. Use of energy efficient lighting/plugs is the most commonly used green retrofit technology in terms of EA feature while there are other technologies such as improvement of luminaries and use of controllers, retrofitting of walls and windows, heating system retrofits, implementing energy-efficient equipment and appliances, and adoption of renewable energy. Improvement in ventilation, air infiltration reduction, installation of sensors and controllers, and use of sky lights are of the same level of usage under IEQ feature. However, a lower level of application is achieved for other technologies such as use of insulation, improvement of boiler efficiency, use of energy efficient glazing, installation of a building management system, use of energy meters, and installation of shading devices. Further, in terms of SS, WE and MR, the application of retrofit technologies is in a lower level.

Likewise, there are more retrofit technologies available, and the cost and the benefits could vary for each retrofit. For example, Mahlia et al. (2005) highlighted significant savings of energy and cost of \$37–\$111 million through retrofitting incandescent lamps with compact fluorescent lamps. In another study, Aktas and Ozorhon (2015) highlighted green retrofits such as upgrade of roofs, provision of alternative transportation facilities and improvements to the heating system collectively save up to 25% of the energy. Moreover, Dascalaki and Santamouris (2002) conducted a study on the energy conservation potential of retrofits using computer simulations for five office buildings situated in different European climatic zones. In this study, the authors considered the retrofit options such as, building interventions on the envelope, HVAC, artificial lighting systems, and the integration of passive components for the heating and cooling, and concluded that the reduction of total energy use ranges between 48 and 56%. The study on the energy and environmental performance of an experimental green roof system by Santamouris et al. (2007) found that there is

Table 1 Application of green retrofits

Green retrofits/technologies		Sources	
		Source	No. of sources
EA	Use of energy efficient lighting and plugs	[1] [2] [5] [6] [7] [8] [9] [10] [12] [17]	10
	Improvement of luminaries and installation of reflectors, use of time-scheduled control	[2] [5] [7] [9] [10] [12] [17]	7
	Insulation of walls, window replacement and upgrading, decrease of window area, cladding replacing and insulations	[2] [3] [4] [7] [8] [15] [18]	7
	Install heating controls, waste heat recovery, improvement of heating system equipment, preheat upgrade	[3] [5] [7] [8] [9] [15]	6
	Implement energy-efficient equipment and appliances; chiller plant retrofit, cooling tower replacement	[3] [4] [5] [6] [9] [15]	6
	Adoption of renewable energy; geothermal, wind, biomass and biogas technologies, solar collectors and PV cells	[4] [9] [10] [11] [6]	5
	Insulation of floors and foundations	[4] [8] [10] [15]	4
	Boiler efficiency economizer and replacement with a condensation gas heater	[3] [5] [8]	3
	Change of glazing system, low-e double glazing	[7] [8] [6]	3
	Install a building management system	[1] [7] [11]	3
	Use of energy meters on major mechanical systems and sub metering for all systems	[1] [6]	2
IEQ	Implement demand control/mechanical ventilation, provide natural ventilation	[1] [3] [5] [7] [9] [11] [15]	7
	Air sealing of ventilation system, air infiltration reduction, install CO2 sensors	[3] [5] [6] [7] [9] [11] [15]	7

(continued)

Table 1 (continued)

Green retrofits/technologies		Sources	
		Source	No. of sources
	Install day light sensors, manual or occupant sensing device, motion control systems, Automatic photocell-based controls	[1] [5] [6] [7] [9] [11]	6
	Use sky lights and task lights	[1] [5] [7] [9] [11] [14]	6
	Install insulated reflective barriers, exterior and interior permanent shading devices	[7] [14] [6]	3
SS	Construct green/vegetated roof, use of high emissivity roof, roof insulation	[1] [6] [16]	3
	Provide bicycle racks, changing facilities, parking spaces and alternative-fuel refueling stations	[1] [6]	2
	Construct open grid paving, use high-albedo materials and light colored surface (white asphalt)	[1] [6]	2
WE	Install low-flow showerheads, install automatic controls, dry fixtures and fittings	[1] [10]	2
	Implement greywater and rainwater recycling systems, micro irrigation systems	[1] [6]	2
	Install a building-level water meter and subsystem-level water meters	[1] [6]	2
MR	Use environmentally friendly finishes	[13]	1
[1] Aktas and Ozorhon (2015) [2] Al-Ragom (2003) [3] Ascione et al. (2011) [4] Bin and Parker (2012) [5] Chidiac et al. (2011) [6] USGBC (United States Green Building Council) (2009) [7] Dascalaki and Santamouris (2002) [8] Dowson et al. (2012) [9] Fluhrer et al. (2010)		[10] Verbeeck and Hens (2005) [11] Li et al. (2017) [12] Mahlia et al. (2005) [13] McGraw Hill Construction 2009 [14] Mohd-Rahim et al. (2017) [15] Nabinger and Persily (2011) [16] Santamouris et al. (2007) [17] Stefano (2000) [18] Stovall et al. (2007)	

a remarkable energy saving of the green roof system of up to 49% due to the reduction of cooling load in summer. On the other hand, Fluhrer et al. (2010) revealed that the use of these retrofits reduces 105,000 metric tons of CO_2 emission over the next 15 years. Furthermore, renewable energy projects provide high return on major investment within a short payback period (Bond 2010). However, Kasivisvanathan et al. (2012) stated that the industries are unenthusiastic about green retrofits due to the long payback periods.

In the context of Sri Lanka, Karunarathna and De Silva (2017) revealed that the most commonly used retrofit techniques in office buildings were variable frequency devices, LED lighting and low emissivity coatings. Furthermore, Fasna and Gunatilake (2018) identified forty-two (42) barriers affecting the successful adoption of energy retrofits in existing hotel buildings, of which the lack of transparency about energy cost and use and difficulties in properly identifying the energy saving from the retrofitted system were identified as significant barriers.

The literature review revealed that green retrofits contribute to the reduction in operation costs and savings during the lifecycle. However, contradictory views were highlighted by the previous authors, in terms of cost implications and payback periods. Nevertheless, the cost implications were not discussed in terms of industrial manufacturing buildings in previous studies. Considering the current green retrofitting situation in Sri Lanka, the cost implications including initial investment costs and savings throughout the lifecycle should be tracked for green retrofit projects in order to improve the implementation of retrofits in industrial manufacturing buildings in Sri Lanka.

3 Research Methods

This research was approached quantitatively, involving document analysis. Initially, the profile of green certified buildings under LEED O + M Existing Building category was analysed, and it was found that six (6) industrial manufacturing and one (1) warehouse buildings were transformed to green with the integration of green retrofits. Most of these buildings (5 out of 7) have been certified under LEED O + M: Existing Buildings (v2009) category. Those five buildings include four garment manufacturing buildings and one building used for spirits and wines production. From the four garment industrial manufacturing buildings, two buildings were selected as those buildings are certified under the same rating system, in the same business category and achieved same certification level (Gold).

Subsequently, the costs and economic savings of incorporated green retrofits were collected by referring to relevant documents. Finally, Net Present Value (NPV) and Simple Payback (SPB) were calculated. The NPV analysis was carried out for expected life time of retrofits, at the discount rate of 4.26% obtained from the Central Bank of Sri Lanka. It was assumed that an equal annual monetary saving would be earned throughout the life time of the project and no scrap value was considered at the end of the project.

Table 2 Profile of the selected green buildings

Building	Gross floor area (ft^2)	Land area(Acres)	Number of employees	Year of certification	Life-cycle (Years)	Type of function
GB1	124,000	5.2	1800	2009	50	Garment
GB2	181,048	10.25	2400	2014	50	Garment

4 Data Analysis and Findings

4.1 Profile of the Selected Buildings

The study considered two garment manufacturing buildings certified under LEED O+M: Existing Buildings (v2009) and achieved Gold certification level. Table 2 presents the profile of the selected two buildings.

As shown in Table 2, selected buildings are not identical, however approximately equivalent. Both buildings are large scale leading garment factories in Sri Lanka.

4.2 Cost Implications of Green Retrofits in the Industrial Manufacturing Buildings

The cost implications of available retrofits in the selected buildings were extracted from relevant documents. In performing NPV and SPB analyses, cost savings achieved due to the reduction of energy consumptions through the implemented green retrofits were considered as cash inflows and the initial investment costs were considered as cash outflows of the projects. Following that, green retrofits were identified in the selected buildings and the average values of NPV and SPB of the selected two green buildings are presented in Table 3.

As included in Table 3, most of the retrofits implemented in these selected buildings belong to EA and IEQ categories whereas retrofits related to SS, WE and MR categories were not implemented in these buildings. In fact, the sustainable site feature offers several green retrofit technologies that could be applied when converting an existing building to a green one. However, the selected buildings have already implemented parking spaces, light coloured roofing and paving surfaces and low reflectance surfaces, which helped them to convert the existing building to green. Regarding green retrofits related to water efficiency, not all the technologies identified in the literature review were implemented in the selected buildings. The existing building technologies such as water meters, automatic controls, dry fixture and fittings and greywater recycling helped to convert them to green buildings without any retrofit. Considering material and resources, LEED O+M: Existing Buildings (v2009) mainly focuses on sustainable purchasing of consumables and solid waste

Table 3 Costs and benefits of green retrofits - Energy and atmosphere

Green retrofit	Initial cost (LKR)	Annual saving (kWh)	Annual saving (LKR)	Lifecycle savings (LKR)	NPV (LKR)	SPB (Years)	Life (Years)
EA							
Biomass boiler	10,053,850	552,207	7,730,900	102,687,443	46,316,797	1.30	20
Servo motors	1465,000	193,607	2,710,500	25,058,756	15,729,171	0.54	12
LED lights	3,052,500	139,821	1,957,500	13,038,997	9,986,497	1.56	8
Insulate steam lines	220,000	160,732	2,250,250	8,118,368	7,898,368	0.10	4
Sky lights	3,951,250	71,047	994,654	9,195,639	5,244,389	3.97	12
Compressed air line modification	646,050	100,724	1,410,140	2,649,782	1,001,866	0.46	2
Biogas project	1,050,000	33,429	468,000	3,117,369	689,123	2.24	8
IEQ							
Evaporative cooler	5,250,000	965,714	13,520,000	147,624,214	142,374,214	0.39	15
Energy efficient chiller	20,650,250	304,036	4,256,500	52,763,240	21,408,660	4.85	18
Introduce VSD for chiller	556,000	15,257	213,600	1,422,799	433,400	2.60	8
Introduce VSD for compressor	150,600	3814	53,400	355,700	205,100	2.82	8
Total	47,045,500	2,540,389	35,565,444	366,032,307	251,287,585		

management. Therefore, retrofits in this category are the least priority among the selected buildings.

Energy retrofits have been given the top priority over other retrofits due to the economic savings. The focus on energy efficiency was less at the initial construction of those buildings; therefore, a considerable amount of improvements was done when converting the existing buildings to green. The green retrofits such as sky lights, LED lights, steam line insulation and compressed air line modification were used to optimize energy efficiency, and the biomass boilers were implemented in the respective buildings. Few of the energy retrofits indicate both energy efficiency and IEQ, and those retrofits were used to ensure the ventilation and lighting aspects of the buildings. For example, the installation of sky lights provides daylight into the building, LED has been used as task lighting for the sewing machines, and the use of evaporative cooler, energy efficient chiller and VSDs aids in the demand control and air infiltration of ventilation systems. The main reasons for the limited adoption of green retrofits are: those features were already implemented in the selected building and the building owners focused on achieving sustainability via sustainable strategies (not involving any additions, rearrangements, deletions and replacements of one or more parts of the facility).

As seen from Table 3, twelve (12) energy retrofits were implemented in the selected buildings which have positive NPV values and payback period less than 5 years. Amongst them, replacing the existing chiller system with evaporative cooler has the highest NPV of LKR 142,374,214 with the highest saving of annual energy cost of LKR 13,520,000 within a small payback period (0.39 years). Other retrofits with higher energy savings are biomass boiler, energy efficient chiller, servo motors, LED lights, insulated steam lines, sky light installation and compressed air line modification which provide overall savings of more than LKR 1,000,000. The energy efficient chiller and sky lighting have higher payback periods of 4.85 and 3.97 years, respectively, compared to other retrofits and those given a less priority by the investors who expect payback period of less than 3 years. However, evaporative cooler, biomass boiler, servo motors, LED lights, insulated steam lines, compressed air line modification, biogas project, and VSD for chiller and compressor have payback period of less than 3 years. Of note is that the steam line insulation has the minimum payback period (0.10 years) with a NPV value of LKR 7,898,368. Overall, the implemented retrofits provide LKR 251,287,585 of lifetime gain over a total investment of LKR 47,045,500. Therefore, the ratio of initial investment to lifetime gain equals 1:5.34.

5 Discussion and Conclusions

Considering the cost implications of green retrofits, contradictory views were indicated by previous studies on the initial cost of green retrofits (McDonald et al. 2008; Zhai et al. 2014). In the current study, the positive NPV values show significant financial returns over the initial investment, and the findings related to the payback period are different from literature findings which suggest that the green retrofits involved long payback periods (Kasivisvanathan et al. 2012). Similar to Bond (2010), who indicated that the renewable energy projects provide high return on major investment within a short payback period, most of the retrofit projects in this study have recovered the higher initial investment very quickly, within less than 5 years. For biomass boilers, the payback period is even shorter (about 1.4 years). Accordingly, the study recommends appropriate green retrofits options such as evaporative cooler, biomass boiler, energy efficient chillers, servo motors, LED lights, steam line insulation, sky lights and compressed air line modification, which provide higher return within a short time.

The findings indicate the financial viability of the implemented retrofit projects under the energy and IEQ with positive NPV values and less SPB periods. Moreover, considering the lifetime financial returns of those retrofits, each indicates significant benefits compared to the initial investment. In addition to those monetary savings, all the retrofit projects were expected to generate additional benefits in terms of environmental and social sustainability. Natural resource depletion and environmental degradation are continuously rising with the increasing construction activities. One of the fast options to save resources, including energy and water, and to reduce GHG emissions and global warming is to construct green buildings which have a great potential on environmental, social and economic sustainability. However, the portion of resources demanded and environmental emissions by the existing buildings are significant. Therefore, green retrofitting is one of the key solutions to the current global environmental crisis. The success of these real retrofit scenarios would enable us to identify the most appropriate retrofit technologies based on the potential expenses and returns involved, thereby allowing building investors and owners to apply those retrofits in existing buildings.

Acknowledgements The authors highly acknowledge and appreciate the financial support given by the Senate Research Committee of University of Moratuwa under Grant SRC/ST/2018/11.

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Advances in Project Management Practices

Investigation of the Earned Value Method (EVM) Applicability for Construction Operations Affected by the Learning Phenomenon

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Abstract The Earned Value Method (EVM) has been extensively applied for the analysis of construction projects. However, in cases where the productivity is not constant, but rather varies due to accelerations attributed to the learning phenomenon, it is challenging to assess the implications on productivity estimation and forecasting. In that sense, such an investigation is crucial for the scheduling and coordination of the remaining works in a realistic manner. The purpose of this paper is to compare the progress reporting results using the Earned Value method both for the theoretical project time schedule (without learning) and the actual on-site scheduling following the learning curve. A real, large-scale infrastructure project is used as a case study. The research method involved the "transformation" of productivity data to cost data, with the purpose of quantifying the productivity improvements through the use of statistical learning models. The straight-line model was used, due to its wide acceptance in related studies. An algorithmic approach is developed and assessed via, inter alia, the Schedule Variance (SV) and the Cost Variance (CV) indices. The results of the research indicate that EVM is significantly affected by the learning phenomenon,

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_20

which, if neglected, leads to ineffective decision making procedures, regarding the deployment of project resources.

Keywords Earned Value Method · Construction productivity · Estimation · Learning curves

1 Introduction

Contemporary construction projects are complex ventures that can be affected by learning. Learning is a process which may result in increased productivity during the course of each activity, affects the effectiveness of teams and increases efficiency of future construction activities (Afshari et al. 2019). All organizations compete on time and cost effectiveness, therefore it is of critical importance to be able to accurately forecast the project duration and deliver according to the promised schedule (Panas and Pantouvakis 2010). However, the learning effect (stemming either from the crew-level or senior project executives) is rarely taken into account in evaluating project progress, since current project management tools assume that productivity is a constant function over time (Anbari 2003). A typical example of such an approach is the Earned Value Method (EVM) or Earned Value Analysis (EVA), one of the most popular multidimensional project management systems that has been successfully used in many construction projects since the 1960s (Olawale and Sun 2015).

The assumption of constant productivity makes EVM ineffective on projects affected by knowledge and learning, especially in construction projects which entail "sufficiently complex", repetitive activities (Thomas 2009). In such projects, the average experience and resulting performance of the project team increases at a fast pace, which is called the "Learning Rate". Due to the learning effects the project team's performance will continue to increase. Therefore, if "non-linear" factors are excluded from the analysis and the duration is estimated from the linear factors only, the project manager would presume that the performance would stay at a low level until the end of the project and would add more resources in order to compensate for this (Plaza and Turetken 2009). This paper aims at factoring in both the non-linear performance and the learning rate by proposing a project management method that takes into account the learning effect in evaluating project progress. A large-scale infrastructure marine project has been used as case study for the research. It is, to the authors' best knowledge, the first research attempt to investigate thoroughly the combined implementation of Earned Value Analysis and learning curve theory in marine works from a productivity stance.

The structure of the paper is as follows: First, background information on pertinent research on learning curve theory and Earned Value Method is going to be provided, followed by a concise description of the construction process that served as the research tested. Then, the research methodology is going to be delineated and, subsequently, the research results will be presented. The main inferences emerging from the study will be described and, finally, the delineation of future research directions will conclude the study.

2 Background

2.1 Learning Curves

Learning curves are used for the graphical representation of the time span, the cost and/or the labour hours that are required for the execution of a series of "sufficiently complex" construction activities (Pellegrino and Costantino 2018). The learning curve theory suggests that the required time (labour hours) for the production of a single unit (e.g. floor of a high rise building) is incrementally decreasing as a percentage of the time that was demanded for the production of the previous unit (Panas and Pantouvakis 2018). This percentage is called "learning rate" and is a characteristic variable for the extent of the learning phenomenon in a single construction activity (Thomas et al. 1986). From a mathematical point of view, the learning rate coincides with the inclination of the learning curve. The smaller the value of the learning rate, the more intense the learning phenomenon, since each subsequent production cycle is a smaller percentage of the time required for the previous production cycle. For instance, when the learning rate equals 80%, then the required labour-hours for the production of a single unit is 20% less than the time needed for the production of the previous unit. If an activity presents a learning rate equal to 100%, then no learning phenomenon is developed for that specific task.

The learning curve theory may be applied to the effort (typically measured in units of time) related to individual units or to the cumulative average time to complete a number of units (Lee et al. 2015). The learning curve phenomenon is studied through the use of specific mathematical models, which interpret the variation of productivity in relation to critical factors such as the number of units. Although there have been many models presented in published literature, this research adopts the straight-line model, which has been proven to provide very satisfactory results in construction productivity studies (Thomas et al. 1986; Everett and Farghal 1994). A simplified mathematical expression for the estimation of productivity via the straight model is

$$k_n = k_1 * n^b = k_1 * n^{(\log LR/\log 2)},$$

where k_n = total time or cost for n-th unit; k_1 = total time or cost for the first unit; n = number of units produced; b = logLR/log2; LR = learning rate.

2.2 Earned Value Method

The Earned Value method has been developed as a tool facilitating project progress control. It can determine the project's current status and the scale of current variances from the plan. It also extrapolates current trends and makes inferences on the final effect on the project time and cost. The basic concepts of the Earned Value Method are depicted on Fig. 1 (Czarnigowska 2008). An EVM analysis requires following inputs (assuming "T" is the planned duration of the project) and calculation of project status indicators:

- **BCWS (Budgeted Cost of Work Scheduled)**: it represents the baseline for the analysis, by cumulating planned costs related to time of their incurrence. It is also called "Planned Value".
- **BCWP (Budgeted Cost of Work Performed)**: it is a measure of physical progress of works expressed by cumulated planned cost of works actually done related to time. It is also called "Earned Value".
- **ACWP (Actual Cost of Work Performed)**: it is the cumulated amount payable for works done related to time. It is also called "Actual Value".
- **BAC (Budget at Completion)**: it is the total planned cost of the whole project. It equals BCWS at the planned finish.
- **PC (Percentage Complete)**: it is calculated as PC = BCWP/BAC.
- **CV (Cost Variance)**: it is a measure of deviation between planned and actual cost of works done until the date of recording progress in money units. If CV < 0, then the project is over budget. It is calculated as CV = BCWP − ACWP and CV(%) = CV/BCWP.
- **SV (Schedule Variance)**: it is a measure of deviation between the actual progress and the planned progress. Though it is interpreted as time deviation, it is expressed

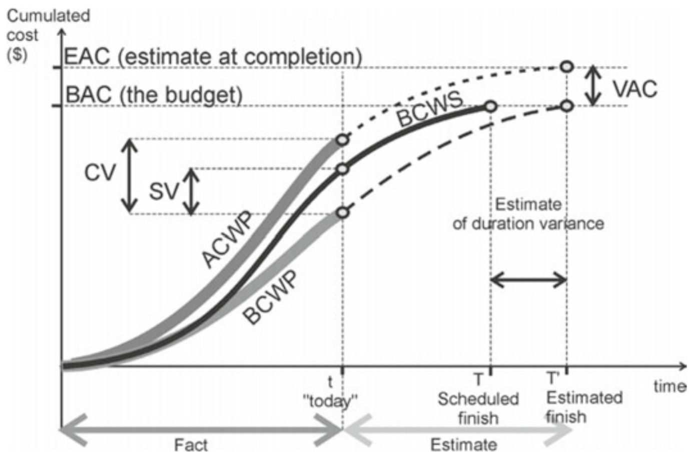

Fig. 1 Graphical representation of EVM concepts (adopted from Czarnigowska 2008)

in money units. In other words, it is the difference between the planned cost of works that have been done and planned cost of works that should have been done by the reporting date. If SV < 0, then the project is behind schedule. It is calculated as SV = BCWP − BCWS and SV(%) = SV/BCWS.

- **EAC (Estimate at Completion)**: it is calculated at the date of reporting progress (i.e. control point) to serve as an estimate of the effect of deviations cumulated from the project's start on the total project cost, so it informs how much the project is going to be in the end, for a constant productivity. It is calculated as EAC = ACWP/PC.

2.3 Caisson Construction Operations

In general, floating caissons are prefabricated concrete box-like elements with rectangular cells that are suited for marine and harbor projects and are usually cast on floating dry docks (Panas and Pantouvakis 2014). Due to the standardized shape of the caissons and the repetitive nature of the works, since caissons are always constructed in batches, the concreting process is most commonly executed with the use of the slipforming construction technique. Slipform is a sliding-form construction method, which is used to construct vertical concrete structures (Zayed et al. 2008). Generally, the concreting and slipforming process comprises three sub-phases (see Fig. 2): (i) slipform assembling phase, (ii) slipforming phase (including an initial concreting phase) and (iii) slipform dismantling phase. Although Pantouvakis and Panas (2013) identified nineteen activities for the construction of a caisson, this study focuses only on the aforementioned activities, because a fundamental prerequisite for the learning phenomenon to develop is for productivity improvements to be able to occur as a result from repeating "sufficiently complex" activities (Thomas 2009). As such, in the case of caissons construction operations, only these activities were found to inherently possess such characteristics, since the observed productivity of the other activities did not fluctuate significantly during the construction phase. The selected project under study was executed in 2015 and comprised the construction of 40 caissons.

Fig. 2 Floating caisson production cycle

3 Research Methodology

The research methodology is depicted in Fig. 3, while an analytical description of the implemented steps follows in the next paragraphs.

- **Step 1—Field data management**: All field data from the case study project (caisson construction) are entered in an electronic database and categorized in two types—time data (labour workhours, days based on project calendar) and cost data (cost per caisson, equipment/labour costs).
- **Step 2—Specification of work scenarios**: There are two main work scenarios. The first one represents a theoretical time scheduling scenario where the productivity unit rates are determined based on average values and are held constant (no improvement or deterioration) during the whole project duration. The second scenario is a historical record of the actual productivity (time/cost) data of the project. In addition, progress evaluation milestones or control points are specified. In our case, progress controls were performed every 10 caissons.
- **Step 3—Production of Gantt charts**: The two aforementioned scenarios are graphically represented in a Gantt chart, so as to be able to visually compare the achieved progress. The assumed productivity is measured on a crew-level and does not refer to management or team members.
- **Step 4—Earned Value Analysis**: All metrics presented in the previous section (i.e. BAC, BCWS, PC, ACWP, BCWP, SV, SV%, CV, CV%, EAC) using data stemming from both work scenarios. The comparative analysis of the results will enable the assessment of the learning phenomenon impact on productivity in terms of the Earned Value.
- **Step 5—Learning model implementation**: The straight-line model is going to be implemented so as to determine the Learning Rate (LR) at the control points, namely the progress evaluation milestones set at every 10 caissons. The solver function of MS Excel has been used in conjunction with the least squares method, so as to determine the optimum Learning Rate value at each milestone.
- **Step 6—Comparative analysis**: A comparison of the theoretical (no learning) and actual (learning prone) scenarios delineates the variations in productivity from the Earned Value perspective. As such, the project manager is provided with valuable

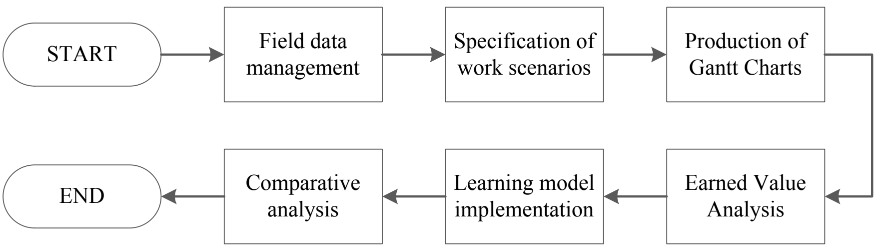

Fig. 3 Research methodology

information that quantifies the learning effect on project progress which directly affects decisions relating to the amount of deployed resources.

4 Results

Step 1—Field data management

The electronic database contains grouped field data which depict the workhours per caisson, the cost per caisson and the time period (in days) that is required for the completion of each caisson.

In addition, the cumulative work-hours and cost is estimated along with the cost per day per caisson. For brevity reasons, Table 1 presents an excerpt of the created database for the first 10 caissons. In total, 71,255.35 labour-hours were required, with a total cost of 943,822.56€ and a total duration of 626 days for the construction of all caissons.

Step 2—Specification of work scenarios

The actual scenario is easily derived from the historical project data contained in the respective database. The theoretical scenario required the determination of constant unit rates and productivity data, as stated above. In order to increase the research validity the estimated productivity data were not set arbitrarily, but stemmed from the average values of the first four caissons, which represent the 10% of the whole project (4 out of 40 caissons). In addition, the first units are not heavily affected by the learning phenomenon, because it has not been fully developed yet. Taking into account the aforementioned assumptions, Table 2 was constructed as follows:

Therefore, the theoretical scenario is built upon (a) 2482.13 total labour-hours per caisson, (b) 32,874.96€ average total cost per caisson, (c) 18 actual productive days per caisson (rounded up to the next integer from 17.25 → 18), (d) 23 total calendar days (including any delays, disruptions etc.) per caisson (rounded up to the next integer from 22.75 → 23) and (e) 1429.35€ average labour cost per day per caisson (derived from 32,874.96€/23).

Step 3—Production of gantt charts

Due to limited space, an excerpt of the actual and theoretical Gantt Chart for the first six caissons is presented in Fig. 4a/b. It is evident, that there is a “delay” in the project progress for the first two caissons, which is absorbed though by the improvement in the completion of the next pair of caissons due to the learning phenomenon. On the other hand, the theoretical scenario presents a constant productivity rate, as expected.

At this point, we should highlight that the observed delay was attributed to the lower sliding rate due to the initial learning rate. As the learning rate improved, the sliding rate improved as well. Indicatively, sliding operations started with an average sliding rate of approx. 12 cm/h and the project was completed with an average sliding

Table 1 Field data representation in the project database

Caisson	Labour-hours/caisson	Cost (€)/caisson	Days/caisson	Cost (€) (cumulative)	Labour-hours (cumulative)	Cost (€)/day/caisson
1	2,976.33	39,314.38	33.00	39,314.38	2,976.33	1,191.34
2	2,890.50	38,328.44	32.00	77,642.81	5,866.83	1,197.76
3	1,947.00	25,806.72	13.00	103,449.53	7,813.83	1,985.13
4	2,114.67	28,050.31	13.00	131,499,84	9,928.50	2,157.72
5	1,824.50	24,146.56	15.00	155,646.41	11,753.00	1,609.77
6	1,770.83	23,442.19	14.00	179,088.59	13,523.83	1,674.44
7	1,718.00	22,742.50	15.00	201,831.09	15,241.83	1,516.17
8	1,667.67	22,081.88	12.00	223,912.97	16,909.50	1,840.16
9	1,675.00	22,215.63	35.00	246,128.59	18,584.50	634.73
10	1,535.00	20,309.38	32.00	266,437.97	20,119.50	634.67

Table 2 Average productivity values based on first four caissons

Caisson	Total labour-hours	Total cost (€)	Actual days/caisson	Total (calendar) days/caisson
1	2,976.33	39,314.38	23.00	33.00
2	2,890.50	38,328.44	22.00	32.00
3	1,947.00	25,806.72	12.00	13.00
4	2,114.67	28,050.31	12.00	13.00
Average	2,482.13	32,874.96	17.25	22.75

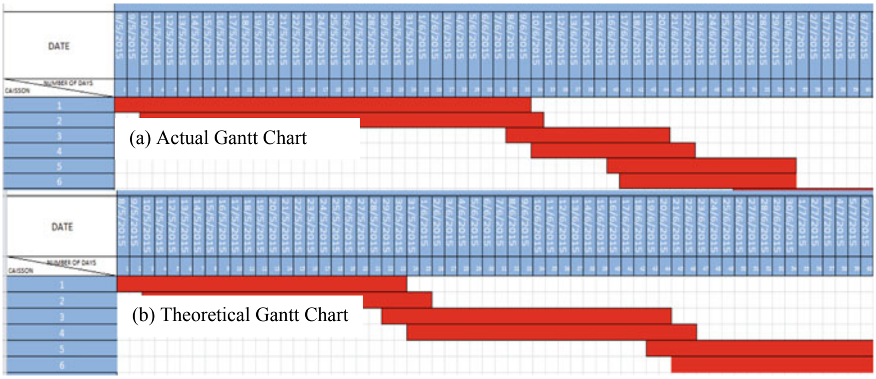

Fig. 4 **a** Actual gantt chart. **b** Theoretical gantt chart

rate of almost 30 cm/h. No other factors were statistically significant in influencing the achieved on-site productivity.

Step 4—Earned value analysis

The Earned Value Analysis was implemented for the labour cost, while the control points were set (as already explained) at 10, 20, 30 and 40 caissons. BAC, BCWS, PC and ACWP must be estimated and the rest of the EVM metrics (ACWP, BCWP, SV, CV, EAC) can be calculated subsequently. The budget at completion (BAC) is estimated by multiplying the average total cost by the total number of caissons to be constructed, i.e. BAC = 40 * 32,874.96€ = 1314,998.44€. The Budgeted Cost of Work Scheduled (BCWS) should be calculated by multiplying the average labour cost per day per caisson (1429.35€) by the amount of constructed caissons and the required time (in calendar days) for their completion.

For example, we know that the first 10 caissons were completed on 10th August 2015 (control point on the actual Gantt Chart). On the theoretical Gantt Chart, on the same day, it was programmed that 8 caissons would be completed with an average of 23 calendar days per caisson and some works on the 9th and 10th caisson would already have started, which represent an additional time period of 20 calendar days. Therefore, for the first 10 caissons BCWS = 1429.35 * (23 * 8 + 20) = 291,586.61€.

Table 3 Earned value analysis data

Control point	BAC (€)	BCWS (€)	PC (%)	ACWP (€)	BCWP (€)
10 caissons	1,314,998.44	291,586.61	25%	274,959.04	328,749.61
20 caissons	1,314,998.44	451,673.38	50%	516,793.21	657,499.22
30 caissons	1,314,998.44	586,031.91	75%	736,372.36	986,248.83
40 caissons	1,314,998.44	708,955.68	100%	943,822.56	1,314,998.44
Control point	SV	SV%	CV	CV%	EAC (€)
10 caissons	37,163.00	12.75%	53,790.57	16.36%	1,099,836.16
20 caissons	205,825.84	45.57%	140,706.01	21.40%	1,033,586.42
30 caissons	400,216.92	68.29%	249,876.47	25.34%	981,829.81
40 caissons	606,042.76	85.48%	371,175.88	28.23%	943,822.56

The Percent Complete is estimated proportionally according to the pace of works (i.e. PC(10) = 10/40 = 25%).

The Actual Cost of Work Performed is derived from the actual Gantt Chart (Fig. 4a), where the actual direct labour cost is estimated for each day and then cumulatively added up to each control point. For brevity reasons, the analytical calculations for all metrics are omitted and indicative calculations are presented for the first 10 caissons (Table 3).

BCWP = PC * BAC = 25% * 1,314,998.44€ = 328,749.61€
SV = BCWP − BCWS = 328,749.61€ − 291,586.61€ = 37,163.00€
SV% = SV/BCWS = 37,163.00€/291,586.61€ = 12.75%
CV = BCWP − ACWP = 328,749.61€ − 274,959.04€ = 53,790.57
CV% = CV/BCWP = 53,790.57€/328,749.61€ = 16.36%
EAC = ACWP/PC = 274,959.04€/25% = 1,099,836.16€

Step 5—Learning model implementation

The straight-line learning model was implemented to simulate the construction of all 40 caissons. The estimation of the Learning Rates at the 10, 20, 30 and 40 caissons control points yielded 83.50%, 84.30%, 85.17% and 85.89% respectively. It is evident that the LR was more intense for the first batches of caissons and it smoothed as the construction process neared completion. It should be noted that all construction and operational parameters were held constant throughout the project duration, namely construction process, main equipment (e.g. floating barge) and crew composition.

Step 6—Comparative analysis

The improvement of productivity in the studied construction process due to the development of the learning phenomenon was evidently proven by the EVM metrics. It is very characteristic that the budgeted cost based on the average values of the first four caissons (1,314,998.44€) for the theoretical works scenario (no learning) was ~40% higher than the actual cost of works performed (943,822.56€) under the influence of the learning phenomenon. In addition, the Schedule Variance indicates that the project was ahead of schedule (SV > 0) even from the first 10 caissons. Same goes for the Cost Variance as well, namely the project was under-budget (CV > 0) from its essential beginning. In fact, both SV and CV metrics incrementally increased, which means that there was a constant improvement in productivity throughout the course of the project. The latter highlights the importance of the achieved Learning Rate, as stated above.

It should be noted that numerous other factors may affect the achieved on-site productivity per se, since the activities were executed in an open environment which is prone to other influencing factors that can deviate the project performance. In our case though, no significant changes have been observed to either operational or managerial factors. In other words, the main operational framework for the execution of the works was held unchanged during the project duration. All project crews started and finished the project with the same composition. Same goes for the deployed equipment and materials, as stated above. In addition, a quantitative statistical analysis was performed to identify any significant correlations of productivity to other factors, without ultimately getting any such indication. In that sense, it was derived that the main productivity driver for the observed improvements was the achieved learning rate. The latter is also corroborated by the improvement rates in the examined learning models. This direct relationship of learning and productivity improvement is reflected on the EVM metrics and highlights the significance of this research.

5 Conclusions

The research intended to interpret Earned Value Method metrics under the effect of learning phenomena for complex construction operations. The research framework was presented in a step-wise fashion and its implementation was conducted for a large-scale infrastructure project which served as a case study. The estimations evidently proved that if learning effects are not included in the analysis, then planning becomes unreliable. The most important issue is that neglecting learning effects leads to a false project progress assessment, since the classic EVM approaches assume a constant productivity rate throughout the project duration. However, under the influence of the learning effect, the productivity is gradually improving, leading to significant savings in time and cost as demonstrated in the previous section.

In terms of their applicability, the examined models are well established in relation to their internal mathematical robustness. However, it should be highlighted that research results cannot be extended beyond the scope of the studied construction process and with similar operational parameters (e.g. construction method, equipment etc.). In that framework, it would be practical to gradually examine the introduction of the studied learning models to "similar" activities, namely high-rise constructions such as silos or industrial chimneys.

On any case, however, the research has clearly demonstrated that, if learning is not taken into account in EVM analyses, there is a risk of misjudging project progress and deciding to enhance its resources to the detriment of the project's cost. Of course, the EVM analysis should be based on reliable data which may be difficult to gather or handle especially in large-scale construction projects. As such, the implementation of the learning models should be aligned with the organisation's managerial maturity in order to ensure sufficient support (e.g. IT, backoffice, PM Office) along the project duration. In general, project managers should always assess how prone to learning phenomena the project activities are, before taking managerial decisions that affect the deployment of project resources. Possible extensions of the current research approach could be the development of a software tool that would be able to capture real-time project progress data and through the implementation of one or more learning curve models yield EVM metrics that are realistic and dynamically estimated. In addition, the computational capabilities of the algorithmic approach could be enhanced by the addition of stochastic tools, such as discrete-event simulation, in order to overcome the limitations of the deterministic statistical analysis.

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A New Project Scheduling Control Method Based on Activity Quantities

Hsien-Kuan Chang, Wen-Der Yu and Tao-Ming Cheng

Abstract The traditional Earned Value Management (EVM) suffers in many theoretical weaknesses. The improved Earned Schedule Method (ESM) and Earned Duration Management (EDM) still adopt the basis of Planned Value (PV) and Earned Value (EV) for evaluating the overall schedule performance. They tend to mislead the manager's conception of de facto schedule performance. To resolve the abovementioned problems of traditional schedule control methods, this paper proposes a new method, namely the Quantity-based Project Schedule Control Model (Q-PSCM), which adopts the concepts of EDM, but calculates the project schedule performance based on 'activity quantities' of the critical path instead of the overall 'activity values' in the traditional EVM. The quantity information is used to compute the project's 'Estimate to Complete (ETC)' duration using critical path method. The overall project schedule performance index is evaluated based on the information of current schedule, project ETC duration and project planned duration. The result of case study shows that the proposed Q-PSCM can evaluate the project schedule performance more effectively and provide a more useful and effective tool for schedule control of construction projects.

Keywords Schedule control · Earned Value Management · Earned Schedule Method · Earned Duration Management · Quantity survey

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_21

1 Introduction

The Earned Value Management (EVM) is the mostly widely adopted method for schedule control of construction projects (Anbari 2003; PMI 2011); however, it has been found to suffer in some theoretical weaknesses, e.g., highly influenced by costly activities, and the final schedule performance will resume to the baseline, regardless of how poor the schedule performance was for the activity (Lipke et al. 2009). New methods such as Earned Schedule Method (ESM) (Lipke 2003) and Earned Duration Management (EDM) (Khamooshi and Golafshani 2014) were proposed to improve the traditional EVM. However, ESM and EDM still adopt the basis of Planned Value (PV) and Earned Value (EV) for the overall project. They ignore the impact of individual critical paths to the project completion date and tend to mislead the manager's conception of de facto schedule performance.

In order to resolve the abovementioned problems of traditional schedule control methods, the current research aims at developing a new schedule control method, namely the Quantity-based Project Schedule Control Method (Q-PSCM), which adopts the concepts of EDM, but calculates the project schedule performance based on 'activity quantities' of the critical path instead of the overall 'activity values' in the traditional EVM. The proposed Q-PSCM calculates the required residual duration of an activity using the quantity information and compute the project's 'Estimate to Complete (ETC)' duration using critical path method; finally, the overall project schedule performance index is evaluated based on the information of current schedule, project ETC duration and project planned duration.

2 Related Works

2.1 Earned Value Management (EVM)

The most widely adopted construction schedule control method in the industry was EVM (PMI 2011). It was originally developed from a project financial control system namely Cost/Schedule Control Systems Criteria (C/SCSC) by the Department of Defense, USA (Fleming 1988). It evolved gradually to become the complete schedule and cost control system in 1990s. It was adopted by the Project Management Institute (PMI) as a measure for schedule and cost control and renamed 'Earned Value Management (EVM)' in the early 2000s (Anbari 2003).

The evaluation of schedule performance in EVM is based on the comparison of the 'Earned Value (EV)' with the 'Planned Value (PV)', which gives two indicators (SPI_c, CPI_c) for schedule and cost performance:

$$SPI_c = \frac{EV}{PV} = \frac{BCWP}{BCWS} \quad (1)$$

where EV = Budgeted Cost Work Performed (BCWP); PV = Budgeted Cost Work Scheduled (BCWS); SPI_c *is the schedule performance indicator based on 'cost'.*

$$CPI = \frac{EV}{AC} = \frac{BCWP}{ACWP} \tag{2}$$

where EV, BCWP, PV, and BCWS are defined as that in Eq. (1); CPI is the cost performance indicator based on 'cost'.

2.2 Earned Scheduling Method (ESM)

Despite its wide adoption, the EVM method has been criticized by many previous researchers for its weaknesses. For examples, Lipke (2003) pointed out that EVM fails to identify the poor schedule performance as the project approaches completion, since the value of EV approaches PV and the cost-based SPI_c approaches '1.0', indicating that the project was performed well no matter how poor the execution process was; Khamooshi and Golafshani (2014) found that the SPI_c shows only slightly delayed for project but the critical-path activities are significantly delayed if the value of the activities on non-critical path are much higher than that on the critical path; Vanhoucke (2009) and Elshaer (2013) found that the variations of schedule performance on the non-critical-path activities may result in erroneous judgements of the overall project schedule performance according to SPI_c. As a result, Lipke (2003) proposed the Earned Scheduling Method (ESM) to improve the problems of EVM.

The two primary differences between ESM and traditional EVM are: (1) the Earned Schedule (ES) is adopted instead of EV in EVM; (2) the Actual Time (AT) is used as time baseline for comparison with ES; (3) a new time-based schedule performance indicator, namely Schedule Performance Index (SPI_t), is proposed to replace the cost-based SPI_c in traditional EVM. The ES and SPI_t are defined in Eqs. (3) & (4) as follows:

$$ES = t + \frac{EV - PV_t}{PV_{t+1} - PV_t} \tag{3}$$

where 't' is the time of PV for condition EV $\geqq$ *PV; EV is defined similarly as that in traditional EVM;* PV_t *is the planned value at 't', and* PV_{t+1} *is the planned value at 't + 1' in traditional EVM; ES is the value of Earned Schedule.*

$$SPI_t = \frac{ES}{AT} \tag{4}$$

where ES is the 'Earned Schedule' as defined in Eq. (3); AT is the 'Actual Time' spent for the project; SPI_t *is the schedule performance indicator based on ESM.*

2.3 Earned Duration Method (EDM)

Although the SPI_t of ESM improves the problem of SPI_c approaching '1.0' when the project approaches completion no matter how poor the schedule performance was, it is still based on the 'cost value' of the activity. As a result, ESM still suffers in similar drawbacks of the cast-based EVM such as the 'high non-critical activity value' problem and the misleading problem of variations in non-critical activities. In order to improve such problems, Khamooshi and Golafshani (2014) invented a new project schedule control method, namely the 'Earned Duration Management (EDM)' method.

In EDM, the 'Earned Duration (ED)' is defined as the duration (in 'days') that can be counted as the planned duration. That is, the unpredicted risk duration cannot be counted as ED, but the 'lost time'. There are two types of earned duration in EDM: (1) the 'Earned Duration of Activity (ED_a)' for a specific activity; and (2) the 'Total Earned Duration (*TED*)' of the project. *TED* is comparable to the EV of EVM. Similar to ED, there are also two types of planned duration in EDM: (1) the 'Planned Duration of Activity (PD_a)' for a specific activity; and (2) the 'Total Planned Duration (*TPD*)' of the project. A new schedule performance indicator is defined in EDM as 'Earned Duration Index (*EDI*)', which equals to the quotient of *TED/TPD.*

In addition to EDI, EDM offers the other schedule performance indicator, namely 'Duration Performance Index (*DPI*)'. DPI is calculated as follows: first, use TED to estimate the ED of TPD_{ed} (Total Planned Duration of Earned Duration); then divide the estimated ED with Actual Duration (*AD*) to give the DPI. Detailed calculations of the indicators in EDM are as follows:

$$ED_a = PD_a \times \frac{AD_a}{AD_a + EDTC_a} \quad (5)$$

where PD_a is the planned duration of activity; AD_a is the actual duration of activity; $EDTC_a$ is the Estimated Duration To Complete for the activity; ED_a is the earned duration of activity.

$$EDI = \frac{TED}{TPD} \quad (6)$$

where TED is the 'Total Earned Duration (TED)' of the project, which is the summation of all ED_a; TPD is the Total Planned Duration, which is the summation of all PD_a; EDI is the Earned Duration Index.

$$ED = t + \frac{TED - TPD_t}{TPD_{t+1} - TPD_t} \quad (7)$$

where 't' is the time of TPD for condition TED $\geqq$ TPD; TED is defined in Eq. (6); TPD_t is the summation of all PD_a at 't'; TPD_{t+1} is the summation of all PD_a at 't + 1'; ED is the estimated earned duration of the project.

$$DPI = \frac{ED}{AD} \tag{8}$$

where ED is defined in Eq. (7); AD is the actual duration of the project currently; DPI is Duration Performance Index.

Even though the primary objective of EDM was to improve the problems of EVM and ESM, it is still based on the 'overall planned project duration' and 'overall earned project duration'. It ignores the influence of individual activities on the overall schedule performance of the project and may result in misleading the judgement of construction schedulers and managers. An improved method for construction control is desirable.

2.4 Scenarios for Evaluation of Schedule Performance

Vanhoucke (2009) designed a sensitivity analysis experiment to evaluate the accuracy of schedule performance of EVM and ESM including 9 scenarios: critical activity is ahead, neutral and delayed (denoted as 'CP^-', '$CP^=$' & 'CP^+'); non-critical activity is ahead, neutral and delayed (denoted as 'NP^-', '$NP^=$' & 'NP^+'). Vanhoucke (2009) found in the 9 scenarios that: the 'Real Duration (RD)' is < 'Planned Duration (PD)' for Scenarios (1)–(3); the 'Real Duration (RD)' is = 'Planned Duration (PD)' for Scenarios (4)–(6); and the 'Real Duration (RD)' is > 'Planned Duration (PD)' for Scenarios (7)–(9). From Vanhoucke's 9-scenario experiment, 3 types of schedule performance can be further concluded for ESM: Type-(I) Correct evaluation for (1), (2), (5), (8), (9) with the following conditions—RD < PD & $SPI_t > 1$, RD = PD & $SPI_t = 1$, or RD > PD & $SPI_t < 1$; Type-(II) Misleading evaluation for (4) & (6) with the following conditions—RD = PD & $SPI_t \neq 1$; Type-(III) Erroneous evaluation for (3) & (7) with the following conditions—RD > PD & $SPI_t < 1$. Table 1 shows the 9-scenario experiment and the 3 types of schedule performance evaluation based on ESM.

Although Vanhoucke (2009) pointed out the weakness of ESM method, he didn't consider the following situations when the usage of floats exceeds the allowable values or when the critical activities finish too early to surpass the non-critical activities, so that the non-critical activities may turn into critical. Such situations are especially important in 'Scenario (3)—CP^-, NP^+' and 'Scenario (6)—$CP^=$, NP^+'. In Scenario (3), the real duration (RD) equals the Baseline Planned Duration (BPD) ($SPI_t = 1$) as the delayed duration of NP activities equals the total float, and the NP becomes CP. Similarly, the real duration (RD) will surpass the Baseline Planned Duration (BPD) ($SPI_t < 1$) as the delayed duration of NP activities exceeds the total float, and the NP will take over the CP in Scenario (6). As a result, the scenario judgements of Vanhoucke (2009) may be incorrect.

Table 1 The 9-scenario experiment and 3 evaluation types (Vanhoucke 2009; Lipke 2015)

			Status of non-critical path (NP)		
			NP^{-}	$NP^{=}$	NP^{+}
Status of critical path (CP)	CP^{-}	RD	<PD	<PD	<PD
		SPI_t	>1	>1	<1
		Scenario judgement	(1) correct	(2) correct	(3) erroneous
	$CP^{=}$	RD	=PD	=PD	=PD
		SPI_t	>1	=1	<1
		Scenario judgement	(4) misleading	(5) correct	(6) misleading
	CP^{+}	RD	>PD	>PD	>PD
		SPI_t	>1	<1	<1
		Scenario judgement	(7) erroneous	(8) correct	(9) correct

3 Proposed Quantity-Based Project Schedule Control Method (Q-PSCM)

3.1 Methodology

In order to resolve the problems with the traditional project schedule control methods, a new method for evaluating the project schedule performance based on work quantities of activities of the critical path is proposed in this section, namely the Quantity-based Project Schedule Control Method (Q-PSCM). The proposed Q-PSCM is an improved version of the previously proposed EDM, except two critical features: (1) the work quantity of the activity is used in place of the activity duration as the basis for calculating the 'earned duration (ED)'; (2) the project duration (rather than the summation of all activity durations) of the critical path (re-calculated after updating the duration information) is used as the index for evaluating project schedule performance.

The development of the proposed Q-PSCM is described as follows: (1) the previous EDM model is reviewed to identify the essential problems with the traditional EDM, then the schedule performance indicators of traditional EDM are used as the basis for developing Q-PSCM; (2) a critical improvement of Q-PSCM to the traditional EDM in calculating the Estimated Duration To Completion (EDTC) both for activities and the project is proposed; (3) a set of new project schedule performance indicators are defined for the proposed Q-PSCM; (4) finally, a construction project from literature is selected as the case study to verify the correctness and applicability of the proposed Q-PSCM based on the sensitivity analysis experiment proposed by Vanhoucke (2009).

3.2 Basic Model of Q-PSCM

The method of EDM has been reviewed in the second section. Comparing with EVM and ESM, the EDM is built on the foundation of 'activity duration' rather than the 'cost of activity'. Such a modification has resolved the problem of the 'high-value but non-critical activities' on the overall project schedule performance, which causes misleading performance evaluation. However, EDM still adopts the overall project duration value for schedule performance evaluation but ignores the influence of CP activities on the overall project schedule. In some cases, the CP and NP may swap as the activities on CP surpass the activities on NP or the consumption of floats on NP exceeds the allowable limit. The abovementioned problems will be tackled in the proposed Q-PSCM.

Most schedule performance evaluation indicators of EDM are adopted as the basis for developing the proposed Q-PSCM, including ED_a, AD_a, AD, TED, and TPD defined in Eqs. (5)–(8). Other indicators, such as the Planned Duration of Activity (PD_a), the Estimated Duration To Completion for the activity ($EDTC_a$), the Estimated Duration To Completion (EDTC) for the project, the Realistic Duration of Project (RD), the Earned Duration of Project (ED), and the Quantity based Schedule Performance Index (SPI_Q) for overall schedule performance will be defined.

The Planned Duration of Activity (PD_a) is calculated by the estimated work quantity of the activity divided by the planned work production rate ($Rate_{PD}$) as defined in Eq. (9).

$$PD_a = \frac{Q_a}{Rate_{PD}} \tag{9}$$

where Q_a is the estimated work quantity for the activity; $Rate_{PD}$ is the planned the planned work production rate considering available resources and equipment; PD_a is the planned duration of activity.

3.3 Calculating the Estimated Duration to Completion (EDTC) for Activity and Project

As discussed previously, the CP and NP will swap as the activities on CP surpass the activities on NP or the consumption of floats on NP exceeds the allowable limit. It is noted that the influence of the delayed duration of an individual activity on the EDI will be inversely proportional to the 'overlap' of activities with the delayed activity. In order to resolve such a problem, this research suggests to adopt 'the updated critical path duration' as the basis for evaluating the overall project schedule performance instead of 'the summation of the activities durations of the project'. In doing so, the EDTC of the project and the EDTC of activity ($EDTC_a$) defined in Eq. (5) should be calculated first.

Although $EDTC_a$ needs to be estimated in Eq. (5), no practical method was suggested by Khamooshi and Golafshani (2014) in their original paper of EDM. In this research, $EDTC_a$ is estimated with 'ETC_Q divided by the actual production rate ($Rate_{AD}$)' as defined in Eq. (10).

$$EDTC_a = \frac{ETC_Q}{Rate_{AD}} = \frac{PQ - EQ}{Rate_{AD}} = \frac{PQ - EQ}{\frac{EQ}{AD_a}} = AD_a \times \frac{PQ - EQ}{EQ} \tag{10}$$

where ETC_Q is the work quantity left to complete for the activity; $Rate_{AD}$ is the actual production rate to date; PQ is the planned quantity for the activity; EQ is the earned quantity for the activity; AD_a is the actual duration of the activity; $EDTC_a$ is the estimated duration to completion for the activity.

The remaining duration of the project, EDTC, is obtained by calculating the overall project duration using CPM with the activity duration of $EDTC_a$ (obtained from Eq. (10)) for all activities. The Realistic Duration of the project (RD) is then calculated by adding the Actual Duration of the Project to date (AD) with the EDTC, as defined in Eq. (11) as follows:

$$RD = AD + EDTC \tag{11}$$

where AD is the actual project duration to date; EDTC is remaining project calculated by CPM with the $EDTC_a$ of all activities.

The Earned Duration of the project (ED) is calculated by Eq. (12) defined as follows:

$$ED = AD + (PBD - RD) \tag{12}$$

where AD is the actual project duration to date; PBD is the planned project baseline duration calculated by CPM duration planning phase; RD is the realistic duration of the project defined in Eq. (11).

3.4 Evaluating the Overall Project Schedule Performance

With Eq. (10), the $EDTC_a$ for each activity is calculated based on the 'work quantity left to be finished' and the realistic productivity rate. Such a method is more accurate than using the activity duration estimated by the experienced engineer in the traditional EDM. The Realistic Duration of the project (RD) can be obtained by adding the actual duration to date with the EDTC. Finally, the project schedule performance evaluation indicators—the Schedule Performance Indicator based on quantity (SPI_Q) for the project is defined in Eq. (13) as follows:

$$SPI_Q = \frac{ED}{AD} = \frac{AD + (BPD - RD)}{AD} = 1 + \frac{BPD - RD}{AD} \tag{13}$$

where ED is the earned duration of the project; AD is the actual duration of the project to date; BPD is the planned baseline duration of the project; RD is the estimated realistic duration of the project; and SPI_Q is the schedule performance indicator based on quantity.

3.5 Application Procedure of the Proposed Q-PSCM

The application procedure of Q-PSCM is proposed in Fig. 1 and described in detail as follows. There are two phases for the application of the proposed Q-PSCM: the Planning Phase and the Control Phase.

Planning Phase

1. The Work Breakdown Structure (WBS) of the project is developed by reviewing the project contract documents and the drawings;

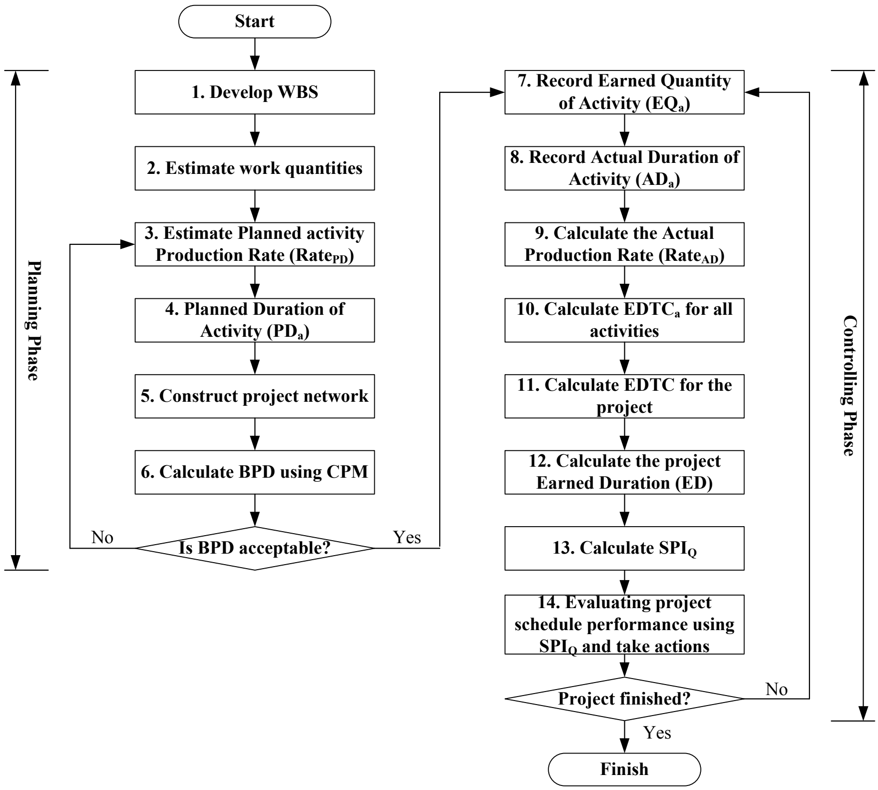

Fig. 1 Application procedure of the proposed Q-PSCM

2. The quantities of all activities in the project are estimated using quantity take-off methods and tools (Building Information Model is a very useful tool in this step);
3. The Planned Production Rate of Activity ($Rate_{PD}$) is estimated by referring to existing database or by experienced engineers;
4. The Planned Duration of Activity (PD_a) is calculated by dividing the work quantity with the planned production rate for the activity ($Rate_{PD}$) as defined in Eq. (9);
5. The project network is constructed by defining the precedence relationships among the activities;
6. The CP is calculated using traditional CPM to obtain the Early Start time (ES), Early Finish time (EF), floats for all activities, and the project Baseline Planned Duration (BPD).

Control Phase

7. Record the actual finished work quantity for each activity as the Earned Quantity of Activity (EQ_a);
8. Record the actual duration spent for each activity as the Actual Duration of Activity (AD_a);
9. Calculate the Actual Production Rate ($Rate_{AD}$) of actual activity duration;
10. Calculate the Estimated Duration To Completion of Activity ($EDTC_a$) using Eq. (10);
11. Calculate the Estimated Duration To Completion of the project (EDTC) using traditional CPM with updated duration information ($EDTC_a$) of all activities;
12. Calculate the project Earned Duration (ED) using Eqs. (11) and (12);
13. Calculate Quantity based Schedule Performance Index (SPI_Q) using Eq. (13);
14. Evaluating project schedule performance using SPI_Q: (1) $SPI_Q \cong 1.0$—the project schedule is 'Normal', no action required; (2) $SPI_Q > 1.0$—the project schedule is 'Ahead', consider cost reduction actions; (3) $SPI_Q < 1.0$—the project schedule is 'Delayed', actions are required to catch up the schedule.

4 Demonstrated Example

4.1 Description of Example Project

In order to demonstrate the applicability of the proposed Q-PSCM, a small example project used in Khamooshi and Golafshani (2014) is selected for comparison of schedule performance evaluations by the traditional EVM, ESM, EDM and the proposed Q-PSCM. The activity list of the sample project is shown in Table 2.

Table 2 Information of example project (Khamooshi and Golafshani, 2014)

Activity	Duration	Predecessor	PV	ES	EF	EV	AST	AFT
A*	7	Start	50,000	0	7	50,000	0	7
B*	8	A	20,000	7	15	0	–	–
C	4	Start	40,000	0	4	40,000	0	4
D	10	C	120,000	4	14	120,000	4	14
E*	8	B, D	60,000	15	23	0	–	–

PV = planned value (cost based), EV = earned value (cost based), ES = activity early start time, EF = activity early finish time, AST = activity actual start time, AFT = activity actual finish time
*Critical path activity; Date for project performance evaluation: Day 14

4.2 Performance Evaluation

Due to some unexpected risk events, the de facto schedule for the example project on Day 14 is shown in Fig. 2, where two critical activities, B & E, are not started. From the bar chart, it is noted that the project's CP (A→B→E) progressed only 7 days (SPI_R = 7/14 = 0.50). However, based on the de facto schedule information, the schedule performance evaluated by $SPI_c = 0.923$ by EVM and $SPI_t = 0.914$ by ESM. Both of SPI_c and SPI_t indicate relatively good schedule performance. The DPI = 0.75 and EDI = 0.75 of EDM, which indicate relatively poor schedule performance, but are still too optimistic. The schedule performance indicator evaluated by the proposed Q-PSCM can be obtained as follows: EDTC = 16, RD = 30, ED = 7, and thus $SPI_Q = 0.50$, which is most closed to the realistic progress evaluated manually by experienced engineer or manager.

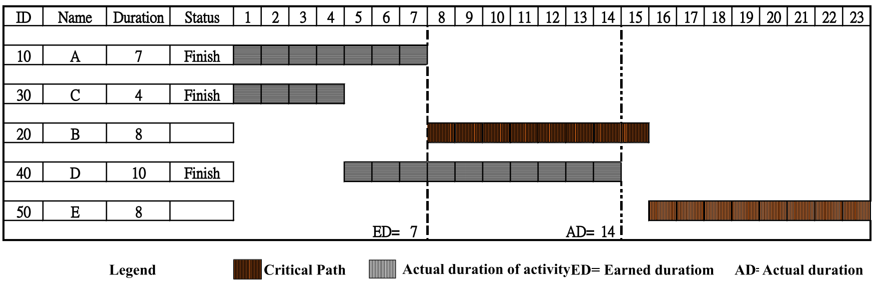

Fig. 2 The bar chart of de facto schedule for the sample project

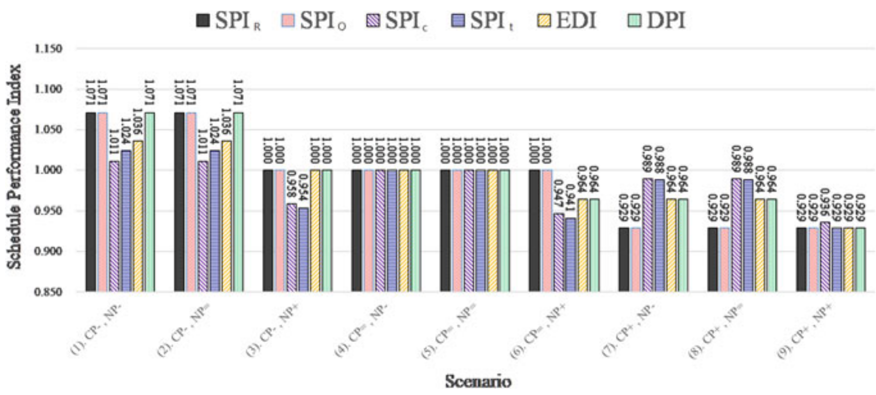

Fig. 3 Comparison of the 5 different schedule performance indicators

4.3 *Performance Evaluation of Example Project with the Proposed Q-PSCM*

In order to compare the results of schedule performance evaluation with the traditional methods (EVM, ESM, and EDM) and the proposed Q-PSCM, the performance indicators for the sample project are calculated for the 4 different evaluation methods. The 9-scenario sensitivity analysis of Vanhoucke (2009) is conducted for the 4 different evaluation methods, with sensitivity of ±1 day. The sensitivity analysis results are shown in Fig. 3. The realistic schedule performance indicator (SPI_R) evaluated manually by the experienced engineer is obtained by dividing the observed Earned Duration (ED_R) with de facto project duration referring to Fig. 2. There are 5 different schedule performance indicators selected for the sensitivity analysis are: (1) Q-PSCM—SPI_Q; (2) EVM—SPI_c; (3) ESM—SPI_t; (4) EDM—EDI and DPI. The results are shown in Fig. 4. The comparison can be better visualized in Fig. 3, where in most scenarios, e.g., Scenarios (1)–(5) & (9), the evaluation results of SPI_Q are identical to that of DPI; however, their results in Scenarios (6)–(8) are different. In two scenarios (Scenarios (4) & (5)), are methods reach the same evaluation results. It is noted that all performance indicators obtained by Q-PSCM—SPI_Q are the same as SPI_R, which implies that SPI_Q is the best estimator of the realistic schedule performance, SPI_R (Table 3).

5 Conclusions

This paper presents a new method to evaluate the schedule performance of construction projects, namely the Quantity-based Project Schedule Control Model (Q-PSCM), which adopts the concepts of EDM, but calculates the project schedule performance based on 'activity quantities' of the critical path instead of the overall

Table 3 Calculated schedule performance indicators for 2 activities with Q-PSCM

Activity	Scenario	$Rate_{PD}$	PQ	EQ	AD_a	$Rate_{AD}$	$EDTC_a$
B (CP)	Ahead	0.125	1.000	1.000	7	0.143	0.000
	Neutral	0.125	1.000	0.875	7	0.125	1.000
	Delayed	0.125	1.000	0.777	7	0.111	2.000
D (NP)	Ahead	0.100	1.000	1.000	9	0.111	0.000
	Neutral	0.100	1.000	1.000	10	0.100	0.000
	Delayed	0.100	1.000	0.910	10	0.091	1.000

'activity values' in the traditional EVM. The proposed Q-PSCM uses the quantity information, instead of the cost value of EVM/ESM or overall duration of EDM, to compute the project's realistic duration (RD) using critical path method. Such a method has been shown to be able to overcome the drawbacks of the great influence caused by the costly activities, the schedule performance approaching the baseline regardless of the level of the schedule performance for the activity, the ignorance of individual activity's impact on the project completion date, or the misleading of de facto schedule performance, which were found in traditional schedule control methods.

After comparison with the three other traditional schedule performance evaluation and control methods, e.g., EVM, ESM, and EDM, the schedule performance evaluation results of the proposed Q-PSCM are shown to be the most accurate to the de facto progress of the project. It is concluded that the proposed Q-PSCM has the potential to replace the traditional schedule performance evaluation and control methods and improve the effectiveness of construction project control.

Although this research has proposed a promising schedule performance evaluation and control method, more works on practical implementation and verification of the proposed method need to be done, just like that of ESM and EDM, when these methods were first proposed in 2000s and 2010s.

Acknowledgements This research project was funded by the Ministry of Science and Technology, Taiwan, under project No. MOST 107-2221-E-324-007. Sincere appreciations are given to the sponsor by the authors.

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Outcomes of Current Project Management Practices in South Africa

Godfrey Monyane, Fidelis Emuze, Bankole Awuzie and Gerrit Crafford

Abstract With the decline of the current economic conditions in South Africa, project performance is a great concern that needs attention. A qualitative multiple case study strategy and semi-structured interviews were undertaken to determine the outcomes of current project management practices in South Africa. In terms of the performance of projects, the status quo paints a disconsolate picture. The poor performance continues to dominate the construction sector, especially in the public sector. Findings reveal protracted processes, and the use of unqualified and inexperienced contractors contribute to the poor performance of public sector projects. In addition, ineffective initiatives to curb the abuse of the procurement processes are directly affecting the outcomes of construction projects due to loopholes in the procurement process, and if this status quo remains, the sector will continue to have a bad image and continued waste of taxpayers' money will not cease until the public sector remove non-value adding activities in their operations.

Keywords Cost performance · Project performance · Project management · Public sector projects · Time performance

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_22

1 Introduction

Construction projects are unique and they tend to assume a greater dimension of complexity as they increase in size. A project's success is primarily dependent upon the iron triangle of cost, time and quality (Ali et al. 2010). Although project performance success is dependent on who is measuring the success, the most important performance indicator depends on the constraint imposed on the project by the client (Bello 2018). The poor performance of projects is a common reality that project stakeholders have come to accept, this phenomenon has become the rule, not the exception (Lavagnon 2012).

South Africa like any developing nation is confronted with numerous challenges of improving its infrastructure performance to boost the economy. The past decade has seen minimal growth and volatility in the markets and the country experienced low business confidence due to the vast majority of reasons. Unemployment remains high and the construction industry has been a major driver in contributing to employment in the past years before low business confidence by the investors. The public sector has accepted that delivering the right infrastructure, at the right time and economically will eventually yield the intended outcome, which will boost the economy.

Research conducted previously in project management has identified a wide variety of measures that describe the outcomes of a project and the features that influence on that outcome. Measuring performance is the foundation for continuous improvement, as Niven (2002) has reiterated the importance of performance management in the sentence "If you cannot measure it, you cannot manage it". To overcome this recurring problem of poor performance, this reported study assessed the outcomes of current project management practices in South African public sector projects to better understand the reasons why public sector project are prone to poor performance. The evaluation is intended to lead to an intervention that creates value throughout the life cycle of the project, in developing countries such as South Africa.

2 Outcomes of Current Project Management

2.1 Causes of Poor Cost Performance

Poor cost performance of construction project relates to projects not completed within the cost objectives planned prior to the commitment of the project. Cost overruns are an ongoing phenomenon, which is referred to with several terms such as "change orders", cost growth, or cost escalation (Zawawi et al. 2010; Odediran and Windapo 2014). Several reports have highlighted the problem of poor cost performance of projects over the years (Flyvbjerg 2011; Merrow 2011; Love and Sing 2013; Ahiaga-Dagbui et al. 2015). The problem of poor time performance has been similarly reported on such projects as an additional contributing factor to poor cost performance. Numerous researchers have conducted studies to identify the causes of poor cost performance in infrastructure projects. The most prolific and influential writer has been (Flyvbjerg et al. 2009). Moreover, Flyvbjerg et al. (2009) study provide an indication of the severity of cost overruns in large infrastructure projects by reinforcing the notion that over budgeting and overtime is happening repeatedly. However, Love (2011) argues that simply assuming that strategic misrepresentation and optimism bias as overarching actions that lead to the unsuccessful delivery of social infrastructure projects is misleading considering the complex array of conditions and variables that interact with one another during the project's procurement. Table 1 cover studies carried out in South Africa on causes of poor cost performance of project.

3 Causes of Poor Time Performance

Similar to the ongoing problem of poor cost performance, poor time performance also leads to a lack of project success in construction. In fact, both phenomena are interrelated in most times that poor time performance has cost implications. An easier example of the interrelatedness of the two phenomena is a common statement saying, "Time is money". Poor time performance can be referred to a prolonged duration of a project beyond the planned date specified for completion (Zou et al. 2007; Aiyetan et al. 2011; Kikwasi 2012; Gbahabo and Ajuwon 2017; Bello 2018). Additionally, Auma (2014) says that the factors affecting time performance of construction project include the late delivery of orders, delay in claims approval and delay in payment of valuations to the contractor. A study by Kadiri and Shittu (2015) ranked causes of poor time performance and top on the list from the contractors' perspective was "lack of experience of the client in construction" (Table 2).

4 Research Methodology

The qualitative case study method was adopted for this research. The research techniques used under the qualitative collection seek to gain an in-depth understanding of the research problem. The qualitative strategy gathered unstructured data that tends to be detailed and rich in both the content and the scope (Fellows and Liu 2015). These data were systematically gathered, keeping in mind the analytical procedure that would reveal patterns, insights, or concepts that seemed promising (Yin 2014). These promising concepts emerged through various forms of data manipulation. The author requested the public sector official to randomly select projects to rule out bias into all the projects executed under the auspices of the National Department of Public Works. The use of multiple cases were employed to test a range of cross-case propositions to improve external validity and the replicability of the results. The study purposefully selected five cases from the Department of National Public Works.

Table 1 Factors influencing poor cost performance on construction projects

S/N	Author	Year	Country	Top-rated factors
1	Ramabodu and Verster	2010	South Africa	Changes in scope of work on site, incomplete design at time of tender, contractual claims (extension of time with cost, lack of cost planning and monitoring of funds, delays in costing variations and additional works
2	Baloyi and Bekker	2011	South Africa	Increase in material cost, inaccurate material estimates, shortage of skilled labour, client's late contract award, project complexity, increase in labour cost, inaccurate quantity take-off, difference between selected bid and the consultants' estimate, change orders by client during construction, shortage of manpower
3	Monyane and Okumbe	2012	South Africa	Inadequate project preparation, planning, lack of co-ordination at design phase, incomplete design at time of tender, procurement and non-related procurement related factors, delays in issuing information to the contractor during construction stage, contractual claims, such as, extension of time with cost claims, delays in decision making by government, failure of specific coordinating, changes in owner's brief, delays in costing variations and additional works, improvements to standard drawings during construction stage, monthly payments difficulties from agencies, poor contractor management, contractor's unstable financial background, poor workmanship, late contract instruction after practical completion, delay in resolving disputes, delay in final account agreements, works suspended due to safety reasons

(continued)

Table 1 (continued)

S/N	Author	Year	Country	Top-rated factors
4	Mukuka, Aigbavboa, and Thwala	2014	South Africa	Contractors project inexperience, poor project management, inadequate planning, contractors inefficiency, inadequate financial provision, shortage of skilled site workers, poor workmanship, inaccurate estimate, project complexity, site conflicts, delay from employer, material price fluctuations, lack of executive capacity by employer, overdesign, shortening of contract period, unsteady material supply, ceaseless variation order, change in project design, insufficient time for estimation, unpredictable weather condition, breach of local regulation, unstable economy, project site location, inflation
5	Akinyeded and Fapohunda	2014	South Africa	Increase in income of workers, increase in outputs during production, application of effective techniques on site during production process, site control structure during production process, reduced construction time during production, site planning processes for production, reduced accident rate during production process, site development during production process, predictability for effective production, defects planning during production process, influence of workers behaviour on site during production, reduced capital cost during production process

Table 2 Shows the studies undertaken in South Africa in terms of the poor time performance of projects

S/N	Author	Year	Country	Top-rated factors
1	Baloyi and Bekker	2011	South Africa	Incomplete drawing, design changes, client's slow decision-making, late issue of instructions, shortage of skilled labour
2	Nkobane	2012	South Africa	Design changes, poor communications, and misunderstanding, poor quality basic engineering leading to rework, lack of adherence to material's standards, change of scope
3	Oshugande	2016	South Africa	Mistakes and discrepancies in contract documentation, poor communication between the parties, delay in decision making process by the client, strikes (employee strikes), unavailability of equipment, delay in decision making by the client, rework due to errors during construction, weather conditions, unforeseen ground conditions, delay in material delivery, change order by client during construction, delay in approving changes in the scope of work, delay in issuing work drawings, poor communication between the parties

Because of availability related challenges, only 15 interviews were conducted. Interviewees had job titles that include construction project managers, quantity surveyors and architects, and engineers. The number of interviews was considered appropriate following the views of Leedy and Ormrod (2010) that opined that between 5 and 25 interviews should yield enough data for analysis. The interview sessions were recorded with the express permission of interviewees and subsequently transcribed, verbatim. Thematic analysis was applied in making sense of the data (Kulatunga et al. 2007). As multiple sources of evidence improve the quality of analysis, findings and conclusions (Yin 2014), four main methods of data collection were utilized in this study. These include (1) project document analysis, (2) project discussions, (3) informal conversations with the site professionals, and (4) semi-structured interview with the project participants.

5 Findings and Discussion

The projects were selected from the National Department of Public Works Project Management System and were uniquely codified starting with case and then a number assigned to each project for identification. The DPW checks the requirements against state-owned properties and performs a feasibility study of all possible options. The best option is then decided based on the outcome of the feasibility study. The decision to construct, refurbish, or lease is the outcome of the feasibility study done internally by the public sector (Table 3).

Project 1 incurred cost overruns to the value of R185 million, which accounts for 40.5% of the original contract value on the date of award of the bid to the contractor and the final contract amount of R643 million. Again, this is attributable to variation orders an extension of time claims with costs to the contractor and escalation costs. The major increase was due to Variation Orders amounting to the value of R46 million and Contract Price Adjustment Provision R98.8 million and contingencies of R6.8 million. Project 2 incurred and realized cost overruns to the value of R42.4 million which accounts for 42.9% of the contract amount on the date of award of the bid to the contractor and the final contract amount of R141.2 million (Table 4).

The construction contract period for Project 3 was scheduled for 24 months and was supposed to have been completed on 16 January 2015. However, two years later,

Table 3 Project case 1 and project case 2

Project 1		Project 2	
Date contractor appointed	24-Feb-12	Date contractor appointed	17-Apr-12
Site hand over date	23-Mar-12	Site hand over date	09-May-12
Practical completion date	23-Jul-14	Practical completion date	26-Nov-14
Actual completion date	03-Aug-15	Actual completion date	30-Nov-15
Contract amount	R458,000,000	Contract amount	R98,800,000
Final amount	R643,000,000	Final amount	R141,200,000
Overrun amount	R185,000,000	Overrun amount	R42,400,000

Table 4 Project case 3 and project case 4

Project 3		Project 4	
Date contractor appointed	08-Jan-13	Date contractor appointed	27-Aug-08
Site hand over date	17-Jan-13	Site hand over date	22-Oct-08
Practical completion date	16-Jan-15	Practical completion date	22-Apr-11
Actual completion date	30-Jun-17	Actual completion date	30-Nov-15
Contract amount	R117,000,000	Contract amount	R374,300,000
Final amount	R243,000,000	Final amount	R437,600,000
Overrun amount	R126,000,000	Overrun amount	R42,400,000

the project is still under construction, the payment to date is at 18.8% of the total contract value, which depicts the slow pace of the construction. The consultants were appointed on 7 December 2005, which is eight years before construction starts, and funds for the project were approved on 30 October 2011 (six years later). As a result, there is a potential risk to increase contract amount owing to contract price adjustment provision (CPAP) and penalties to be levied on the contractor for late completion. The construction contract duration for Project 4 was planned for 30 months and this was to achieve completion on the 22nd April 2011. Six years later after the construction period, the spending is at 14.8%, which depicts a snail pace of the construction. The needs of the client were received on 14 June 2005 (12 years later), the project remains incomplete at status 5B. There is an increase of R63.3 million (16.9%) between the contract amount of R374.3 million on the date of award and the final contract amount of R437.6 million as at 30 June 2017. The aforementioned amount has a potential risk to increase beyond R437.6 million, especially for CPAP and penalties. An increase of R63.3 million is principally owing to the delays in the project. CPAP would have been incurred even if the project were on time. Therefore, the delays have inevitably resulted in a significant CPAP that could have been avoided.

The project has an amount of R44.9 million CPAP and R18.7 million for unforeseen expenses. The final contract value as of 30 June 2017 is R437.6 million. The project's expenditure as at 30 June 2017 was R65 million (14.8%). As of 30 June 2017, the project is behind by 106 months and remain at the construction stage. The extension of time would result in additional financial loss (Table 5).

Project 5 above displayed noteworthy progress from the contractor until June 2015 when the majority of subcontractors abandoned the site owing to non-payment by the main contractor. The contractor appointed new sub-contractors, which affected the progress of the project. There was also dispute on payment certificates and the contractor was not satisfied with the dispute resolution, as it was not in his favor and decided to vacate the site. A notice to cancel the contract was issued on 25 September 2015.

The above findings from case studies demonstrate projects that have failed and realized poor performance in terms of completion within the stipulated budget, and completion within the planned duration of the projects. The above information is

Table 5 Project case 5

Project 5	
Date contractor appointed	08-Nov-13
Site hand over date	25-Nov-13
Practical completion date	09-Apr-15
Actual completion date	Contract terminated due to non-performance after double the duration has elapsed
Contract amount	R27,000,000
Final amount	R31,000,000
Overrun amount	R4,000,000 at the time of termination of the contract

collected from documents perused of the sampled projects from the NDPW from different provinces of South Africa. The subsequent section that follows is from semi-structured Interviews of the participants of the projects that have been analyzed to gain a deeper understanding of the perception of participants for such poor performance of projects.

6 Findings from Interviews

In terms of the overall performance of projects, thirteen of the respondents indicated that projects were underperforming or performing poorly. Only one respondent felt that project performance was average with room for improvement. The main reasons given for the poor performance were: the inexperience of contractors, clients and project managers that results in poor project execution; poor financial control; projects over-running time leading to escalated costs; and projects being abandoned. Ten of the respondents felt the current outcomes of project practices were poor to very poor. Two respondents felt the outcomes were average or good. On the one hand, respondents explained that, generally, few projects are ever completed without complications and that projects in the public sector were performing as well as could be expected. On the other hand, respondents believed the performance of projects in the public service was poor because of the processes in the sector and that lack of experience and qualifications was the main cause of many problems experienced on site.

7 Conclusion and Further Research

Through case studies, it was clear that current project management practices lead to poor cost and time performance of infrastructure projects in South Africa. Time overruns played a major role in contributing to the cost overruns incurred by the projects. The procurement process of the public sector contributed to longer delays, which allowed cost escalation adjustments. Therefore, the project already inherited overruns before it commenced. Most professionals seemed to put the blame on the contractor as the leading cause of poor performance. Overall, the project displayed a total of 2555 days of slippage times from the original date scheduled for the project to be completed. This exhibits poor project performance, which negatively affects the image of the construction industry. It is evident that poor performance is normal day-to-day business for public sector projects and this requires new ways to eliminate such occurrences. Clearly, these outcomes are calls for concern for the industry to commence with collaborative practices and employ technology to improve project outcomes.

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Using Analytic Hierarchy Process to Evaluate Implementation Barriers of Agile Project Management in Australian Project Environments

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Abstract In today's complex environments, projects are facing many challenges to being delivered successfully. Lacking appropriate change management, adaptation and transformation, disruptive technologies, competitive demand and supply, acquisition of scarce resources, and fluctuations of stakeholder and customer needs could become impediments in delivering successful projects. Agile project management (APM) is one of the project delivery approaches believed to be effective in creating responsiveness and efficiency for projects in achieving customer satisfaction, delivering high quality, productivity and project performance as well as accomplishing project goals. Nevertheless, the magnitude of non-traditional agile implementations in project environments can be at variations depending on methodology, sector and extent of agile practices. This research aims to identify and evaluate implementation barriers of APM in projects across different sectors in Australia. The Analytic Hierarchy Process (AHP) technique was employed to conduct the research analysis by organising and analysing the APM barriers across different industrial sectors in Australia. The research was designed in two consecutive stages. In the first stage, 15 barriers to agile implementation, as evaluation criteria, were identified and finalised by a panel of APM experts. The agreed barriers were organised into four categories of agile manifesto values. The second stage, 10 APM practitioners working in Australian projects were invited to analyse and rank the barriers to agile implementation. The results of AHP analysis include the pairwise assessment matrices of the studied categories and the overall rank of barriers to the APM implementation. The research findings aim not only at facilitating agile project practitioners to recognise the most

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_23

important agile implementation barriers but also the contribution to the improvement of future APM implementation in Australian projects.

Keywords APM · Agile implementation · Agile barriers · Australian projects · AHP

1 Introduction

Innovative and complexity of today's projects drive the demand for different approaches and methodologies to deliver these projects (Conforto and Amaral 2010). According to the CHAOS report (The Standish Group 2011), challenges faced by projects, such as changes in the business environment, new government policies and funding as well as technology disruptions, can result in high visibility and continuity of project failure. While traditional project management (TPM) has been criticised as an approach with rigid details in project planning and execution (Conforto et al. 2014), Agile project management (APM) approach is believed to assist project teams to deal with challenging environments using its iterations and value adding in delivering required outputs to stakeholders in a short-time sprints (Highsmith 2004). Despite being praised with its flexibility, ability to embrace uncertainty and higher customer interaction and satisfaction (Serrador and Pinto 2015), not all projects adopt APM implementation. Furthermore, Leffingwell (2010) reveals that APM faces many impediments when it is implemented in larger-scale projects.

The purpose of this paper is to investigate the possible barriers of APM implementation within the Australian project environments. The paper is structured in five main sections. The next sections provide an overview of APM implementation in projects and the analysis that was conducted in this research. Then research findings are presented leading to the research discussion. The last section concludes this research study.

2 Concepts of APM Implementation

Since the revelation of the Agile Manifesto (Fowler and Highsmith 2001), Agile has been known as a promisingly responsive and satisfactory approach used in delivering software development projects. Vandersluis (2014) states the success of Agile implementation in helping these projects to be completed on time. Furthermore, Agile supports the integral contribution of customers into projects which leads to a higher level of satisfaction. With the increased awareness of APM implementation, Vandersluis (2014) also recommends the aspects of backlog, sprint, cross-functional team, continuous integration, information radiators, iterative and incremental development, scrum meetings, time boxing, use case and use story of APM to be implemented in non-IT project environments. Although APM is deeply rooted in software development, the release of A Guide to Project Management Body of Knowledge (PMBOK), the 6th edition, by Project Management Institute (PMI) has an extension of the Agile Practice Guide to encourage the APM application in project planning and execution for non-software development environments.

According to Agile Practice (PMI 2017), APM is suggested as an approach to managing disruptive technologies in project delivery. APM places customers at the highest priority and primarily focuses on the customer experience. While the TPM approach has shortcomings when used in high-uncertainty projects, APM provides greater flexibility and adaptive short delivery of project outputs. The 12 principles of the Agile Manifesto emphasize on satisfying customer needs, embracing changes, continuing delivery, collaborating, motivating and building trust, communicating, measuring progress and performance, developing sustainability, simplifying and maximising tasks, understanding requirements, and providing feedback (Highsmith 2001; PMI 2017). It is believed that APM is driven by the Agile mindset which is "defined by values, guided by principles and manifested through many different practices", and therefore, APM is selected and practised on the basis of needs identified by practitioners (PMI 2017, p. 10). The four Agile manifesto values covered in the Agile Practice Guide (PMI 2017, p. 97) are:

1. Individual and interactions over process and tools.
2. Working software over comprehensive documentation.
3. Customer collaboration over contract negotiation.
4. Responding to change over following a plan.

Benefits of APM are demonstrated in many scholarly publications (Kidd and Karwowski 1994; Nerur et al. 2005; Sherehiy et al. 2007; Fernandez and Fernandez 2008) including its ability to accommodate projects with extensive variability, highly-perceived product and service value and innovative delivery.

Regardless of the APM's benefits, not all project environments are suitable for the implementation of this approach. Chow and Cao (2008) mention the basic management dimensions for APM implementation to be suitable for most projects, i.e. organisational, people, process, technical and project. Furthermore, Agile projects are effectively managed with the presence of small organic teams, appropriate guidance from agile managers, light touch management and adaptive leadership (Augustine et al. 2005). Rigby et al. (2016) state that the APM approach is most suitable when it is implemented under the conditions of the software development including solving complex problems, solutions to the problems remain unknown, constant changing of requirements and demanding for collaboration. Furthermore, they identify unfavourable conditions for APM implementation including predictable and stable market conditions, unwilling/inadequate customer's collaboration, the existence of clear solutions, no innovation, impermissible changes, and catastrophic impact of interim mistakes.

3 Research Methodology

To understand the barriers to the APM implementation, this research was conducted in two stages using the Analytic Hierarchy Process (AHP) as a primary data analysis technique. The demonstration of data analysis with AHP is shown in the Data Analysis section. In the first stage of the research, barriers to agile implementation, as evaluation criteria, were identified using literature review, and validated and finalised by the panel of experts. The agreed barriers were organised into four categories of agile manifesto values. The second stage, 10 project management practitioners and academics working in Australian projects were invited to analyse and rank the barriers to agile implementation using the pairwise comparisons as part of the AHP method.

4 Data Analysis

The Analytic Hierarchy Process (AHP) was employed as an analysis technique in this research. The AHP analysis is conducted using pairwise comparison and expert judgement to develop decision through the priority scales for intangibles in relative terms (Saaty 2008). The AHP provides a structural decomposition to a complex problem with a multi-level of criteria and decision alternatives through the following steps (Thanki et al. 2016, p. 287):

- Define the problem and determine the objectives
- Development of the hierarchical structure from objective through the intermediate levels and the lowest level
- Employ pair-wise comparison matrices for each of the lower levels
- Undertake the consistency test
- Estimate the relative weighting of the component at each level.

The pairwise comparisons using expert judgement are made using Saaty scale from 1 to 9. The scale of 1 represents two alternatives/criteria/sub-criteria with equal contribution to the objective, and 9 is the most important of an alternative/a criteria over another affirmed on the highest possible order, are used to determine the level of importance in the pairwise comparison (Saaty 2008; Thanki et al. 2016). To develop a decision hierarchy of APM barriers existing in the Australian project environments, two consecutive stages were conducted. In the first stage, a group of three APM experts was formed to identify and finalise the barriers to APM implementation from their professional perspectives. The identified barriers were grouped under the four Agile manifesto values as shown in Table 1 to demonstrate the impediments to satisfactorily achieving the values. The pairwise comparisons for evaluating the importance of the Agile manifesto values were included in the first stage.

In the second stage, the hierarchical structure was developed using the expert's view performed in the first stage. The structure consists of 3 different levels as shown in Fig. 1.

Table 1 Identification of barriers to APM implementation

Agile manifesto value	SI no.	Barriers to APM implementation
Individual and interaction over processes and tools (I)	1	Lack of communication (I1)
	2	Low commitment (I2)
	3	Poor implementation skills (I3)
	4	Unclear authority/accountability (I4)
Working software over comprehensive documentation (W)	5	Inefficient systems (W1)
	6	Shortage of process assets (W2)
	7	Low maturity of processes (W3)
Customer collaboration over contract negotiation (C)	8	Lack of leadership (C1)
	9	Inadequate support (C2)
	10	Low interest/motivation (C3)
	11	No collaborative strategy (C4)
Responding to change over following plan (R)	12	Ineffective decision making (R1)
	13	Absence of APM mindset (R2)
	14	Poor change management strategies (R3)
	15	High resistance to change (R4)

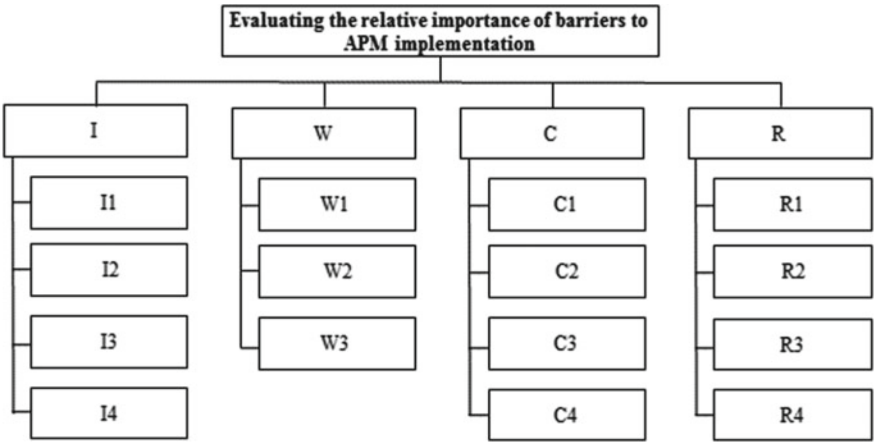

Fig. 1 AHP model to evaluate the relative importance of APM barriers

As per Fig. 1, the AHP model consists of three levels: Goal, Criteria (4 agile values) and Sub-criteria (15 APM barriers). In this stage, 10 APM practitioners working in Australian projects were invited to analyse and rank the identified barriers to APM implementation using a pairwise comparison matrix for each related category of the Agile manifesto values. To obtain the overall rank of barriers to the APM implementation, all results of the pairwise comparison were transferred to the final matrix with the presented relative weights of the values.

5 Research Findings and Discussion

The pairwise comparison metrics were constructed in Tables 2, 3, 4, 5 and 6 to demonstrate the relative weights of the Agile manifesto values and the barriers to APM implementation from Australian perspectives. As shown in Table 2, the most relative importance of the Agile manifesto values was reported to be "Customer collaboration over contract negotiation (C)", followed by "Individual and interaction over processes and tools (I)", with the relative weights of 0.394 and 0.287, respectively.

The results of pairwise comparison for "Individual and interaction over processes and tools" as in Table 3 showed that the "Lack of communication (I1)" and "Unclear

Table 2 Relative weights of the agile manifesto values

Agile manifesto value	I	W	C	R	Relative weight	Rank
I	1	3	1	1	0.287	2
W	1/3	1	1/3	1/3	0.096	4
C	1	3	1	3	0.394	1
R	1	3	3	1	0.223	3

Table 3 Pairwise comparison matrix for "individual and interaction over processes and tools"

Barriers	I1	I2	I3	I4	Relative weight	Rank
I1	1	2	6	6	0.559	1
I2	1/2	1	4	1/3	0.142	3
I3	1/6	1/4	1	1/6	0.046	4
I4	1/6	3	6	1	0.253	2

Table 4 Pairwise comparison matrix for "working software over comprehensive documentation"

Barriers	W1	W2	W3	Relative weight	Rank
W1	1	2	2	0.493	1
W2	1/2	1	2	0.311	2
W3	1/2	1/2	1	0.196	3

Table 5 Pairwise comparison matrix for "customer collaboration over contract negotiation"

Barriers	C1	C2	C3	C4	Relative weight	Rank
C1	1	2	4	3	0.458	1
C2	1/2	1	3	2	0.278	2
C3	1/4	1/3	1	3	0.159	3
C4	1/3	1/2	1/3	1	0.105	4

Table 6 Pairwise comparison matrix for "responding to change over following plan"

Barriers	R1	R2	R3	R4	Relative weight	Rank
R1	1	3	4	5	0.542	1
R2	1/3	1	2	4	0.247	2
R3	1/4	1/2	1	2	0.134	3
R4	1/5	1/4	1/2	1	0.077	4

authority/accountability (I4)" were the two most important barriers, with the relative weights of 0.559 and 0.253, respectively, to the APM implementation within individuals and interactions while executing projects. According to Freedman (2016), communication is amongst the skills required when performing APM. Communication, especially in a large team, encourages innovation and throughputs of the APM implementation. On the other hand, weak communication contributes to clear failure patterns of the implementation. Furthermore, PMI (2017) states that without unclear purpose or mission, working agreements, work assignments or work progress for the team can create the pain points in implementing APM.

The research analysis into "Working software over comprehensive documentation (W)", as shown in Table 4, found that "Inefficient systems (W1)" and "Shortage of process assets (W2)" with the relative importance of 0.493 and 0.311 were the most concerned barriers from the perspectives of software application within projects. According to PMI (2017), this Agile manifesto value covers the implementation of backlog presentation, backlog refinement, demonstrations/reviews and execution practices that help teams deliver value. It is believed that without appropriate and efficient systems as well as sufficient process assets, the implementation of APM to deliver the Agile manifesto value of "Working software over comprehensive documentation" can be impeded as the barriers identified lead inefficient and ineffective results in conveying information within the APM team (Wagenaar et al. 2018).

For the pairwise comparison of "Customer collaboration over contract negotiation (C)", this research found that "Lack of leadership (C1)" and "Inadequate support (C2)" were the most important factors impeding customer collaboration in projects. Their relative weights of these two barriers were 0.458 and 0.278 respectively (as in Table 5). According to Serrador and Pinto (2015), APM requires early and continuous involvement of project customers to attain satisfactory outcomes. Leading and sustaining customer engagement, therefore, is crucial for the success of APM implementation. Furthermore, leadership skills are strongly required not only to resolve multiple and conflicting perspectives in the stage of project conceptualization, but also to affirm the value of outcomes with project customers at this early stage (Fuentes et al. 2019). Chau and Maurer (2004) emphasize the role of adaptive leadership to facilitate the APM implementation process, remove impediments, and motivate Agile teams.

The last matrix of the pairwise comparison reports the relative importance of "Responding to change over following plan (R)". As shown in Table 6, it was discovered that the two most important barriers related to change responses impeding the implementation of APM were “Ineffective decision making (R1)” and “Absence of APM mindset (R2)” with the relative weights of 0.542 and 0.247 respectively. APM is an approach that helps to overcome limitations of TPM in dynamic environments with changing requirements and technology disruptions that require fast-learning and focusing on long-term outcomes (Bergmann and Karwowski 2019). As the APM implementation attempts constantly on updating project works, and focusing on rapid product development, agile teams require low hierarchies and effective decisions (Stare 2013). Furthermore, it is stated that how project teams deliver outputs or outcomes as well as respond quickly and transparently are associated with the adoption of an agile mindset (PMI 2017).

Further analysis was conducted using the overall weights and the overall ranks to identify the most critical barriers to the APM implementation from all four categories (I-W-C-R) of barriers identified in this research (see Table 7). From the 15 barriers, “Lack of leadership (C1)” was the most important barriers to the APM implementation followed by “Lack of communication (I1)” and “Ineffective decision making (R1)” with the overall weights of 0.181, 0.160 and 0.121 respectively. Noticeably, the combined weights of these top three barriers were 0.462, which carried nearly half of the overall weights presented in Table 7.

6 Conclusion

Although benefits of the Agile Project Management (APM) implementation have been addressed in many scholar works included in this research, barriers to the implementation can result in lower achievement and attraction in uptaking the APM approach. This research identified 15 barriers to the APM implementation from the perspectives of Australian project management practitioners. The identified barriers were grouped according to the four values of the agile manifesto. The research analysis using the Analytic Hierarchy Process (AHP) allowed the collected data to be examined and the degrees of the relative importance of the identified barriers to be ranked.

The research findings revealed that in each category of the Agile manifesto values, 1–2 prominent barriers were identified as they carried the highest relative weights within the categories. To evaluate the relative importance of barriers to the APM implementation from a holistic perspective, the AHP was employed further to develop overall relative weights and ranking for all studied barriers. The research results urge further investigation via the industry-specific lenses into the top barriers (such as “Lack of leadership”, “Lack of communication”, “Ineffective decision making”, “Inadequate support” and “Unclear authority/accountability”) and development of appropriate strategies to overcome the barriers before implementing the APM.

Table 7 Overall ranking of barriers to the APM implementation

Agile manifesto value	Relative weight	Barriers to APM implementation	Relative weight	Relative rank	Overall weight	Overall rank
Individual and interaction over processes and tools (I)	0.287	(I1) Lack of communication	0.559	1	0.160	2
		(I2) Low commitment	0.142	3	0.041	9
		(I3) Poor implementation skills	0.046	4	0.013	15
		(I4) Unclear authority/accountability	0.253	2	0.072	5
Working software over comprehensive documentation (W)	0.096	(W1) Inefficient systems	0.493	1	0.047	8
		(W2) Shortage of process assets	0.311	2	0.030	11
		(W3) Low maturity of processes	0.196	3	0.019	13
Customer collaboration over contract negotiation (C)	0.394	(C1) Lack of leadership	0.458	1	0.181	1
		(C2) Inadequate support	0.278	2	0.110	4
		(C3) Low interest/motivation	0.159	3	0.063	6
		(C4) No collaborative strategy	0.105	4	0.041	10
Responding to change over following plan (R)	0.223	(R1) Ineffective decision making	0.542	1	0.121	3
		(R2) Absence of APM mindset	0.247	2	0.055	7
		(R3) Poor change management strategies	0.134	3	0.030	12
		(R4) High resistance to change	0.077	4	0.017	14

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Investigating the Association Between Project Portfolio Management Office Functions and Project Success: An Australian Case Study

Nick Hadjinicolaou, Jantanee Dumrak and Sherif Mostafa

Abstract The functions of Project Portfolio Management Offices (P*f*MOs) support not only implementation of organizational strategic management and investment decisions but also ensure that organizational benefits are realized and successfully delivered by projects and programs. Nevertheless, the association between P*f*MO functions and project success remain under-researched. The aims of this research are to address P*f*MO functions commonly performed and review magnitude of the functions from Australian perspectives. Furthermore, the research significantly focuses on the association between P*f*MO functions and project success. The research data collection was conducted using questionnaire survey with 27 senior project and portfolio management professionals working in 6 Australian sectors. The relationships of 52 P*f*MO functions were cross-examined against 8 project success criteria using a statistical correlation analysis. The significance of P*f*MO functions in project success is highlighted. The correlation findings reveal diverse combinations of relationships between P*f*MO functions and project success in differing Australian sectors. Further discussion is provided for specific sectors to achieve higher performance of P*f*MO functions.

Keywords Project portfolio management · Project portfolio management office · Project success

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_24

1 Introduction

The area of project portfolio management has increased in popularity over the last decade in both organizations and academia. It is generally considered as the best improvement in project management since the development of methods in the 1950s (Petrinska-Labudovikj 2014). Several recent studies, including the work of Guo and Yu (2013), have investigated the necessity of project portfolio management (PPM).

A portfolio management office (P*f*MO) is a standardization of management structure that incorporates processes used in the portfolio-related governance. P*f*MO aims to facilitate shared resources, methodologies, tools and techniques between projects. A group within an organization is set up to perform functions to assist the management and support of portfolios (PMI 2013b). According to Milosevic et al. (2007, p. 20), portfolio management process undertaken by a P*f*MO is "a process utilized to evaluate, prioritize, select and resource new ideas that best contribute to the attainment of the strategic objectives of an organization".

It is important to realize benefit factors created by a P*f*MO including ongoing communications, simplification of the structure and ongoing monitoring of performance. The levels of performance can be increased through: the prioritization of PPM functions, clarity of the mission, and use of consistent terminology and ongoing education to improve maturity of both the organization and P*f*MO (Hadjinicolaou and Dumrak 2017). This research aims to investigate the association between P*f*MO and project success with the focus on the views of senior management from differing sectors in Australia. This paper is structured in five sections. The next section provides a review of literature on the relation between project success and project portfolio management (PPM).

2 Project Success in Project Portfolio Management (PPM)

A key component of PPM is the decision-making process required for the selection of projects, which is used as a means to align projects with strategy (PMI 2017; Cooper et al. 2001; Levine 2005). PPM focuses on the alignment of organizational goals and objectives with planned investments in projects by measuring, ranking and prioritizing investments in these shared organizational resources (PMI 2013b) to achieve project success. Furthermore, researchers have increasingly measured success by examining the impact of projects on the organization rather than only the success at meeting the triple constraints. Voss and Kock (2013) state that overall business success, average project success, future preparedness, the use of synergies, strategic fit and the balance of the portfolio can be used to evaluate PPM's success.

Measuring project success, according to Thomas et al. (2008), may not be simply translated and implemented. Shenhar and Dvir (2007) introduce a five-dimensional model that uses different time-scales for assessing project success. The model suggests that project success in relation to project efficiency and team satisfaction is to be measured at the end of project implementation while the impact on the project customer is to be measured months following the project. Business success and preparing for the future are the last two success dimensions which are to be measured years following the project. From the time-scale measurement of the model, it can be said that the project success factors, apart from the triple constraints (scope, time, and budget), also includes team and customer satisfaction, business success and preparing for the future.

According to the PMI (2013a), the improvement of project outcomes is a result of performing the most effective decision making. *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)*, is one example of a formal decision-making framework, provides a formal, methodical approach including: (1) Problem definition, (2) Problem solution definition, (3) Ideas to action (4) Solution evaluation planning and (5) Evaluation of the outcome and process. The benefits of this five-step process and other models of this type are that the process is defined and, if followed, it can bring about consistency in the decision-making process. In terms of project selection decisions within PPM, several factors need to be considered to align projects with organizational strategy and other aspects including financial and risk considerations. Furthermore, the timeliness and data required for a decision, together with the time frame in which a decision will be revisited, all require consideration. As stated in Al-Arabi and Al-Sadeq (2008), the key roles of the P*f*MO are as an ongoing project center of excellence to oversee project execution and control from a multiple-project perspective and a shared resources orientation.

3 Functions of Portfolio Management Office (P*f*MO)

Some organizations have used P*f*MOs to overcome some of the challenges identified by Elonen and Artto (2003). Furthermore, the use of P*f*MO has been extended to provide support, standardize project-related governance and processes, and facilitate the sharing of resources, methodologies, tools and techniques for projects (PMI 2013b). Unger et al. (2012) quantitatively analyze P*f*MOs in 278 portfolios with the focus on the quality of project portfolio management (PPM) in three different activity patterns interpreted as the distinctive roles of coordinator, controller and supporter. A cross-industry samples of firms from Europe, North America and Asia were collected. The findings showed a significant positive effect of P*f*MOs' coordinating and controlling roles on performance in terms of PPM quality.

Many literature works (Meskendahl 2010; Heising 2012; Voss 2012; Beringer et al. 2013; Doloi and Baradari 2013; Jonas et al. 2013; Teller and Kock 2013; Teller 2013) focus on the success of PPM in terms of its components, such as project delivery, risk management, portfolio stakeholders and quality management. However, one area that has not been fully explored is that of the relationships between portfolio management practices, portfolio management offices (P*f*MOs) and project success. Building on the previous works of Hobbs and Aubry (2007) and Pinto et al. (2010), this research adopted the 27 functions (see Table 1 for F1 to F27). Furthermore,

Table 1 P*f*MO functions

Portfolio management office functions	
F1	Report project status to upper management
F2	Develop and implement a standard methodology
F3	Monitor and control of project performance
F4	Develop competency of personnel, including training
F5	Implement and operate a project information system
F6	Provide advice to upper management
F7	Coordinate between projects
F8	Develop and maintain a project scoreboard
F9	Promote project management in organisation
F10	Monitor and control performance of PMO
F11	Participate in strategic planning
F12	Provide mentoring for project managers
F13	Manage one or more portfolios
F14	Identify, select and prioritise new projects
F15	Manage project documentation archives
F16	Manage one or more programs
F17	Conduct project audits
F18	Management of customer interfaces
F19	Provide a set of tools without an effort to standardise
F20	Execute specialised tasks for project managers
F21	Allocate resources between projects
F22	Conduct post-project reviews
F23	Implement and manage database of lessons learned
F24	Implement and manage risk database
F25	Benefits management
F26	Networking and environmental scanning
F27	Recruit, select, evaluate and determine salaries for project managers (PMs)
F28	Assist with business case development and review
F29	Manage portfolio dependencies
F30	Set up project portfolio systems and software
F31	Assist with the categorisation and prioritisation of projects within the portfolio
F32	Track the portfolio benefits
F33	Maintain the project portfolio inventory
F34	Perform project portfolio analysis
F35	Perform project portfolio planning
F36	Manage the tracking of project portfolio resources

(continued)

Table 1 (continued)

Portfolio management office functions	
F37	Track the alignment of projects with strategy
F38	Manage the optimisation of the portfolio
F39	Define and maintain project portfolio policies and frameworks
F40	Provide project portfolio reporting
F41	Negotiate and coordinate enterprise resources
F42	Identify and manage portfolio risks
F43	Identify and manage portfolio issues
F44	Conduct and manage portfolio communications
F45	Develop and improve portfolio templates and checklists
F46	Monitor compliance to portfolio policies
F47	Provide project portfolio knowledge management
F48	Manage the operations of systems that provide portfolio management
F49	Manage portfolio stakeholders
F50	Directly manage projects within the portfolio
F51	Conduct training in portfolio management skills and tools
F52	Manage and support project portfolio software

the P*f*MO functions are explored in detail in the 3rd edition of PMI's Standard for Portfolio Management (PMI 2013b). The additional 25 functions were previously omitted as there had not been identified in the work of Hobbs and Aubry (2007) were include (see Table 1 for F28 to F52).

4 Research Methodology

This research was to answer if there was an association between project success and P*f*MO functions. The research data collection, with an online link, was promoted to potential participants via LinkedIn Australia and national project management conferences to undertake the research questionnaire survey. At the ending period of data collection, 64 questionnaires were found completed. A screening process was applied to ensure that only respondents whose positions equivalent to the senior PPM level with more than 2 years of experience in PPM were included in this research. The screening result showed that 27 senior project portfolio practitioners in Australia met the established criteria for this early stage of an exploratory research. Both descriptive and correlation statistics from the collected questionnaire survey presented in this research were performed using the Statistical Product and Service Solutions (SPSS).

The analysis of the association between P*f*MO functions and project success was conducted using a correlation analysis. The results of the association between the factors were described according to Pallant (2013) as when correlation coefficient

(r) values are between ±0.10 to 0.29, ±0.3 to 0.49 and ±0.5 to 1.00, they indicate no relationship to a weak relationship, a moderate level of relationship and strong relationship respectively.

5 Research Findings

The descriptive statistics was conducted to provide general demographic information of the research respondents and their sectors (as shown in Table 1). It was found that 27 senior practitioners participated in this research were from 6 different sectors. The majority worked in the government and IT and telecommunication sectors (23%) followed by the education (18%) and energy and utilities (14%) sectors. Furthermore, the descriptive results showed equal participation of 22% from the top management, senior project manager and program manager positions followed by the senior project officer and portfolio manager positions of 17% equally (Table 2).

The research found that the 52 identified P*f*MO functions can be grouped into 7 possible categories according to their contribution areas as seen in Table 3. The most functions were associated to the management and implementation areas of P*f*MO followed by the support area with "Allocate/Provide". On the other hand,

Table 2 Research respondents by industry sector and position (%)

Industry sector	% of respondents	Position	% of respondents
Banking	9	Portfolio manager	17
Construction	13	Program manager	22
Education	18	Senior project manager	22
Energy and utilities	14	Senior project officer	17
Government	23	Top management e.g. CEO and general manager	22
IT and telecommunication	23		

Table 3 A summary of functions by keywords

Keyword of function	Function
Allocate/provide	6, 12, 19, 21, 28, 31, 40, 47
Develop	2, 4, 8, 45
Identify/define	14, 39, 42, 43
Implement/conduct/execute/perform	5, 17, 20, 22, 24, 25, 26, 27, 30, 34, 35, 44, 51
Manage	13, 15, 16, 18, 25, 29, 36, 38, 44, 48, 49, 51, 52
Monitor and control	3, 10, 32, 33, 37, 46
Others (coordinate, negotiate, participate, promote, report)	7, 41, 11, 9, 1

the studied functions emphasized less on the "Coordinate, Negotiate, Participate, Promote, Report" area.

The results of Spearman's Rho (r) for the correlation analysis between the P*f*MO functions and project success are presented in Table 4. It can be seen that not all of the functions were associated to project success. The function "Provide a set of tools without an effort to standardize" was the only function that showed its high correlations ($r = 0.574^{**}$, 0.468^{*}, 0.540^{**}, 0.633^{**}, 0.637^{**}, 0.560^{**} and 0.604^{**} respectively) with all studied dimensions of project success—SC1: Completion on time, SC: Completion on budget, SC3: Delivery of agreed specifications, SC4: Team satisfaction, SC5: Stakeholder satisfaction, SC6: Delivery of business success and SC7: Preparation for future business growth. Additionally, 6 P*f*MO functions were also found accountable for most of project success dimensions including F3, F8, F12, F17, F18 and F23 with high correlations to the project success.

Nevertheless, the research also discovered 11 P*f*MO functions that contained no association with project success. These functions were F31, F33-35, F38, F40-45

Table 4 Spearman's Rho correlation of P*f*MO functions and project success

	SC1	SC2	SC3	SC4	SC5	SC6	SC7
F1	–	–	0.450^{*}	0.421^{*}	0.602^{**}	0.457^{*}	0.549^{**}
F2	0.406^{*}	–	0.438^{*}	0.419^{*}	0.434^{*}	–	0.465^{*}
F3	0.399^{*}	–	0.422^{*}	0.415^{*}	0.490^{*}	0.477^{*}	0.585^{**}
F4	–	–	–	0.452^{*}	–	–	–
F5	–	–	–	0.410^{*}	0.521^{**}	–	–
F6	0.452^{*}	–	0.435^{*}	–	0.460^{*}	–	0.485^{*}
F7	–	–	0.423^{*}	0.529^{**}	0.526^{**}	0.478^{*}	0.404^{*}
F8	0.449^{*}	–	0.539^{**}	0.662^{**}	0.623^{**}	0.428^{*}	0.586^{**}
F9	–	–	0.450^{*}	0.505^{*}	0.497^{*}	–	0.523^{**}
F10	–	–	–	0.484^{*}	0.422^{*}	–	0.408^{*}
F11	–	–	0.421^{*}	–	0.453^{*}	–	0.465^{*}
F12	0.414^{*}	–	0.654^{**}	0.515^{*}	0.681^{**}	0.532^{**}	$.631^{**}$
F13	–	–	0.543^{*}	0.643^{**}	0.589^{**}	0.528^{*}	0.567^{**}
F14	–	–	–	–	0.541^{**}	–	0.452^{*}
F15	–	–	0.463^{*}	0.734^{**}	0.424^{*}	–	0.448^{*}
F16	–	–	0.483^{*}	0.473^{*}	–	–	–
F17	0.486^{*}	–	0.615^{**}	0.623^{**}	0.663^{**}	0.653^{**}	0.506^{*}
F18	0.504^{*}	–	0.797^{**}	0.729^{**}	0.651^{**}	0.534^{*}	0.714^{**}
F19	0.574^{**}	0.468^{*}	0.540^{**}	0.633^{**}	0.637^{**}	0.560^{**}	0.604^{**}
F20	–	–	0.561^{*}	0.645^{**}	0.583^{**}	0.541^{*}	0.608^{**}
F21	–	–	0.637^{**}	0.618^{**}	0.554^{*}	–	0.556^{*}

(continued)

Table 4 (continued)

	SC1	SC2	SC3	SC4	SC5	SC6	SC7
F22	–	–	0.435*	0.498*	0.423*	0.647**	0.443*
F23	0.532*	–	0.577**	0.641**	0.552**	0.466*	0.488*
F24	0.451*	–	0.559**	0.622**	0.498*	–	0.467*
F25	–	–	0.475*	0.635**	0.483*	–	–
F26	–	–	0.521*	0.561*	0.608**	–	–
F27	–	–	–	–	0.649**	–	–
F28	–	0.476*	–	–	–	0.455*	–
F29	–	–	–	0.486*	–	–	–
F30	–	–	–	0.454*	–	–	–
F32	–	–	0.451*	0.470*	–	–	–
F36	–	–	–	0.595**	0.525*	–	–
F37	–	–	0.600**	0.456*	0.546*	–	0.461*
F39	–	–	–	0.525*	–	–	–
F46	–	–	0.471*	0.634**	0.535*	–	–
F47	–	–	–	0.488*	–	–	–
F48	–	–	–	0.522*	–	–	–
F49	–	–	–	0.507*	0.472*	–	–
F51	–	–	–	0.629**	–	–	–
F52	–	–	–	0.557*	0.610**	–	–

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

and F50. The summary of all studied associations between the P*f*MO functions and project success are demonstrated in Table 5.

From Table 5, a cross-examination was conducted to count the number of connections between the P*f*MO functions in 7 areas and the project success dimensions. The results showed that SC4: Team satisfaction was the project success dimension that associated the most number of connections (36 connections), followed by SC5: Stakeholder satisfaction (30 connections), SC3: Delivery of agreed specifications (25 connections) and SC7: Preparation for future business growth (21 connections). On the other hand, SC2: Completion on budget, SC1: Completion on time and SC6: Delivery of business success were found with the least project success dimension associated to the P*f*MO functions with 2, 9 and 12 connections counted respectively. From the functions area perspectives, the percentage of connections calculated from the possible connections between the number of P*f*MO functions and the project success dimensions revealed that the areas of "Others (Coordinate, Participate, Promote, Report)", "Associate, Provide", "Develop", "Monitor and Control" and "Implement, Conduct, Execute, Perform" showed the highest percentages of counted connections (60.72%, 57.14%, 57.14%, 51.43% and 45.71% respectively). On the other hand,

Table 5 A summary of P*f*MO functions, function areas and project success

Key area of function	F	Project success						
		SC1	SC2	SC3	SC4	SC5	SC6	SC7
Allocate, provide	6	✓		✓		✓		✓
	12	✓		✓	✓	✓	✓	✓
	19	✓	✓	✓	✓	✓	✓	✓
	21			✓	✓	✓		✓
	28		✓				✓	
	47				✓			
Develop	2	✓		✓	✓	✓		✓
	4				✓			
	8	✓		✓	✓	✓	✓	✓
Identify, define	14					✓		✓
	39				✓			
Implement, conduct, execute, perform	5				✓	✓		
	17	✓		✓	✓	✓	✓	✓
	20			✓	✓	✓	✓	✓
	22			✓	✓	✓	✓	✓
	24	✓		✓	✓	✓		✓
	25			✓	✓	✓		
	26			✓	✓	✓		
	27					✓		
	30				✓			
	51				✓			
Manage	13			✓	✓	✓	✓	✓
	15			✓	✓	✓		✓
	16			✓	✓			
	18	✓		✓	✓	✓	✓	✓
	25			✓	✓	✓		
	29				✓			
	36				✓	✓		
	48				✓			
	49				✓	✓		
	51				✓			
	52				✓	✓		
Monitor and control	3	✓		✓	✓	✓	✓	✓
	10				✓	✓		✓
	32			✓	✓			

(continued)

Table 5 (continued)

Key area of function	F	Project success						
		SC1	SC2	SC3	SC4	SC5	SC6	SC7
	37			✓	✓	✓		✓
	46			✓	✓	✓		
Others (coordinate, participate, promote, report)	7			✓	✓	✓	✓	✓
	11			✓		✓		✓
	9			✓	✓	✓		✓
	1			✓	✓	✓	✓	✓

the area of "Identify, Define" showed the least percentage of counted connections between the P*f*MO area of functions and the project success dimensions. Furthermore, the area of "Manage" which contained the most possible connections (77) was the second last with 37.66% of counted connections reported.

6 Conclusion

This research aimed to investigate the association between the P*f*MO functions and project success from Australian perspectives. The research identified 52 functions of P*f*MO using the scholarly publications and discovered that not all of the P*f*MO functions were associated to the studied dimensions of project success. Furthermore, the research also discovered that the numbers of counted connections between the areas of functions and the project success dimensions were varied. It was revealed that the areas with the highest possible connections did not attain the highest percentages of connections developed. The research findings suggest further studies to be carried to gain more understanding of the missing or weak connections between the identified P*f*MO functions, the function areas and project success dimension. This research can be used to develop or improve any possible strength of associations that enhance the benefits of the P*f*MO functions for the identified project success dimension. However, it needs to be noted that only the 27 research respondents participated in this research through the research questionnaire were the senior practitioners who had extensive years of experience working for the Australian public and private sectors. Therefore, it is recommended for future research to be undertaken in order to gain broader understanding on the association between P*f*MO and project success at multiple levels.

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Bridging Strategic Project Planning with Tactical Planning in the Design Process

Kai Haakon Kristensen and Bo Terje Kalsaas

Abstract The paper studies the issue of bridging strategic planning with tactical/operative planning in the design process of complex AEC-projects. The paper present user-friendly planning methods on a tactical level which gives the planner intuitive control over dependent, independent, and interdependent tasks during the design process. In our understanding the planning process starts at the strategic level using integrated milestones as a prerequisite for handling progress and strategic coordination in projects. Moving forward in the planning process towards the operative level, the process requires flexible and agile methods which ensures robustness in the various plans that must be made. In this paper we will address the design phases between front-end planning and project execution. The design science research approach is applied. The paper adds to the body of knowledge practical methods and tools suited for efficient planning of the design process. Our study contributes both to theory and practice regarding development of tactical planning in the design processes.

Keywords Design · Control · Milestones · Planning

1 Introduction

The appropriate phase for mastering the strategies of the client's business plan and the subsequent strategy for the building project is the front-end phase of a project, as defined by Williams et al. (2009). They further specify this stage as prior to the inception of the scheme design. Defining the strategy is a prerequisite for a successful project, and the subsequent planning of integrated milestones as described by Kalsaas and Kristensen (2018). Our contribution in this paper is the natural extension of the

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_25

strategic planning and the necessary translation between the strategic and the tactical level.

Kalsaas and Kristensen (2018) argue that the method of describing the project's integrated milestones and connecting them in networks, will ensure the proper bridge between strategy and the starting point for all other activities. Descriptions on how to proceed efficiently and effectively into the tactical level of planning ensuring the proper information between all involved stakeholders is vaguely described in literature. As noted by Grey and Hughes (2006), the strategic plans at the front-end should gradually be refined until the point of the inception of the scheme phase of design. When the scheme stage is reached, the planning becomes more and more detailed 'and should include every significant interaction between all designers, including every works and specialist contractor'. Grey and Hughes (2006) end their overall description of planning by discussing the finest level of planning with the requirements of a schedule for all drawings to be produced by each designer with the link to other stakeholders.

Our aim in the paper is to bridge strategic milestone planning for design (Kalsaas and Kristensen 2018) and tactical/operative management of design. With this we will create an artefact as in design science research, which is addressed below.

In the first section below, after the method section, we highlight some findings from a case study to verify examples of challenges in design management. Thereafter we conceptualize how to understand the design processes and sum up the challenges to be handled in methods for tactical planning and control in design. From there we offer an overview of related current methods and tools before we present and discuss our proposed method for bridging the gap between strategic and tactical/operative design management.

2 Method

Design science research (DSR) has been applied as the methodical framework, as it is aimed at developing a solution to a problem with practical and theoretical relevance (March and Smith 1995; Koskela 2008). Hevner et al. (2004, p. 82) argue that the fundamental principle of DSR states 'that knowledge and understanding of a design problem and its solution are acquired in the building and application of an artefact', a process from which they derive seven guidelines: (1) design as artefact; (2) problem relevance; (3) design evaluation; (4) research contribution; (5) research rigor; (6) design as search process; (7) research communication.

This paper is primarily based on the first two guidelines of DSR. An innovative, purposeful artefact (1) is constructed based on theory and data from a case study. Problem relevance (2) is based on findings from the case study. Evaluation (3) will be developed through future research. Moreover, the study takes up novelty in research contributions (4) in terms of how it might solve a familiar problem more effectively.

3 Call for Improved Structure in Design Management

Fisher et al. (2017) argue for the importance of integrating several aspects of construction to succeed in the delivery of high-performance buildings, which include integrated organization and processes. Kalsaas (2019) reports from a case study of the detailed design of a high school organized as a lean project delivery. This example can be regarded as an example of a call for the importance of a well-designed structure as a backdrop for operative design planning and control. The findings include the following causes to a design process characterised by the author (op cit.) as "muddling through":

- Late changes to the building method
- Late contracting of suppliers of building parts where the supplier is responsible for design
- Weak integration between design and production
- Limited interaction between the designers and the client
- No systematic attempt to manage gradual maturity in design
- No clear strategy for change management
- Limited success to coordinate reciprocal interdependencies
- Design planning was to a high degree attempted to be conducted on the general contractor's terms and to a lesser degree on the Mechanical, Electric and Plumbing (MEP) contractor's terms
- Work tasks with corresponding deliverables were often imprecisely specified
- Lack of consistent structure for communicating within the design team

However challenges in the design processes, the BREEAM certified building project wins prizes and reaps praise as an excellent environmental project, and the client appears to be satisfied with the final delivery. Hence, this case appears to not be an example that supports Samset's (1998) findings and arguments addressed in the introduction. The case is more an example of, even for on-the-surface quite successful project deliveries, there might be a big potential for improving and integrating processes which will benefit all parties, also the customer value, to a lower cost and a larger profit.

4 Understanding the Challenges in Design

The design process is in its nature a problem-solving effort in order of transforming a Client's requirement and needs into sets of conceptual production material (drawings, 3D models, schemes etc.) needed to construct the physical building. The core of design lies in a structured analysis of a problem, and at some point, creativity is the key to solve the problem. The general problem-solving is in its simplest interpretation a conscious selection of standard solutions which attempts to meet the Client's needs. The real problem lies in the following hypothesis based on the works of Conklin and

Weil (1998): "A definite problem has several sets of definite solutions. An unclear problem has no definite solution, but merely sets of possible solutions in need of further clarification of the problem." From this prospect, it seems natural to address the iterative problem-solving process in the outline design phase as a prolongation of the front-end phase. The first potential and embedded challenge which needs to be addressed is whether the problems to be solved could be wicked as described by i.e. Ritchey (1998) or considered a tame problem (Conklin and Weil 1998). A wicked problem has no best solution or natural stop. The design can always be improved by increasing the number of iterations. Whereas a tame problem is solved easily in the first run.

Design understood as a wicked problem can be associated with the Cynefin framework for understanding complexity (Snowden 2000) with its four domains: simple, complicated, complex and chaos. In the simple domain, cause and effect is well known and traditional planning and control techniques as Critical Path Method (CPM) works well. Cause and effect can be understood in the complicated domain as in design processes, while in the complex domain cause and effect can only be understood after the work is done. Cause and effect will thereby emerge over time. The complex domain is also relevant for design, where design is a wicked problem. A domain we should avoid for the design processes is the chaos domain, in which we for instance will fall into if we apply the traditional CPM to complicated and complex processes.

Thompson (1967) introduce the terms of pooled, sequential and reciprocal interdependencies. A reciprocal situation often occurs in the design work when different disciplines work on the same object, for example a building façade. The coordination method for handling reciprocal interdependency is denoted mutual adjustment which is best solved in face to face collaboration between the involved parties. Plan is the coordination method for sequential interdependencies and standardisation for pooled. When we deal with reciprocal issues there are also always sequential and pooled interdependencies present.

It is a lot of strong reciprocal interdependencies in design that needs to be managed by the method we propose below for bridging strategic and tactical/operative design management. Reciprocal interdependencies can be observed as iterations, which we associate to experimental learning circles (Kolb 1984). Furthermore, we associate learning circles to the phenomenon of gradual maturing in design, which need to be understood and handled in our artefact proposal. Our proposal is a call for creating spaces in construction projects for learning and continuous improvement.

4.1 Summary of Challenges to Be Managed in the Design Processes

Initial problems:

- The lack of proper generated information in the phase shift between the front-end and the design process
- The lack of collaborative environment and active use of cross functional teams, hence common understanding of the problem prior to deciding solutions.

Problem solving:

- The lack of the ability to separating tame problems from wicked ones
- The lack of tools, strategies and ability to treat different domains of complexity
- The lack of understanding the nature of wicked problems and interdependencies.

Design manager's responsibility of planning:

- The lack of knowledge and tools for pull-based scheduling and reducing the batch sizes of design tasks
- The lack of understanding of iteration as a powerful tool in design and at the same time treating iteration in respect of not generating waste.

The Client:

- The sometimes-volatile set of requirements and the absence of participation in the problem-solving efforts.

These issues could be explained in short as problems with the information flow, coordination and collaboration, a general lack of understanding the problems at hand, and finally a lack of understanding of which tools to use when in order to make progress.

5 Current Tactical Planning Tools

Our first mapping of current literature covered classical planning tools as Bar Charts (Grey and Hughes 2008) and Network analysis (Hamilton 2006). We continued with central tools from concurrent engineering and the lean community such as Design Structure Matrix (Eppinger 1997) and Last Planner System and ADepT (Ballard 2000) and DePlan (Choo et al. 2004). Our mapping of available tools covers the most basic tools which are described theoretically. Most projects implement at least some of these tools, but to our knowledge, projects still suffer from inadequate design planning and control. We found in our mapping presented that all these methods have both benefits and disadvantages. In general, the theoretical described benefits of these tools are their ability to facilitate control over identified tasks, control iterations and control the requirements of information exchange necessary to plan, schedule, execute and control the process. The described tools have one general disadvantage which every approach will suffer from; the risk of not being able to identify all design tasks or providing the necessary information needed in order of performing tasks (as described in Samset (1998)). Other disadvantages are described over the realm of quality control of the process and the difficulty of handling set-based design as premise for the planning and scheduling.

Our motivation for our proposal is to preserve the benefits and address the disadvantages in each mapped method. Our proposal will as well have benefits and suffer from disadvantages. However, our approach is based on a multilevel involvement of key designers, dispersing the responsibility for planning, scheduling and control, thus relieving the master planner for tedious planning on levels he/she probably do not master. Our approach will further identify—indirectly—the interdependent task and rely on its solving during regular meetings. The approach is quite simple and is presented below.

6 Approach to Develop Tactical Plans as a Start-Off Point for Operative Planning Methods

Our recommendations for bridging the strategic levels of the project with the necessary tools for the design process, based on our findings in both literature and praxis follows this list:

1. Initiate planning sessions for the design phase:
    a. Divide the design project into *themes* and assign responsibility for each *theme*
    b. Plan each *theme* in the appropriate detail using a reverse pull plan approach using *steps* as intermittent decision points and the output of work packages as the logical sequence of work to be done in each theme.
    c. Combine all *themes* in an activity plan and adjust the *themes* per duration, start- and end time, critical decisions, and meetings within the activity plan.

We will verify our proposal in the next section.

7 Verification: The Practical Example from KHiB

The collaborative planning effort (from KHiB as described in Statsbygg 2017) started with the development of integrated milestones for the entire project (see Kalsaas and Kristensen 2018). Table 1 presents an example of the information level present for all milestones. The network of milestones is not shown in this paper.

These plans resulted in a solid basis for developing detailed design, procurement plans and construction plans. What was observed at the inception of the design

Table 1 Examples of a Set of Integrated Milestones

#	Milestone	Input	Activity	Output	Due date
M1	Floor plans approved	Floor plans, Requirements	Assessment meetings	Approved plans	[Date xx.xx.xxxx]
M2	Freeze BIM	All requirements and M1	The design process in general	A complete model ready for tendering	[Date xx.xx.xxxx]
M3	Tender material approved	M2	Align all material	Tender material ready for tender	[Date xx.xx.xxxx]
M4	Equipment approved	All input form contractors	Assessment of products	Approved equipment	[Date xx.xx.xxxx]
M5	Shop drawings finished	M3, M4 + Info from contractors	Producing drawings, Quality work	Complete and approved shop drawings	[Date xx.xx.xxxx]
M6	Complete design delivery	All relevant information from the construction phase	Producing final drawings, descriptions, Quality work	A finalized set of design material to be used by facility management	[Date xx.xx.xxxx]
M7	Etc. etc.				[Date xx.xx.xxxx]

planning process was an extension of the milestone-driven planning process in combination with an intuitive decomposition of the project at hand—and not the classical activity-based division of the project per predefined and generic structures. The various design activities were divided in *themes* named after their most logic topics and dedicated to the actor best suited for the responsibility of each theme. The sum of all *themes* defined and constituted all activities within the design process (other plans were made for the other core processes).

An example of the theme "Door access control", is verified in Fig. 1. This is a topic which to our experience is conceived as complicated by the involved disciplines in the detailed design phase. The listed activities and requirements (1–10) in Fig. 1 are placed in the actor-week matrix, while the third dimension of decision/meeting type is indicated by different shading symbols. There are, for instance, scheduled meetings for mutual adjustment in week 2 and 6.

When all design themes are developed, the first activity-based plan for the design process is made, confer Fig. 2. The various themes are dispersed on the schedule by when each theme was rational to execute compared to each other. Alignment and adjustments can be performed by studying the plans according to variables as duration, the network of decisions, design meetings and steps. The final activity plan consists of the output from the planning of milestones on the strategic level and the detailed plans for each theme, resulting in a mature and clear activity plan on the tactical level. This forms the basis for performing the design process and application of other lean methods on the operational level (e.g. by applying agile

Activities/premises before Step 1
1. Principal Requirements from fire consultant must be present
2. Number system for doors must be finished
3. Design meeting focusing on the functions of the doors
4. The client/user must define the buildings security zones

Activities/premises before Step 2

5. Door schedule must be developed ready for population of data
6. Electrical engineer populates the door scheme

Activities/premises before the milestone

7. Design meeting
8. Quality work/finalizing of the door scheme
9. Final version of the door scheme
10. Clients Approval

Legend
- Steps and milestone
- Coordination meeting
- Decision point

Actor	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Steps and milestone			Step 1		Step 2			Milestone
Architect	2	3		5		7	8	9
Electrical consultant		3			6	7	8	9
Fire consultant	1	3				7	8	
Client/user			4					10
Main Contractor		3				7		

Fig. 1 The milestone plan for the themes “Access Control Doors”

Week #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Project brief	X														
Themes															
Structural			M/d		D										
Floor plans			M		M/d		M	D							
Ceilings							M	d	M	D					
Doors									M	d			M		D
HVAC					M	d	M		M		D				
Electrical					M	d	M		M			D			
Furniture											d				D

Fig. 2 Example of design activity plan. (M = Coordination meeting; d = intermittent decision; D = Concluding decision)

inspired methods), ensuring a proper production and control for the process as in Lean Design Management.

Intermittent decisions in Fig. 2 is designed to handle gradual maturity and iterations in design, which we also regard as learning milestones.

Observations by one of the authors from the design process at the KHiB-project indicate an astonishing level of easy flow of information and a low degree of waste within the design process. The intermittent results of design outputs were timely and had a low degree of flaws. The construction process was planned in detail applying *takt* as the primary planning method. The project reported being on time during the entire process. The project participants at the front-end pointed backward to the inception of the project and specifically on the development of the milestone chart as the "first of many right things to do".

8 Conclusion

A basic idea in the paper is to apply a process approach to create tactical/operative activity plans for the stage between the front-end and the construction phase of the project. Our focus in this paper has been on the design process, but the method is applicable to all core processes as well.

Based on strategic project and production management theory, design management theory and examples from practice, we propose a new approach to develop robust activity plans for planning and production control in the design phase. The activity plans will render the planner intuitive control over dependent, independent, and interdependent tasks during the design process. In addition, the suggested approach will integrate the designers within the planning process, increasing the likelihood of consistent plans and anticipated progress.

The proposal is detailed in this paper has as other methods its benefits and disadvantages:

The benefits of our proposal: By distributing the responsibility for the planning of each team to the designers, we see a similarity to the praxis of involving the last planners. This leads to higher quality in the identified activities to enter the plans and a higher degree of integration amongst the different task and actors involved. The approach also represents a better chance of identifying all relevant tasks, since more people are engaged in the planning process. In addition to increased dedication to the plans, the level of monitoring and control increases. Interoperability issues and interdependent challenges are easily managed since the planning focus is on a collaborative level. All this is critical factors for a reliable and steady production of design deliverables.

The experienced disadvantages of our proposal: No direct disadvantages of this approach have been experienced so far. However, a few implementation issues have been registered and should be handled in the initiation of the planning process. These are:

- A new way of managing the planning process and subsequently changes the responsibility for planning, scheduling and control. This affects contractual issues and must be addressed here. Resistance and scepticism could be the unwanted effect if this is omitted from the contracts
- The planner must accept the distribution of the plans and the subsequent "loss of control over the details". A high level of trust amongst the planners is important and the main planner must incorporate action to achieve this.

The proposal is verified by documentation of the successful application in the design phase in a construction project. Moreover, verification by experienced challenges in another studied construction project is presented, which miss a robust structure for planning and control during its various phases. We argue that such problems can be sorted out with the envisaged method. However, necessary, but it is not sufficient to only rely on an efficient structure (as in tools and methods). A projects staff capacity, their knowledge of pertinent tools and implementation capability is of equal importance.

The proposal fills a gap in project management literature, which appear to address the bridge between the milestones of a project and the necessary robust activity plans in a shallow way, which is also the case for the presented theoretical background.

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Interactive Effects of Agile Response-to-Change and Project Complexity on Project Performance

Tuan Son Nguyen and Sherif Mohamed

Abstract Complexity is a critical factor in managing a project, as it presents an additional difficulty in achieving the project's objectives. As complexity makes a project more challenging to understand and keep under control, agile methodologies have been developed to enable increased flexibility and responsiveness to changing conditions. Therefore, it is essential to empirically examine the moderating effect of project complexity on the relationship between agile response-to-change (AR) and project performance. To address this objective, a questionnaire was used to measure project complexity, project performance and AR. Structural equation modelling was used to explore the relationship between these variables. The results suggested that internal AR has a positive effect on budget performance. Project complexity appears to lower the relationship between internal AR and schedule performance. As one would expect, the higher the level of project complexity, the more likely the project is to experience delays.

Keywords Agile response-to-change · Project complexity · Project performance

1 Introduction

It is widely reported in the literature that many projects fail (Damoah and Akwei 2017). Many reasons can lead to project failure, and complexity is one such reason, as it creates difficulty in finishing projects and requires that more effort be devoted to overcoming challenges (Dao et al. 2016). Complex projects are susceptible to running over budget and behind schedule (Lu et al. 2015; Bjorvatn and Wald 2018). Time and budget are two of the main criteria used to evaluate project performance (PMI 2008). Bosch-Rekveldt et al. (2011) found that project complexity negatively affects project performance in large engineering projects. Furthermore, Floricel et al. (2016)

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_26

found that complexity factors were correlated with a reduction in completion performance, where completion performance was measured as whether a project achieved its planned resource expenditures and deadlines. For instance, the 2A line metro project in Hanoi, Vietnam, began in 2011 and was scheduled to commence commercial operation in 2016, with an initial budget of about 550 million dollars. However, in early 2019, the project is still not operating commercially and is approximately 40% over budget (Kieu 2018).

To overcome the challenge of project complexity, many project management strategies have been proposed to mitigate the negative effect of complexity. AR is one of the practical strategies used to deal with complexity in projects. Agile methodologies were designed to enable greater flexibility and responsiveness to the changing conditions in a project to improve project performance (Fowler and Highsmith 2001). Agile methodologies are commonly applied for managing complex projects (Lappi and Aaltonen 2017). Moreover, Serrador and Pinto (2015) suggested that the higher the agile approach reported, the better the reported project performance.

The concept of AR and its effects on project performance have been discussed by Nguyen and Mohamed (2018b). However, little research has been undertaken to empirically examine the effect of AR and project complexity on quantitative project performance (time and cost). It remains unclear whether a project with a higher level of AR sustains its quantitative project performance under changing levels of project complexity. Therefore, this study aims to examine the interactive effects of AR and project complexity on project performance. It investigated the moderating effect of project complexity on the relationship between AR and project performance.

2 Literature Review and Hypothesis Development

This section presents the literature related to project performance, project complexity and AR. Following this, a conceptual framework and a set of hypotheses are proposed.

2.1 Project Performance

Indicators for project performance measurement are well established, and include time, budget and performance goals (Shenhar et al. 2001). The Project Management Body of Knowledge (PMBOK) refers to project performance with regard to time, cost, quality, scope and customer satisfaction (PMI 2008); commonly known as the ‘triple constraint’. Project performance is evaluated depending on achieving the project’s objectives within the constraints of time, cost, quality and other project achievement requirements (Ika 2009).

Project performance measurement indicators can be grouped into different components. Serrador and Pinto (2015) classified project performance indicators into two groups; namely, efficiency factors and stakeholder success factors. The efficiency factor indicators include project scope, time and budget. The stakeholder success factor indicators include project team satisfaction, end user satisfaction, client satisfaction and project success as evaluated by stakeholders. It can be seen that the stakeholder satisfaction indicators are separate from project time, budget and scope. However, the efficiency measurement indicators have both quantitative measurement items (time and cost) and qualitative project measurement items (project scope). Using both quantitative and qualitative project performance measurement indicators as one component may raise issues, since time and budget are precise criteria in comparison with project scope criteria. Consequently, project performance indicators can be classified into different components, such as quantitative project performance and qualitative project performance (Nguyen and Mohamed 2018a).

2.2 Project Complexity

In the context of complex projects, 'complexity' refers to 'the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonable complete information about the project system' (Vidal et al. 2011). In theoretical terms, project complexity depends on both the characteristics of the project and the capacity of project management teams to tackle the diverse factors that influence project outcomes (Nguyen et al. 2018). Since complexity refers to an intrinsic property of projects (Floricel et al. 2016), scholars have attempted to quantify and measure it (Vidal et al. 2011); and studies on project complexity have been undertaken for years (Aitken and Crawford 2007; Vidal et al. 2011; Dao et al. 2017). One of the primary project classification methods applied by institutions in the project management field (Bosch-Rekveldt et al. 2011) is the Crawford-Ishikura seven-factor table for evaluating roles (CIFTER) (GAPPS 2007).

Although complexity is an intrinsic property of a project (Floricel et al. 2016), the influence of complexity on project performance has not been extensively studied in empirical terms (Bjorvatn and Wald 2018). Bakhshi et al. (2016) stated that complexity is one of the most highly controversial topics in the management field. Project complexity has been reported as the main factor having a negative effect on project performance (Floricel et al. 2016; Luo et al. 2017). Project complexity negatively influences project success in complex construction projects (Luo et al. 2017). A negative statistical correlation between technical complexity and budget and schedule performance had been identified by Floricel et al. (2016). Project teams encounter a greater risk of running behind time and over budget as the number of internal and external project tasks increases.

3 Agile Response to Change

The concept of agile methodology was proposed by 17 experts in the USA in 2001; and is widely known as the 'Agile Manifesto' (Fowler and Highsmith 2001). Four foundation values of agile development were recommended in the Manifesto. These are: (i) 'Individuals and interactions over processes and tools'; (ii) 'Working software over comprehensive documentation'; (iii) 'Customer collaboration over contract negotiation'; and (iv) 'Responding to change over following a plan' (Fowler and Highsmith 2001).

Agile methods are commonly applied in technology projects (Lindvall et al. 2002) as they directly tackle the challenges associated with dynamic projects in rapidly changing environments (Serrador and Pinto 2015). The project management team's ability to respond to these difficulties plays an essential role in managing project success or failure (Park et al. 2017). AR is one of the critical components in the stakeholder management framework for mega construction projects (Park et al. 2017). Serrador and Pinto (2015) reported that the higher the agile method used, the better the project performance. In order to add to this discussion, the correlation between AR and project performance, particularly regarding budget and schedule, should be empirically studied.

4 Conceptual Model and Hypothesis Development

As discussed in the previous section, AR plays a critical role in the context of complex projects. Agile methodologies may have a positive effect on project performance; especially in preventing running over budget and behind schedule. However, project complexity is one of the sources that influence project performance. The positive effect of AR on project time and cost is more likely to be moderated by the complexity of the projects. Thus, the following hypotheses are proposed:

Hypothesis 1: AR has a positive effect on quantitative project performance.
Hypothesis 2: Project complexity lowers the positive correlation between AR and quantitative project performance.

Figure 1 depicts the research model.

5 Research Methodology

5.1 Construct Operationalisation

This study was a cross-sectional design study with quantitative research using survey questionnaire to gather data. Guided by the research model, in this study, three

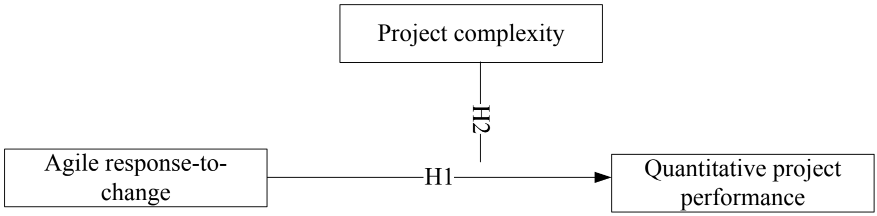


Fig. 1 Research model

constructs, namely project complexity, quantitative project performance and AR, were operationalised. Each measurement indicator for the individual constructs was adopted from previous studies.

Project complexity. CIFTER has been adopted to evaluate the level of project complexity. Project complexity is estimated by how each of these factors is assessed in comparison with its level in an 'average' project. In the survey, respondents were requested to consider a recently finished project undertaken by their organisation and were required to compare their selected project with the average project with respect to the CIFTER factors. The total score of these factors estimates the level of project complexity. Higher scores determine a greater level of project complexity.
Quantitative project performance. The quantitative project performance indicators are the project's time and cost. A five-point Likert scale (1–5) was used to measure each criterion. Higher scores refer to better performance.
AR. This study used six items to operationalise AR. The first four items were adopted from Park et al. (2017), and the remaining two items were proposed based on the project complexity characteristics (Baccarini 1996; Floricel et al. 2016). A five-point Likert scale (1–5) was used to measure each criterion. Higher scores indicate a better level of AR.

5.2 Data Collection and Data Analysis

Data were collected using an online survey. The target participants were either a project manager or a project team member of any projects. The online survey was distributed via a link through email, Australian Institute of Project Management, Project Management Institute, and social media. There were 436 participants who accessed the survey, which 234 completed. In total, 136 sets of responses were proven valid for the final data analysis.

Structural equation modelling (SEM) was applied for the data analysis as it is commonly applied in social science research (Bryman and Bell 2015). Confirmatory factor analysis was used to assess a measurement model. SEM was used to examine the structural model, which assessed the relationship between AR and quantitative project performance and the moderating effect of project complexity. The model fit indices were used to evaluate the adequacy of the model fit (Kline 2015).

6 Results

6.1 Validity and Reliability Analysis

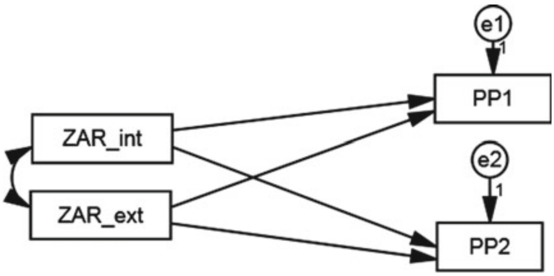
Cronbach's alpha was calculated to evaluate the reliability of the measurement constructs. The Cronbach's alpha values of the measurement scales were at an acceptable level, with the project complexity construct ($\alpha = 0.683$) very close to the suggested value of 0.70 and the AR value ($\alpha = 0.785$) higher than suggested level, thereby indicating the reliability of the constructs.

To develop a reduced set of components from the six-item questionnaire assessing AR, the data collected from 136 participants were subjected to principal component analysis factoring with varimax rotation. Two factors (with eigenvalues exceeding 1) were identified as underlying the six questionnaire items. These two factors were derived from the six items for internal AR and external AR (Appendix).

6.2 Structural Model Analysis

To test the hypotheses, SEM was used to assess the correlation between AR and quantitative project performance. Figure 2 presents the direct effect testing model. The results indicated that there was a significant and positive correlation between internal AR (AR_{int}) and budget performance (BP) ($\beta = 0.229$, t-value $= 2.042$, $p = 0.041$). No significant effect was observed between (i) internal and external AR and schedule performance (SP); (ii) external AR (AR_{ext}) and BP. Therefore, the H1 should be revised:

Fig. 2 Direct effect testing model



Note: PP1 = SP; PP2 = BP.

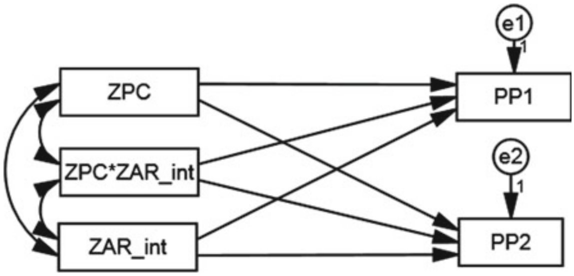


Fig. 3 Interactive effect testing model

H1: Internal AR has a positive effect on BP.

SEM was applied for interactive effect testing. In this study, the two-way interaction was examined (Dawson 2014). Figure 3 presents the interactive effect testing model. There was a significant negative correlation between the interaction effect (PC * AR_{int}) and SP (β = -0.277, t-value = −2.736, $p = 0.006$). No significant correlation was observed between (i) interaction effect (PC * AR_{int}) and BP; (ii) interaction effect (PC * AR_{ext}) and SP and BP. Therefore, the H2 should be revised:

H2: Project complexity lowers the positive correlation between internal AR and SP.

7 Discussion and Conclusion

Internal AR was measured via assessment of the capacity of project management teams to adapt to changes in technology and rapidly changing tasks in a project (Appendix). As anticipated in *H1*, the results showed that internal AR is positively correlated with BP (β = 0.229, t-value = 2.042, $p = 0.041$). This result suggests that improving the capacity of project management teams to respond to changes in tasks and technology may help to prevent or mitigate project delays. This finding is reinforced by that of Serrador and Pinto (2015), who state that the better the agile approach reported, the better the project performance. However, the regression weight for external AR in the prediction of both BP and SP was not statistically significant at the 0.05 level. This result suggests that project management teams should pay more attention to improving their capacity to respond to internal changes rather than external changes.

As anticipated in *H2*, the results of the study indicate that the effect of internal AR on SP does not remain constant at different levels of project complexity. The results of the interaction analysis show that project complexity negatively moderates the influence of internal AR on SP. Our finding is consistent with previous results showing that project complexity acts as a moderator and interferes in the relationship between certain independent variables and dependent variables (Açıkgöz et al. 2016). For example, project complexity negatively moderates the relationship between knowledge exploitation and new product development (Açıkgöz et al. 2016).

In the context of complex projects, where dynamic and uncertain environments exist, it is reasonable to assume that overcoming these difficulties will take time while the quality of the project is maintained.

In conclusion, this study makes a significant contribution to the existing literature by empirically examining the relationship between AR and quantitative project performance, and the moderating effect of project complexity on this relationship. First, this study has revealed that internal AR positively affects BP. However, project complexity reduces the effect of internal AR on SP. These findings suggested that internal AR might help to prevent over-budget in the context of complex projects. However, the effect of internal AR on mitigating delay might not be the same when the level of project complexity increases. This implies that BP relies on the ability to respond to internal changes. The best option for a project management team is to reduce the level of project complexity and thus enhance the capacity to respond to rapidly changing project tasks and technological changes.

The current study finding also suggests that project managers should pay more attention to improving their ability to respond to internal changes like changing project tasks and technological changes rather than external changes – such as political, economic, policy and social value changes.

This study conducted a quantitative approach that focuses on testing theories. Therefore, it might not take a view of social reality as constantly changing; therefore, the current practices might slightly differ from the theories. This can be seen as a limitation of the study.

This study only examined the relationship between AR and project time and budget. The future study might discover the relationship between AR and qualitative project performance, such as stakeholder satisfaction and other business values, in the context of complex projects.

Appendix: Measurement of constructs

Construct	Items
PP_{qn}	*Quantitative project performance*
	PP1: Extent to which the project was delivered on schedule
	PP2: Extent to which the project was delivered on budget
PC	*Project complexity*
	PC1: Number of different organisations involved in the project
	PC2: Number of distinct disciplines, methods, or approaches involved in project execution
	PC3: Level of stakeholder agreement about the project outcomes

(continued)

(continued)

Construct	Items
	PC4: Level of importance of legal, social, or environmental implications on project execution
	PC5: Overall financial impact (positive or negative) on the project's stakeholders
	PC6: Level of importance of the project to my organisation
	PC7: Level of stability of the overall project context
AR*	*Agile response-to-change*
AR_{ext}	AR1: Project management team had the abilities to respond to political changes that affected the project
	AR2: Project management team had the abilities to respond to economic changes that affected the project
	AR3: Project management team had the abilities to respond to policy changes that affected the project
	AR4: Project management team had the abilities to respond to social value changes (e.g. awareness of environmental issues, safety standard and climate change) that affected the project
AR_{int}	AR5: Project management team had the abilities to respond to technology changes that affected the project
	AR6: Project management team had the abilities to respond to rapidly changing tasks in the project

* Sub-constructs. AR_{ext} External agile response-to-change. AR_{int} Internal agile response-to-change

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Realization of Benefits from Best Value Approach by Proper Utilization of Expertise in Infrastructure Projects

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Abstract In the search for improved contract and project management in construction, the Best Value Approach (BVA) is a concept that has been introduced with a proven track record for better performance. The BV-philosophy stresses the importance of proper utilization of vendor expertise, as well as reducing management, direction and control by assumed non-expert clients. The development of BVA has mainly taken place through lessons learned from a number of projects, and existing research is mostly concerned with practicalities and "how" to apply it. However, research is scarce on what characterizes an expert in a BV-context, and the concept lacks scientific documentation regarding underlying premises. To fill this void, we pose the following research question: How can vendor expertise be utilized in order to achieve BVA benefits? We develop a framework for vendor expertise in BVA, and how it can be utilized to realize proposed BVA benefits. The framework is based on both relevant theories and findings from an in-depth case study. Our contribution is an increased understanding of the expert-role in BVA, and how clients can facilitate the experts in BVA projects. In this paper, we question the rationale behind BVA and discuss the underlying premises for transferring supreme responsibility of public construction projects to private marked vendors.

Keywords Best value approach · Expertise · Procurement · Project management · Uncertainty

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_27

1 Introduction

In the search for improved contract and project management in construction, the *Best Value Approach* (BVA) is a concept that has been introduced with a proven track record for better performance. BVA stresses the importance of proper utilization of vendor expertise as well as reducing management, direction and control by assumed non-expert clients (Kashiwagi 2016). In theory, the assumed expert is identified through *Best Value Procurement* (BVP) and rewarded with supreme responsibility of the project with minimal involvement of the client. The role of experts is therefore assumed a success factor in applying BVA. In short, BVA is a model for both contracting and managing complex projects. Existing studies are mostly concerned with the contracting model (BVP), and the project management aspect of BVA lacks scientific examination, that is, how expertise can be utilized to manage the project in the best possible way. The identified knowledge gap is mainly what characterizes an expert in a BVA context, and how projects should be managed by the BVA principle after completing the BVP process. This paper defines the BVA principle as giving expert vendors the lead role in projects with minimal involvement by clients. According to Performance Based Studies Research Group (PBSRG), the benefits are rather positive compared to other contracting and project models. Among the proposed benefits are claims that 98% of BVA projects deliver on time, budget and client expectations. PBSRG also state that client organizations reduce resource usage by 80% and experience more added value. In addition, vendors increase their profits (Duren and Dorée 2008). However, other researchers have studied 400 of the included projects in PBSRGs BVA portfolio. They give credit to BVA for better performance with regards to time and budget, compared with traditional contracting models. They find that 98% is rather positive, as the studied projects that were the basis for the claim were rather minor and less complex. They confirm that clients are more satisfied with vendor performance, and that vendors are far more enthusiastic about finding creative and value adding solutions. Although the reduction in resource usage is not confirmed, they refer to the size and complexity of the portfolio and question whether 80% is a realistic estimate (Duren and Dorée 2008). The concept of BVA is based on Information Measurement Theory (IMT), which defines an expert as the vendor with best proven ability to perceive and process information to predict future outcomes of an event (Kashiwagi 2002). However, except for IMT the BVA research is scarce on what in fact characterizes experts. Moreover, the concept lacks further scientific documentation regarding the underlying theoretical premises of BVA. To fill this void, the following research question is presented: How can vendor expertise be utilized in order to achieve BVA benefits? The aim is to highlight dimensions of an expert vendor, and how all parties in a project can utilize the expertise in a proper way to realize proposed benefits of BVA.

This article is organized as follows. The problem at hand and knowledge gap have been identified. Next, we present BVA as a concept and findings of what in fact constitutes an expert vendor and how their expertise can be utilized. The in-depth case study serves as the primary method, and by investigating how vendors and client operate in the project, the case study contributes in understanding how traditional project roles change through BVA. The conclusions include pinpointing of contributions and implications for theory and practice.

2 BVA as a Strategy for Project Management

There are different perceptions in literature of what the concept of BVA/BVP involves. The primary understanding is the contracting phase itself, which involves identifying the most qualified vendors based on other criteria than merely price. This is a rigid process with strict requirements for documentations, risk evaluation, reference projects and key personnel interviews. However, the purpose of BVA as a strategy is far more ambitious than merely contracting experts for complex projects (Kashiwagi 2016). By spreading the term "Best Value Approach", the aim is to underline change in the paradigm of traditional mindset and roles with regards to both contract and project management. The ultimate purpose of BVA is to create an optimal project environment with emphasis on vendor performance and minimizing inefficient use of resources by clients. By reducing management, direction and control by the client, BVA aims to push project-based industry towards a win-win situation. As the BVP process in theory should identify the most capable vendors, as price is not the determining factor alone, there is now a legitimate ground for the client to transfer supreme responsibility of the project to vendors (Joudi et al. 2018). Based on the literature, this paper defines the BVA principle as the following: (1) Clients facilitate the expert management by vendors in the project, (2) weekly risk reports serve as primary control scheme where the client follows up on quality, and (3) realization of a win-win environment and other BVA benefits. Studies of Dutch BVA projects have found that there is a negative tendency with projects that deviate from this BVA principle after the tendering process (Storteboom et al. 2017).

In order to realize the benefits of BVA, the first prerequisite is to contract suitable experts through the BVP process. In this paper, we are interested in investigating the second prerequisite, which is to utilize this expertise in a proper way. The win-win environment is a necessity for a successful BVA project and utilization of expertise (Verveij and Kashiwagi 2016). The first step in expert utilization is for the vendors to develop plans for the execution of the project. The execution of the project can thereafter be measured by comparing deviations from the plan. Whenever the reasons for deviations can be tracked back to the vendors, one can establish that the vendors have done poor planning. However, when the deviations are caused by parties other than the vendors, these causes are regarded as risks which the client is financially liable for. Risks that the vendors cannot control should be documented and measured throughout the execution, as risk mitigation is in the interest of all parties in the project. These are the documents that are defined as weekly risk reports (WRR) and should contribute to increase trust and transparency in the projects. Therefore, the remaining task for the client is to facilitate the expert vendors in executing their plans and follow up on quality through the control scheme of weekly risk reports. All other management, control and decisions made by the client is regarded as unnecessary and obstruction of expert management in the project. This is the core of what we can regard as a BVA project, with the win-win environment as a prerequisite. In theory, this win-win environment should minimize client resource usage in the project and increase vendor profit through efficient project management (Kashiwagi 2016).

As the BVA literature and principle is highly oriented around the role of experts and risk management, it is necessary to give a brief understanding of the terms risk and uncertainty in projects. A known distinction between uncertainty and risk can be traced back to the theory of economics, where risk can be quantified from random events with known variables. Uncertainty is, on the other hand, known as random events with unknown variables. A similar understanding can be found within the decision-making theory, where decisions made under risk involves the probability for multiple outcomes of an event. Decisions made under uncertainty, in contrast, does not involve any probability for outcomes from the event (Hillson 2009). Managing uncertainty can be as predicting possible impacts on the project and developing strategies to handle the uncertainty in the best possible ways. The term uncertainty is tightly connected to information and how a project can be affected depending on the level of information. The level of uncertainty can thus be linked to the lack of information (Klakegg et al. 2017). In BVA, the expert vendors should develop relevant strategies that address the most important uncertainties in the project for the client. Hillson (2009) points out that there will always exist different uncertainties, and that all uncertainties cannot be addressed and handled. Therefore, experts should be able to identify the critical uncertainties for the client and the project and relate their strategies to these.

3 Method

Lack of studies on the expert role in the context of BVA warrants an explorative research approach. Given that we are interested in a detailed understanding of the expert role and how it is understood among actors in BVA, a single case study is a good approach (Yin 2003). By building our initial understanding on both acknowledged theories and empirical studies within the field of expertise and others, the aim is to generalize in an analytical way. This includes actively using our framework in analyzing results from qualitative interviews. By doing so, we can determine with both theoretical and practical perspectives what in fact constitutes an expert, and how expertise can be utilized in order to realize the benefits of BVA. As a case in point, we have chosen a Norwegian road construction project, which has completed a BVP tendering process. The project has been chosen for the case study as it is currently transitioning onto the early phase, which includes expert activities such as planning and engineering. This is interesting in answering our research questions, as we can investigate how the BVA principle is upheld during the transition, as the vendors should gain more responsibility and the client should adopt a “hands-off” approach. We conduct eight semi-structured interviews, and the interviewees are selected by determining key roles in the project with regards to both contracting and early phases. These include personnel from client and vendors in the project. Such roles are project manager, design manager, process manager, risk manager and contract advisors. By selecting interviewees from all entities on different levels, we can get a broad perception and uncover the level of understanding for BVA in the project.

4 The Role of Expert Vendors in BVA

The development of this framework started with a literature review, with regards to organizational theory, learning, psychology and backgrounds from artificial intelligence. The purpose has been to expand the understanding of the expert-role beyond *Information Measurement Theory* (IMT), which serves as the sole theoretical ground for BVA. This was necessary to understand *expertise* as a phenomenon itself and to link to an expert organization. The theoretical foundation for developing a framework for vendor expertise is a dual understanding of expertise. Studies show that experts have high level of domain knowledge, which includes having both knowledge and competence which is regarded as extraordinary by others within the domain (Farrington-Darby and Wilson 2006). Other studies show that experts can be distinguished from others based on their ability to learn new concepts and expand their domain knowledge (Hambrick and Meinz 2011). Therefore, experts can be defined as actors with (1) high level of domain knowledge and (2) strong cognitive abilities.

For a vendor organization, organizational capability can be regarded as a fundamental dimension. The literature review shows that relevant knowledge and competence can be linked to the ability to effectively process information to predict future outcomes (Spender 1996; McInerney 2002). An indicator of high organizational capability can be linked to effectively gathering and processing necessary information in the early phases of a project, so that plans can be developed with key information as the basis. This understanding is also shared in IMT, where experts can be distinguished from others in the BVP process as actors with a high ability to process information and predict future outcomes (Kashiwagi 2016). Another indicator of organizational capability is the ability to effectively integrate relevant competencies in the organization (Grant 1996). By combining explicit instructions and routines such as project teams, the organization is able to solve complex problems for the client.

The cognitive abilities from the dual understanding of expertise is incorporated into vendor expertise as a term through organizational learning. This dimension can be regarded as experiential learning in organizations with an established culture for continuous improvement (Kolb 1984). Although experimental learning can differentiate experts from others, they have both motivation and skills to challenge established practice and improve practice by developing different solutions (March 1999). These dimensions have been investigated by Nadarajah (2019) and can be regarded as verified dimensions of an expert vendor. In addition to these dimensions

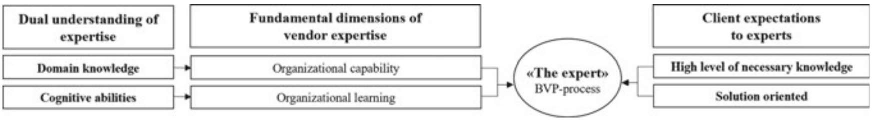

Fig. 1 Framework for vendor expertise in BVA

being investigated and verified through numerous interviews of personnel from both vendors and client, the client expects experts to have a high level of necessary knowledge and to be solution-oriented. This simplification of expectations of experts, the findings from Nadarajah (2019) and the dual understanding show that organizational capability and learning are, in fact, fundamental dimensions of vendor expertise (Fig. 1).

Dominant information is an important concept in BVA (Kashiwagi 2016). By using dominant information as a communication strategy, experts should be able to communicate necessary and important information in a simple matter to non-expert clients. This implies that the message is clear, and that the recipient of the message does not need the same level of expertise as the vendor to understand the message. In the BVP process, vendors are expected to present all documents and evaluations in a manner that is in line with the concept of dominant information. However, our findings show that expert management in the project after completing BVP processes can be distinguished on the basis of communication skills. This is a dimension that seem to enhance both organizational capability and learning as dimensions that reduce perceived uncertainty for the client. Our findings show that dominant information not only ensures appropriate flow of information, but also keeps the level of detail in information uncomplicated. Dutch studies show that increased detail in information leads to higher involvement of the client and can lead to misunderstandings, conflict and risk of not realizing the benefits that BVA proposes. With these arguments and our own findings, communication skills have been developed as a dimension of expert management in the project. In addition to dominant information as a communication strategy, findings from the case study shows that the client appreciates vendors that truly show their role as experts in the project. For instance, the client is more than eager to change the initial conditions of the project with regards to the vendors' arguments in order to achieve a better result. The vendors are also concerned with keeping information dominant, as well as ensure the client that they share similar interests in the project. For instance, dominant information is applied in presenting engineering solutions in the early phase of the project. Key Performance Indicators (KPI) that are relevant for the project goals are used to measure the performance of all solutions with regards to the clients' most important concerns. Therefore, organizational capability, organizational learning and communication skills can be regarded as important dimensions of the expert role in BVA (Fig. 2).

The study shows an implication of reduced perception of uncertainty by the client, through contracting vendors with these dimensions. The findings show that elements of both organizational capability and learning contribute to reduce the total level of

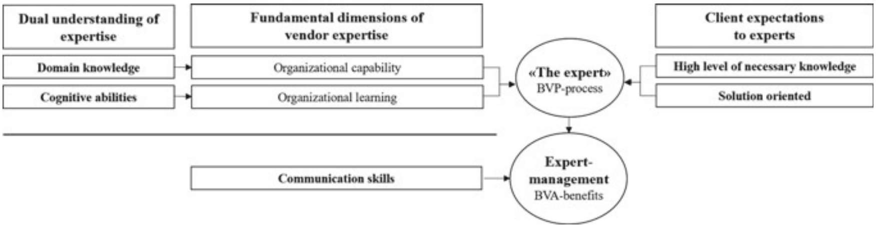

Fig. 2 Framework for expert-management in BVA

uncertainty for the client. Specifically, capability contributes to reduce third-party uncertainty, as experts clearly show the ability to perceive and process key information through high level of domain knowledge and competence, which also ensures a broad and functional perspective of the project. Organizational learning is arguably the dimension that ensures the client that the most viable solutions are developed in the project, as experts have both motivation, established culture and ability to challenge established practice within their own and others' organization. By showing an ability to productive reasoning and double-loop learning, experts ensure that no inexpedient factors are obstructing learning processes in order to develop the best possible solution in the project (Argyris 2002). In combination, organizational capability and learning are enhanced by a clear communication strategy that both assures the client that expert management is taking place in the BVA project and helps to increase the level of trust among the parties.

5 Client Facilitation for Vendor Expertise

As the paper has presented the core of BVA and has given a brief overview of what vendor expertise can be characterized as, this section aims to present findings regarding the clients' role and discuss whether or not traditional mindset and procedures for project management take place. Earlier studies show a negative tendency with BVA projects that experience misunderstanding, lack of goal congruence and conflict after the BVP process. These observations are mainly done in the Netherlands, and this paper aims to contribute to avoid such tendencies in Norway. Such projects can arguably risk realization of BVA benefits due to deviation from BVA as a strategy. BVA benefits are mainly dependent on a win-win environment in the project and should in theory reduce client cost and increase value and profit for vendors. The BVA principle that is presented in an earlier section clearly shows a change in traditional project roles, with the vendors as leading experts and the client as a facilitator for the experts and the project.

However, the research is also scarce on what in fact the facilitator role involves. As most studies criticize clients for not thoroughly understanding their role as a facilitator, it can be argued that there is lack of scientific documentation for what this role in fact includes. The findings from the in-depth case study also clearly show deviations from the BVA principle. All parties agree that the BVA as a strategy is not in focus at the current stage in the project, which is early design, engineering and planning. On the other hand, the parties seem also to agree that the project is performing well in engineering and planning. In theory, clients are supposed to follow up on quality through WRR as the primary control scheme in the project. The findings show that the client is satisfied with contracting experts for their project and is convinced that BVP can contribute to avoid conflicts due to low price and rapid changes in the project. However, the clients are concerned about their own role to include optimization of solutions. This is another indication that the facilitator role lacks examination and research. There is, however, evidence that indicates an initial strategy of utilizing the expertise properly. These findings contribute to increase the understanding in this paper for how the facilitator role can be executed. One measure is early involvement, where the vendors are included in forming the initial conditions of the project. The result of this measure is increased influence of the vendors, and thereby increasing the possibility of a successful BVA project with expert management. The case study shows that the vendors are able to regulate the necessary surrounding area for road construction in accordance with Norwegian law and regulations, and simultaneously tailor the solutions towards their own tactics for construction. This measure results in increasing the influence of experts and minimizing costs and temporary work in the execution phase of the construction project. Another measure is to transfer time and cost planning to the vendors. The client has deliberately excluded milestones for the start of construction. By doing so, the creative process of the experts is not limited by time. However, the experts do need to complete both engineering and construction within the total time and budget of the project. By doing a cost-benefit analysis, the client can keep a strategic perspective of the project and avoid detailed reports to measure vendor performance. The case study also shows that the client is using performance measurement tools to increase the performance of the project. These measures are not solely mentioned by the client, but all interviewed personnel from the vendors agree that these are relevant measures in a BVA context. These findings show that WRR should be the primary control scheme, although the presented measures can help the client to keep a strategic perspective of the project (Fig. 3).

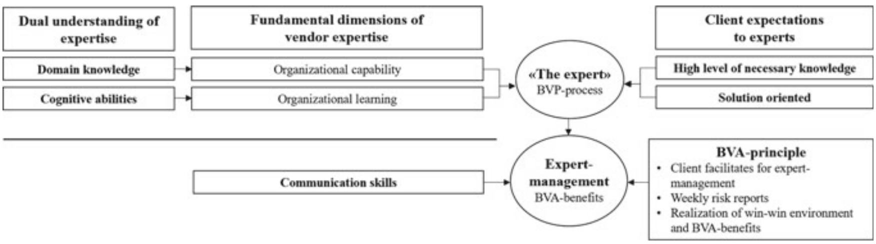

Fig. 3 Framework for realization of BVA-benefits

Based on the findings from the case study and earlier studies, clients clearly use BVP to procure expertise for their most complex projects. However, there is potential for increasing the utilization of the expertise, even though findings show that clients do intend to transfer responsibility of the project to vendors. Public Norwegian client organizations also possess high competence within both engineering disciplines and project management, and one should therefore question whether a "hands-off" approach is suitable for their operations. Given that the client is a one-time buyer of a complex road construction project, the core and principle of BVA is highly suitable, as the client organization presumably does not have the necessary competence. However, public Norwegian builders have a portfolio of 150 billion NOK with road construction projects. This indicates that their own competence for regulations, engineering and construction pose a need to expand the facilitator role. However, the benefits of BVA is in fact dependent on expert management, client facilitation and realization of a win-win environment. Their planned resource usage in BVA projects should therefore be of a strategic manner, using their competence to follow up on quality, facilitate and manage the project with a broad perspective.

6 Conclusion

This paper contributes to the BV-literature with an increased understanding for what in fact constitutes an expert, and how their expertise contributes to reduced perception of uncertainty by the client in the project. Experts can be characterized as actors with high level of domain knowledge and strong cognitive abilities. These components can be operationalized as organizational capability and organizational learning for vendors, and a high level of these dimensions constructs high level of expertise. The level of expertise is further more enhanced by an appropriate communication strategy. The capability of communicating complicated concepts in an understandable fashion for clients increases the perception of their expert role and is an indication of a possible successful BVA project. BVP criteria should thus reconsider exposing these dimensions, so that a client can be sure to procure organizations with a high level of general expertise. Public projects are often characterized by a high level of attention, and expert management can contribute to more successful projects and better use of public funding.

The BVA literature has a poor description of how traditional project roles change through BVA as a strategy for project management. Today, Norwegian BVA project could risk realizing BVA benefits due to confusion and lack of understanding for BVA as a concept. This paper contributes to highlight how both vendors and clients can be more aware of their own roles. The BVA literature is mainly concerned with defining risks that could impact the project and for the client to follow up on the vendors' measures. This paper expands the understanding of expert management, such as establishing a strong learning environment, being aware of their own role as experts, and having an appropriate communication strategy with dominant information. The facilitator role is in need of more research since the "hands-off" approach can be confusing for large public builders to understand when they run complex and high-cost projects.

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Adaptation of Risk Sharing Partnerships (RSP) to New Industries

Theodor Kvæven Halvorsen, Gøril Hannås and Magnus Mikael Hellström

Abstract The aerospace industry has since the 1990s used a partnership model called Risk Sharing Partnerships (RSP) to handle certain challenges faced in the development of new aircrafts. The RSP model allows the client to include key suppliers in the development of a new product, and hence sharing the burden of investment, risk mitigation, as well as the future sales income. This makes it easier to acquire funding for the development of new products and technologies, in addition to accelerating the development process by including key competencies earlier (Buzacott and Peng in Eur J Oper Res 218:656–666, 2012). RSP have raised interest in other industries, which calls for increased knowledge of contingency factors of the RSP, as well as suppliers' perspective on RSP as a partnership model. Both are regarded important if cross-industry learning is to be promoted. By using a literature review of existing studies on RSP, combined with a case study of two aerospace suppliers, this study investigates the contingency factors of the RSP as a foundation for cross-industry transfer of knowledge, and proposes a model to assist cross-industry adaptation in project-based industries. We propose that there are three critical contingency dimensions for RSP-implementation, based on both financial and relational factors.

Keywords Aerospace industry · Partnerships · Reward sharing · Risk sharing · Risk sharing partnerships

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_28

1 Introduction

The level of investments and general economic activity in the Norwegian offshore sector has since the 2014 drop in oil prices been decreasing, and forecasting are not suggesting any increase soon (Hovland 2019). For the sector to stimulate investments and innovation, as well as to improve internal processes, there is a need for change. The sector therefore looks to the aerospace industry for inspiration, as parties in this industry have with success implemented what is known as Risk Sharing Partnerships (Figueiredo et al. 2008). The aerospace industry has since the 1990s used RSP contracts to handle certain challenges faced in the development of new aircrafts. The fundamental concept of the RSP is that the original equipment manufacturer (OEM)/aircraft producer outsources a complete sub-assembly to a partner. The partner will be responsible for both design, production and service costs, and will in return be rewarded with a percentage share of all the future revenue of the planes, corresponding to the value of the sub-assembly (Figueiredo et al. 2008).

The apparent success of this partnership-model in the aerospace industry has caused organizations in other industries to consider whether the RSP could be a viable option in their industries. However, a literature review shows limited research on the RSP across other industries with similar conditional contexts. In addition, most studies on RSP seem to adopt a buyer perspective, whereas the suppliers' perspective has not yet received much attention. Both are regarded important if cross-industry learning is to be promoted.

This study therefore aims at investigating the contingency factors of RSP, including a supplier perspective, to enhance knowledge and understanding of why RSP may be a viable option within a specific industry environment, and under which circumstances these benefits may apply when the product environment is changed. The article elaborates extant theory with insight received from interviews with two suppliers in the airplane industry. A framework is presented describing external and internal factors favoring a possible use of RSP as a contractual model.

2 Risk Sharing Partnerships

The Risk Sharing Partnerships (RSP) as a contractual model originates in the aerospace industry (Figueiredo et al. 2008). It was adopted by some manufacturers in the mid-1990s as a response to challenges both in the market and supply chains. Figueiredo et al. (2008) explains that the RSP was inspired by strategic partnerships in general and developed to reduce investments and dependence on loans for product development from the client side. To reduce investments, the aircraft manufacturers decided to let certain suppliers contribute with funding, with the promise of a future revenue share from the product series in question. The result was reduced commercial risk, as the suppliers paid to be part of the development to ensure long term profits. In addition to the need for capital, the partnership model was adopted to consolidate relationships between international suppliers and the OEM (Armellini et al. 2014; and Peng 2012).

The two control mechanisms in RSP are risk and reward sharing (Tse et al. 2018). Risk sharing focuses on aligning the responsibilities of the different partners. This means that the parties are all responsible for a certain level of risk and participation in mitigation of risk, rather than the client being the sole risk taker in the contract. The reward sharing on the other hand is a behavioral mechanism which aims at creating goal congruence with the involved parties. By sharing the future profits of the product, it is expected that the suppliers will act in favor of the project, and not just themselves. Hence the main criteria for an RSP is that there is a participative sharing of risks, and that the parties involved have the rights to share future sales income from the products (Figueiredo et al. 2008).

An RSP contract is different from traditional collaborative contracts where the supplier delivers a product or service for an initial price that covers both their costs and profit margin. In this traditional setting the client's further refinement of the product allows for a higher price to their customer, which accommodates the cost of goods sold from the supplier, cost of further value-added processes of the product, as well as a profit margin for the client. In the RSP contract, however, the supplier and client cooperate in the design, production and life cycle support of a single product (Wagner and Baur 2015). By doing so, the supplier will collaborate with the client by contributing either by funding, expertise or resources that is necessary for the development of the product. In return, the supplier is considered a co-owner of the product, and are entitled to a share of the future revenue. The characteristics of an RSP, however, is that this arrangement is done through an incentivized contractual model rather than investments in a joint venture arrangement.

In the aerospace industry, initiating RSPs is done on a plane to plane basis, meaning that for every new airplane in a product-series sold, the risk sharing partners will receive an additional compensation for the initial risk undertaken (Buzacott and Peng 2012). This is illustrated in Fig. 1 on the previous page.

The RSP literature provides three strategic intentions from the OEMs' perspectives for using the RSP. These are to get easier access to funding by sharing the

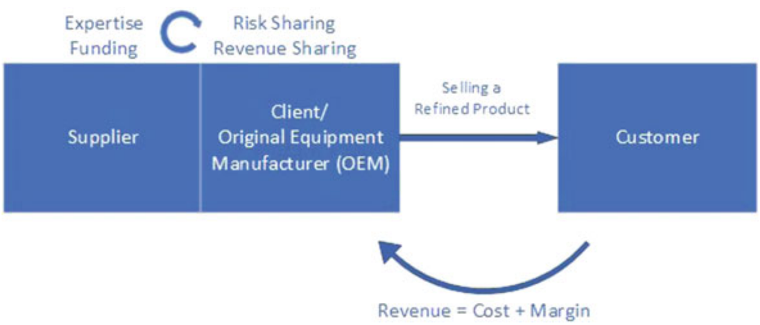

Fig. 1 Collaboration in risk sharing partnerships

developments and production costs, reducing the commercial risk of unsuccessful product lines, and secure long-term relations with key suppliers (Buzacott and Peng 2012; Figueiredo et al. 2008; Wagner and Baur 2015). Whereas a standard LTA in the aerospace industry often covers a period of 3—5 years. After this period, the suppliers need to compete for an extension of the agreement. In contrast, the RSP stretches throughout the production and service periods of the airplanes.

Through a literature review, two main gaps in knowledge of RSP emerged. The first is lack of knowledge concerning the contingency factors of RSP, i.e. are there specific circumstances that contribute to make RSP a viable option in the aerospace industry? The second gap concerns the lack of studies on how RSP is perceived by the supplier side of the collaboration. Both knowledge gaps are of interest when investigating the rigor of the model and adaptation possibilities to other industries. Limited understanding of why it works in one industry poses the risk of adopting the model to a new business context by "shooting in the dark". This study, therefore, aims to uncover specific institutional factors from both the perspective of the OEM and supplier that are prevalent in RSP relationships and their business context, by posing the following research question:

What are the contingency factors of the Risk Sharing Partnerships (RSP), and are these transferable to new industries?

To answer this question, a model will be developed through a case study of the aerospace industry, using a mix of previous case studies on the original equipment manufacturers (OEM) and interviews with suppliers in these RSPs. Data are gathered from a literature review on OEMs using RSP, in addition to primary data from interviews with two supplier organizations within the aerospace industry. These organizations and respondents include:

- Company A: Tier 1 supplier with significant experience with RSP. Produces a wide portfolio of aerospace systems, including hydraulic and flight control system.
- Company B: Tier 2 supplier with significant experience with RSP. Produces vital components used in the aircraft engines.

3 Characteristics of the Aerospace Equipment Industry

In order to understand the contingency factors of the RSP, it is necessary to understand the market context in which the partnership model originated. The focus of this chapter will mainly be on the aviation sector of the aerospace industry, and the production of airplanes, which is where the RSP is predominantly used. It is estimated that the production of airplanes account for close to 80% of the total revenue in the aerospace industry (Goehlich 2008). This number rises to 90% when including the production of the weapons systems for military purposes. It is estimated that military contracts accounts for nearly 50% of the revenue from airplanes. According to Goehlich (2008), the forecasting of demand for airplanes in 2008 was expected to increase drastically over the next decades. Already in 2008, demand was estimated to be 1000 airplanes per year, which by then was above the current production capabilities.

The market structure is what could be considered an oligopoly, with 6 major manufacturers in the aerospace industry (Jordan and Lowe 2004). Out of these 6, Boeing and Airbus are the clearly dominant producers (Goehlich 2008). According to Jordan and Lowe (2004) no companies have all the necessary specialists to develop and produce airplanes on its own. Moreover, the suppliers often have a diversified portfolio and deliver solutions to other industries. This often makes the manufacturers more dependent on the suppliers, than the suppliers are on the manufacturers (Goehlich 2008).

Due to the military contracts, as well as the excessive requirements that focus heavily on safety, there is very limited number of suppliers that can contribute to the production of airplanes (Jordan and Lowe 2004). As a result, the different suppliers are often working as partners and competitors at the same time on different projects. This situation results in a situation that nurtures little trust and communication, as the suppliers' main reason for gaining competitive advantage relies upon the specific knowledge they possess.

The political factor, where governments require manufacturers to include national suppliers on the product results in large, complex supply chains, with several partners on an international scene. The partnerships in the aerospace industry has become known as "shotgun weddings", where the choice of supplier is determined by governmental pressure and lack of competition, rather than being initiated at their own choosing (Jordan and Lowe 2004).

The products are also highly complex and expensive. According to Nystrom (2005), there are several similarities between the aerospace and automobile industry, which both are make-to-order (MTO) industries. An MTO-industry is where a product portfolio is developed, and each individual sale is later tailored to the customer's need. This means that the production of the airplane does not start until after the order is placed by a customer, and the industry is therefore very focused on reducing the lead time of production.

However, unlike the automobile industry, there is a significantly greater extent of complexity (Goehlich 2008). Whereas a car usually contains 7000 components, the airplanes contains up to 6 million. When also considering that the operating conditions for the products are tougher, it means that even a moderate development in technology for the aerospace industry requires large investments (Esposito 2004). This has resulted in high fixed costs of the airplanes (R&D), which leads to lower profit margins and very long payback periods for the products (Goehlich 2008). It also results in a very high financial risk for the individual manufacturer. The costs are further increased due to high bureaucracy levels, numerous design changes, extended schedules due to delays, and poor, belated communication between the partners (Goehlich 2008).

As a result, the industry has become known for excessive outsourcing of large sub-assemblies. This results in reduced lead time in the production of airplanes, as there are several suppliers delivering complete sections of the airplanes directly to the assembly manufacturer. The use of larger sub-assemblies, where the different responsible suppliers coordinates sub-contractors results in a reduced need for inventory management and interdependencies of the other sub-assemblies of the airplanes. This would have not been the case with smaller sub-assemblies, as this would have required a more thorough scheduling to avoid further delays (Goehlich 2008).

However, this complexity and modulation results in a higher performance ambiguity, as it is difficult to assess performance beyond commercial success. Commercial success is also difficult to measure, as the manufacturers normally have only one or two extremely successful products that secures portfolio profits. Most of the production lines are not financially profitable; however, they are necessary to ensure further competitiveness. This is because the airlines prefer to invest in a product family, rather than buying airplanes from different manufacturers (Goehlich 2008), presumably from an operations and maintenance cost perspective.

4 RSP as a Contract and Business Model

The most common examples of how the RSP has been implemented are drawn from Boeing and Embraer. Both companies have adopted this form of partnering by creating a ranked network of suppliers. Initially, they divide the aircraft into several sub-assemblies, and gives each risk sharing partner the responsibility of a certain assembly. Each of the sub-assembly owners can be considered a risk sharing partner. The supply chain network was hence divided into 3 tiers, which could be described the following way (Denning 2013; Figueiredo et al. 2008).

- The first tier included the risk sharing partners. This was the companies that were given ownership of the various sub-assemblies, which includes the funding and development of the new aircrafts, and hence future reward sharing. They are responsible for different sub-assemblies of the aircrafts and oversee coordinating deliveries from the different tier 2 and 3 suppliers.
- The second tier consisted of parties supplying components, systems or services, but not being a part of the R&D team. These companies were presented with a set of technical specifications and asked to develop a solution for the different sub-assemblies. The tier 2 suppliers report directly to the tier 1 partners.
- The third tier consisted of suppliers providing less complex and less expensive components. These were not presented with specifications, but rather with materials and blueprints. This tier supplied manpower in the production of less critical components. The tier 3 suppliers report directly to the tier 1 partners.

The result of implementing RSPs was positive, when considering the intentions of the two manufacturers (Buzacott and Peng 2012; Figueiredo et al. 2008). The RSP did also provide additional benefits beyond the eased access to funding and supplier consolidation. The study on Boeing suggests that the RSP was shown to accelerate the development process, as a result of earlier involvement of key competencies

(Buzacott and Peng 2012). The RSP has also been shown to address agency problems, such as opportunism from the suppliers, if implemented correctly (Tse et al. 2018).

Among the financial benefits it has also proved to be favorable in situations with high uncertainty in demand. Buzacott and Peng (2012) explains how the RSP helped the client by reducing the risk of low sales figures, as the losses are distributed among the participating parties. It is reasonable to believe that the lower financial risk and increased involvement would be beneficial with regards to innovation and technological development.

5 Criticism of RSP

There exists little criticism on the RSP within existing literature both as a concept but also from a methodological perspective. So far, most studies on RSP use case study as a methodology. Hence there are few quantifiable results that have tested the ability to generalize the findings. Additionally, the RSP-studies have to a very limited extent covered the supplier perspective, and since there are more partners than OEMs in an RSP model, existing research on RSP fail to include most of the involved parties in RSP constellations.

Some case studies indirectly criticize the RSP as a concept. One of these are studies conducted on the development of the Boeing 787 Dreamliner, which used the RSP approach (Tang and Zimmerman 2009). The Dreamliner is an example of product suffering from significant delays and post-launch issues. The case study conducted by Denning (2013) points to several flaws that may arise when using the RSP.

Denning criticized Boeing for mainly five (5) different aspects of the partnership model, resulting in unnecessary risks. These were the risks associated with outsourcing, innovation, coordination, communication and tiered supply chains. The Dreamliner project outsourced more than twice as much as usual, as well as using unproven technology in an unprecedented scale. When combined with Boeing's hands-off attitude towards coordination, aiming for complete partner autonomy and no on-site support, it was probably not surprising the events unfolded as they did.

From the RSP perspective one contractual risk on the Dreamliner project was more interesting; namely the risks of tiered outsourcing. This is the business model used by Boeing for RSPs. The critique was that Boeing used 50 partners, meaning the Dreamliner was split into 50 sub-assemblies, resulting in an insufficient screening. Some of the partners lacked the necessary knowledge regarding both the technical design, but also the experience in supply chain coordination, resulting in delays and technical issues.

The flaws presented in the Dreamliner case appear to be preventable, as several of these risks could be blamed on too ambitious use of the RSP, combined with poor coordination and monitoring. The case study could hence be considered a recommendation for certain "best practices" in the future. Wagner and Baur (2015) supports this argument by claiming that the challenges with the RSP so far is mainly due to missing capability or competence of either buyer or supplier. Another critique of the RSP model is the lack of incentives provided to the partners for finishing on time. Tang and Zimmerman (2009) discovered that the lack of incentives for meeting deadlines, resulted in massive delays, and millions of dollars of penalties that had to be paid to the customers.

6 The Benefits of RSP

During the literature review and case study, the benefits for both the supplier and OEM was documented. This is because when organizations consider adopting a new partnership model, then it is ultimately in order to receive the benefits that this model offers.

For the RSP, these can be separated into benefits for the OEM, and benefits for the suppliers. What was discovered is that some of the benefits for one party is considered a disadvantage for the other party. One example of this is the potential for higher revenues for suppliers, which occurs due to the new payment structure where the suppliers' return is dependent on the sales price of the end product, and not a pre-negotiated rate per component. This increase in potential for the supplier will likewise be a reduced potential for the OEM but will be compensated through other benefits. Table 1 summarize the key benefits and disadvantages with the RSP found in the study.

From the OEM's perspective, the implementation of RSP is a consideration of giving up partial ownership of the product, in order to receive other benefits. These benefits range from reduced dependency on loans through supplier funding, a reduced commercial risk as the losses are shared when product revenue is lower than necessary.

According to Tse et al. (2018) risk and reward sharing used together may have a negative effect on quality performance. Tse et al. (2018) assumed that the reason for

Table 1 Benefits and disadvantages of using the RSPs

	OEM	Supplier
Benefits	• Easier access to funding • Reduced commercial risk • Fewer suppliers, with greater responsibility • Reduced lead times • Closer relations with suppliers • Increased SC transparency • Common goal (commercial success of product)	• Long-term, predictable revenue streams • Closer relations with OEM (future projects) • Potentially higher rewards • Direct access to the spare part market (life-cycle revenues)
Disadvantages	• Reduced revenue potential • Reduced incentives for quality performance	• Longer payback period • Locking up capital • Higher commercial risk

this was that the risk sharing aspect of the contracts constitute an accepted "bottom line" for quality, whereas the reward sharing is promoting increased quality due to the potential long-term benefits for the supplier. Company B described in the interviews that the only bad experiences they had with RSPs, were when the prospects of the business case were not achieved. This was when they produced the components of too high quality, meaning the components did not break down, and the company did not get any aftermarket revenue streams as a result. This suggests that RSP incentives concerned with commercial success might conflict with quality performance. Whereas Tse et al. (2018) proposed the quality reduction as the suppliers' wish to produce the bare minimum, this finding suggests that the suppliers are "punished" by losing out on future aftermarket sales for delivering high quality components.

The suppliers included in the case study were all satisfied with the RSP, and one company even claimed that it would not be operating with such high profitability without the use of the RSPs. It was also apparent that the RSP offers a significant stability for the firms through the long-term revenue streams, as well as contributing to securing future projects through the positive relations with the OEM.

7 The Model for Cross-Industry Adaptation

The model developed in this study is based on primary data collected in an ongoing study. This section will discuss the dimensions in the model making the RSP a viable option, before presenting the model at the end. Statements in this section will be based on the interviews with the supplier organizations, unless stated otherwise.

Based on the literature review, it was believed that the contingency factors of the RSP would include the product and market characteristics, motivation for using the RSP, and the business model they used. Hence, the interviews with the suppliers had the focus of investigating how the companies operated when considering these factors. In doing so, it was expected that it was possible to identify a set of contingency factors that would either be required, or contributing, to realize the benefits that has been experienced in the aerospace industry. After the interviews, however, it was discovered that these dimensions did not sufficiently cover the dimensions of the RSP. These dimensions did contribute to making the RSP viable, however, the dimensions included in the model had to be more general. This is because it was found that the RSP in the aerospace industry is used on all types of products and components, regardless of complexity, unit costs, volume or business models. The companies did not have a framework for whether to use the RSP or a standard Long-Term Agreement (LTA) either, but there were a few recurring factors that affected the usability of the RSP.

When also considering that several of the benefits from the RSP are in line with the theories on transaction costs approach and principal-agent, it is expected that the dimensions should also be influenced by some contributing factors from these theories.

To summarize, there are three dimensions that we consider as the contingency factors of the RSP, which would be required to reproduce these benefits. One regarding the financial requirements of the contract, one regarding the relational requirements, and one considering the organizational requirements. These dimensions are proposed to be the following:

- Financial requirement: Financial magnitude of contract.
- Relational requirement: The level of trust in supplier/ product.
- Organizational requirement: Financial capability of involved parties.

7.1 Financial Magnitude of the Contract

The first dimension is the financial magnitude of the partnership. This dimension was originally concerning the product and market characteristics of the partnership; however, it was not possible to define these characteristics other than that the combined financial value of the components in the assembly was very high. This is because the contracts used in the RSP are very complex and expensive to develop and might take up to 1 year to finalize. In addition to this, there is a lot of clauses and contingencies that must be constantly enforced, making it very expensive compared to an LTA. For the RSP to be a viable option, the assembly needs to exceed a certain threshold value to make it worthwhile.

This is very much in accordance with the theories on the transaction cost approach which aims at explaining when an organization should buy a product or service in the market, or if it should produce it in-house (Williamson 1981). Williamson describes that the contract is used to organize the economic transaction, and that more complex contracts gives rise to increased transaction costs. In order to choose the optimal procurement strategy, it is hence necessary to evaluate the supplier's ability to generate economies of scale, versus the need for relational investments necessary for the transaction to be conducted. The three factors that gives rise to transaction costs are according Williamson (1979) also proposed that uncertainty, frequency of transaction and degree of transaction-specific investments required.

Since the RSP is a very complex form of contracting, there needs to be a presence of high transaction costs for justifying spending this amount of resources on developing and enforcing the RSP. This was also highlighted in the interviews, as company A operated with a threshold value that needed to be reached in order to make it worth creating and enforcing the RSP contracts.

This will in turn also be dependent on other factors that may increase the transaction costs, and that is where the role of the product characteristics discussed earlier fits in. It was initially discussed whether the RSP was only used on assemblies of high complexity, however, it turned out that the cost characteristics was the defining factor. However, the cost can be increased by drivers such as complexity, size/volume, cost of components or even the ownership of certain technology. Therefore, the first contingency factor in the model is the financial magnitude of the partnership, and the product characteristics will be used as contributing factors.

7.2 *Trusting the Supplier and Product*

The second dimension considers the behavioral aspects of the RSP that results in a shared desire for commercial success, rather than for suppliers to maximize the profits on a single, short-term transaction. Since the RSP is using the long-term, outcome-based contracts as an incentive to create goal congruence (which is in line with agency theory), it is necessary to discuss the contingency factors for creating goal congruence. This is more challenging than transaction costs, as goal congruence is not a quantifiable measure. However, it was summarized rather well in the interviews by using the word trust. This was a recurring statement, explaining that since this is a partnership that is being used throughout the life-cycle of the product, it is necessary for the involved parties to have the necessary level of trust to commit for such an extended period.

This trust goes both ways, as in an RSP the suppliers are no longer simply supplying a product to a greater assembly, but they are co-owner of the final product. This means that the suppliers must have trust in that the product will be a commercial success. Through the interviews, it was discovered that this trust was generated through the business case and type of business model, but it was also necessary for the supplier to have an in-depth understanding of both the product and market to verify the business case.

Likewise, the OEMs require sufficient trust in the supplier, which is likely to be the reason that both the supplier companies that were interviewed have been recruited based on merit, and not from open competition. This results in the creation of a behavioral contingency factor, which is summarized by the word trust. This will in turn be increased by the contributing factors discussed throughout this section.

To further emphasize the importance of trust in this model, one could only look to the case of the Boeing 787 Dreamliner presented in the theoretical chapter. This product was affected by poor execution from several of the partners, and it was apparent that there had been insufficient effort from Boeing in ensuring that the partners had the required competencies. If the OEM is not able to trust that the supplier is able to contribute to the project, then the RSP is likely to not be providing the benefits, but rather cause additional complications.

7.3 *Financial Capabilities*

The third dimension is discussing the contingency factors, or requirements, that is associated with the individual organization's readiness to use the RSP. Primarily based on the interviews, this is the financial capabilities of both the OEM and supplier.

This represents two sides of the same issue, as it describes a situation where the OEM is not able to fund the project development alone, and that the supplier have the necessary financial strength to cover these investments, in addition to postponing the revenue streams.

The financial strength of the supplier is a necessity, as the supplier will not be able to participate in the product development without having the required stability to survive until the profit appears in the future. This is because in a traditional STA or LTA, the revenue is generated once the OEM purchase the component, whereas in the RSP, the supplier will not receive revenue before the OEM has been able to sell the product.

However, the financial capability of the OEM is not necessarily a required factor, but it tends to explain why the OEM chose to implement the RSP in the first place. By using the RSP, the OEM is essentially giving away parts of its potential future revenue, which is not something one should expect unless the OEM get something in return. This is because they are forced to give away the revenue potential due to missing funds, however, it is also reasonable to believe that the OEM could accept a lower potential revenue to achieve the other benefits as well. Therefore, the financial capability of the supplier is a contingency factor, and the financial capability of the OEM is merely a contributing factor that provides the benefit of reduced interest rates on loans if present.

7.4 A Fourth Dimension— Competitive Situation

The fourth aspect is the role of competitive situation. The respondents' companies in this study were both experiencing competition from other suppliers able to deliver similar products or substitutes, meaning they benefit greatly from such close ties with the OEMs. However, in the study of the aerospace industry characteristics, it was described that the OEMs were more dependent on the suppliers than the other way around. Even though these descriptions of the competitive situations are in contrast, it is reasonable to believe that the suppliers are actually more dependent on the OEMs. This is based on the reasoning that there are two major OEMs in the aerospace industry, and even though the suppliers are diversified, the aerospace divisions in these supplier companies will rely heavily on the few projects presented by the OEMs. Hence, it would be interesting in future studies to investigate whether the power relations in the market is a factor contributing to making the RSP more viable, or if especially the suppliers will still find the RSP attractive if they do not need to secure these long-term relationships due to monopolistic tendencies.

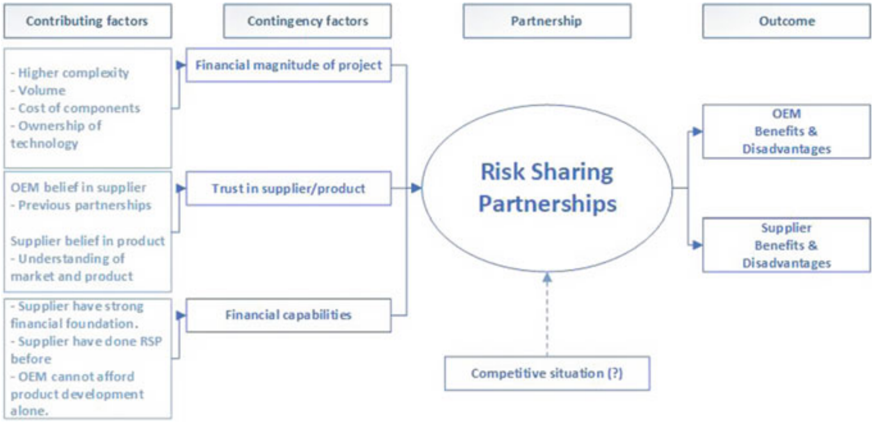

Fig. 2 The model describing contingency and contributing factors of the RSP

7.5 The Model

From the above discussion we propose the model in Fig. 2 to illustrate three dimensions that may make the RSP more attractive for organizations in other project-based industries.

The proposition is that the each of the three dimensions are contingent factors for the transfer of the benefits of RSP experienced by the aerospace industry to other industries. The intention of this model is that it will aid in cross-industry implementation of the RSP by describing in the most general way what factors in the aerospace industry has contributed to realizing these benefits. When applying the model, one should identify whether the existing partnership in the new industry is able to fulfill the requirements established by the contingency factors as a starting point for knowledge transfer.

8 Conclusion

This paper has presented a literature review and a case study on RSP, its benefits and limitations with an additional focus on including the supplier perspective of this partnership. The aim of the study was to theoretically explore the contingency factors of the RSP, as a contribution of knowledge for cross-industry implementation of the partnership model. Based on this we have presented a model where three contingency factors are identified: (1) financial magnitude of the project, (2) supplier trust and (3) the financial capabilities of mainly the supplier, but also the OEM as a contributing factor. In addition, we indicate a fourth dimension as the competitive situation. Further investigations will be conducted to both investigate and test the model on a larger population of RSP companies and explore how business models could be designed to secure the benefits for in other industries.

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Towards Safety and Productivity Improvement

Comparative Evaluation of Learning Curve Models for Construction Productivity Analysis

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Abstract This paper investigates the role of learning curve models in estimating construction productivity. Learning curve theory is actively implemented for both the scheduling and cost estimation of complex construction projects. The purpose of the research is to assess the suitability of published learning curve models in effectively analyzing the learning phenomenon for substantially complex construction operations. The research investigates five (5) learning curve models, namely the (a) Straight-line or Wright, (b) Stanford "B", (c) Cubic, (d) Piecewise or Stepwise and (e) Exponential models. The methodology includes the comparative implementation of each one of the aforementioned models for the analysis of a large infrastructure project with the use of unit and cumulative productivity data. A two-stage investigative process for the five models was applied in order to define (a) the best-fit model for historical productivity data of completed construction activities and (b) the best predictor model of future performance. The assessment criterion for the suitability is the deviation of the real construction data from the predictions generated by each model. The research results indicate that the Cubic model dominates in terms of its predictive capability on historical data, while the Stanford "B" model is a better future performance predictor. Future research directions include the extension of the research scope with the inclusion of more learning curve models in conjunction with a populated database of historical field data.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_29

Keywords Construction productivity · Estimation · Learning curves · Statistical analysis

1 Introduction

The estimation of construction productivity takes into account several factors that reflect the managerial perspective and philosophy of the project personnel (Panas and Pantouvakis 2010; Shan et al. 2011). One of the basic factors that affect productivity is the repetitive nature of construction activities. In view of this fact, the productivity improvement that is observed in subsequent production cycles of a specific repetitive construction process (e.g. high-rise building construction) is often attributed to the learning phenomenon that is developed in relation to the resources that are deployed in the project (Thomas et al. 1986; Pellegrino and Costantino 2018). In other words, the productivity of repetitive tasks is improved as the experience of the deployed crews is increased (Pellegrino et al. 2012). The required time (man-hours) for the completion of repetitive construction activities is decreased, as the repetitions increase, since (i) the crews are familiarized with the nature of the works, (ii) the coordination of the mechanical equipment and the crews is improved, (iii) the project management discipline is enhanced, (iv) more efficient techniques and construction methods are implemented, (v) more effective logistics management methods are followed and (vi) the project scope is narrowed, thus limiting the need for additional corrective activities (Thomas 2009). Within that framework, the learning phenomenon or learning curve effect expresses the influence of the human factor, namely the contribution of the deployed crews' skill and experience in construction productivity.

The integration of the learning effect in construction productivity studies enhances the accuracy of time and cost management (Lutz et al. 1994), improves project control and programming (Pellegrino et al. 2012), as well as provides the required scientific evidence for claiming lost workhours (Thomas 2009). However, learning curve studies have also been criticized for having several limitations such as oversimplification of the construction process and implementation of a one-dimensional research approach where the analysis is based on a single learning model to interpret the actual data (Jarkas and Horner 2011; Jarkas 2016). More specifically, the vast majority of learning curve studies in construction uses the straight-line or Wright model, thus limiting the presented results' scope and possibly ignoring the effect of other learning parameters on the investigated construction process. In that view, this research intends to conduct a comparative analysis of five (5) established and widely acceptable learning curve models with the intent to interpret a relatively complex construction process relating to the realization of a large-scale marine infrastructure project. The purpose is the examination of each model's suitability to interpret historical productivity data and predict future performance, in order to provide project management executives with the necessary information to reach critical project decisions (e.g. increase/decrease of project resources deployment). It is, to the authors' best knowledge, the first research attempt to investigate thoroughly the implementation of learning curve models in marine works from a productivity stance.

The structure of the paper is as follows: First, background information on pertinent research on learning curve theory is going to be provided, followed by a concise description of the construction process that served as the research testbed. Then, the research methodology is going to be delineated and, subsequently, the fitting results for the selected models will be presented. The main inferences emerging from the study will be described and, finally, the delineation of future research directions will conclude the study.

2 Background

2.1 Learning Curves

2.1.1 Theoretical Concepts

Learning curves are used for the graphical representation of the time span, the cost and/or the labour hours that are required for the execution of a series of "sufficiently complex" construction activities (Everett and Farghal 1994). The learning curve theory suggests that the required time (labour hours) for the production of a single unit (e.g. floor of a high-rise building) is incrementally decreasing as a percentage of the time that was demanded for the production of the previous unit (UN 1965; Jarkas and Horner 2011). This percentage is called "learning rate" and is a characteristic variable for the extent of the learning phenomenon in a single construction activity (Thomas et al. 1986). From a mathematical point of view, the learning rate coincides with the inclination of the learning curve. The smaller the value of the learning rate, the more intense the learning phenomenon, since each subsequent production cycle is a smaller percentage of the time required for the previous production cycle. For instance, when the learning rate equals 80%, then the required labour-hours for the production of a single unit is 20% less than the time needed for the production of the previous unit. If an activity presents a learning rate equal to 100%, then no learning phenomenon is developed for that specific task (Jarkas 2016).

The learning curve theory may be applied to the effort (typically measured in units of time) related to individual units or to the cumulative average time to complete a number of units (Farghal and Everett 1997; Jarkas and Horner 2011). If the first category of data is used, then the analysis is based on "unit data", whereas when the second category of data is utilized the analysis falls under the "cumulative data" label. As to the latter, the cumulative average time is the average time required to install or complete a given number of units. It is computed by taking the total time required to install or construct a given number of units divided by the number of units completed (Hinze and Olbina 2009). Although in construction settings it is often most convenient to use the cumulative average time, this research adopts both types of data (unit and cumulative), in order to provide a more robust research framework. In terms of the applied analytical tools, most published research in learning curve productivity analysis adopts the statistical approach for the elaboration of field data (Thomas et al. 1986; Everett and Farghal 1997; Couto and Texeira 2005; Pellegrino et al. 2012; Ammar and Samy 2015; Srour et al. 2016), thus the same approach has been implemented in the current research as well. Regarding the projects' scope for the implementation of learning curve theory, it ranges from concreting activities (Couto and Texeira 2005), to new buildings construction (Pellegrino et al. 2012) and reaching the realization of large-scale infrastructure works (Everett and Farghal 1997; Naresh and Jahren 1999).

2.1.2 Learning Curve Models

The learning curve phenomenon is studied through the use of specific mathematical models, which interpret the variation of productivity in relation to critical factors such as the number of units. There are five (5) main types of learning curve models whose concise description is as follows (Thomas et al. 1986; Everett and Farghal 1994):

- **Straight-Line Model (or Wright)**: It was first formulated by Wright in 1936 and is so named because it forms a straight line when plotted on a log-log scale (Lee et al. 2015). There are two types of Straight-line learning curve models which differ depending on either unit data or cumulative average are used. The underlying assumption of the model is that the learning rate (expressed as a percentage) remains constant throughout the duration of the activity (Thomas et al. 1986). The learning rate, L, can be derived from the slope of the logarithmic form by using $L = 2^{-n}$, where n is the slope of the logarithmic curve (Srour et al. 2016). It is the most commonly used model in construction research (Jarkas 2016) because of its simplicity and its ability to provide acceptable precision (Srour et al. 2018).
- **Stanford "B" Model**: It was developed, by the Stanford Research Institute in 1940's. This model is considered a modified Straight-line model which includes a factor "B" to represent the number of units of prior experience and shifts the learning curve downward (Badiru 1992; Srour et al. 2016). It assumes that the Straight-line model is the normal situation provided the crew has no experience resulting from performing similar activities or constructing similar units in the immediate past. The value of "B" fluctuates within the range of 0–10 (Gottlieb and Haugbølle 2010; Mályusz and Pém 2014). A crew with no prior experience will have a value "B" equal with zero, while an experienced crew may have an experience factor of four or higher (Thomas et al. 1986).
- **Cubic Model**: Carlson (1973) proposed the Cubic model and indicated that a further enhancement of the Straight-line model can be achieved using a curve with multiple slopes (Hijazi et al. 1992). This model assumes that the learning rate is not a constant variable because of the combined effects of previous experience and the levelling off of productivity as the activity nears completion. Factors "C"

and "D" are estimated using the basic equation of the model and another data point along the curve.

- **Piecewise or Stepwise Model**: It is a linearized approximation of the Cubic model with three distinct phases, while each one has a constant learning rate. On a log-log plot, this model appears as three straight line segments with different slopes. As seen on Fig. 1 the first segment represents the operation-learning phase, while the second segment starts at point x_{p1} and denotes the phase where the learning phenomenon develops. The third segment initiates at point x_{p2} and represents the end of the routine-acquiring phase. Hence, this point is also called the "standard production point" as no significant further improvement of productivity is observed beyond that point (Thomas et al. 1986).
- **Exponential Model**: It was developed by the Norwegian Building Research Institute in 1960 (U.N. 1965). It is based upon the rule that part of time/cost per unit is fixed and the other part of time/cost per unit, which can be reduced by repetition, will be reduced by one-half after a constant number of repetitions (Zahran et al. 2016). The ultimate or lowest cost or man-hours or time per unit at the end of the routine-acquiring phase (Y_{ult}) must be known along with constant "H" which represents a "Halving Factor", namely the number of units required for that part of the unit cost which can be reduced by repetition to one-half. A learning curve model for cumulative data was not presented (Thomas et al. 1986).

The mathematical expressions for the estimation of productivity based on the aforementioned learning curve models (LC models) are summarized in Table 1 and their graphical representation is depicted in Fig. 1.

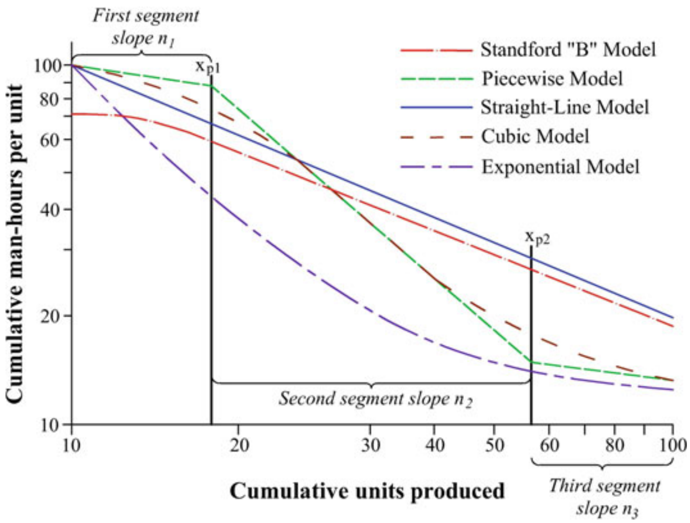

Fig. 1 Shape of various learning curve models (adopted from Thomas et al. 1986)

Table 1 Mathematical expressions for learning curve models

LC model	Mathematical expression
Straight-line	$Y = A * X^{-n}$ or $\log Y = \log A - n * \log X$
Stanford "B"	$Y = A * (X + B)^{-n}$ or $\log Y = \log A - n * \log(X + B)$
Cubic	$\log Y = \log A - b * \log X + C * (\log X)^2 + D * (\log X)^3$
Piecewise	$\log Y = \log A - n_1 * \log X - n_2 * J_1 * (\log X - \log x_{p1}) - n_3 * J_2 * (\log X - \log x_{p2})$
Exponential	$Y_u = Y_{ult} + (A - Y_{ult})/(2 * X/H)$
Where (in order of appearance)	Y = unit or cumulative average cost, man-hours or time; A = cost or man-hours or time of first unit; X = unit number; n = slope of logarithmic curve; B = factor describing the crew's prior experience; b = initial logarithmic slope at the first unit; C = quadratic factor; D = cubic factor; n_1 = slope of the first segment; n_2 = additional slope of the second segment; n_3 = additional slope of the third segment; x_{p1} = first point where the slope changes; x_{p2} = second point where the slope changes; $J_1 = 1$ when $X > x_{pl}$, 0 otherwise; $J_2 = 1$ when $X > x_{p2}$, 0 otherwise; Y_u = unit cost or man-hours or time for unit X; Y_{ult} = ultimate man-hours per unit at the end of routine-acquiring phase; H = constant named "Halving Factor"

2.2 *Caisson Construction Operations*

In general, floating caissons are prefabricated concrete box-like elements with rectangular cells that are suited for marine and harbor projects and are usually cast on floating dry docks (Panas and Pantouvakis 2014). Due to the standardized shape of the caissons and the repetitive nature of the works, since caissons are always constructed in batches, the concreting process is most commonly executed with the use of the slipforming construction technique. Slipform is a sliding-form construction method, which is used to construct vertical concrete structures (Zayed et al. 2008). Generally, the concreting and slipforming process comprises three sub-phases (see Fig. 2): (i) slipform assembling phase, (ii) slipforming phase (including an initial concreting phase) and (iii) slipform dismantling phase. Although Pantouvakis and

Fig. 2 Floating caisson production cycle

Panas (2013) identified nineteen activities for the construction of a caisson, this study focuses only on the aforementioned activities, because a fundamental prerequisite for the learning phenomenon to develop is for productivity improvements to be able to occur as a result from repeating "sufficiently complex" activities (Thomas 2009). As such, in the case of caissons construction operations, only these activities were found to inherently possess such characteristics, since the observed productivity of the other activities did not fluctuate significantly during the construction phase. For space limitation reasons, the total caisson construction process is going to be analyzed in this paper with no particular focus on individual activities.

3 Research Methodology

A large-scale marine project served as the case study for the current research. The project was completed in 2012 and comprised the construction of 34 caissons (Panas and Pantouvakis 2018). A two-stage investigative process for the five learning curve models was applied in order to define (a) the best-fit model for historical productivity data of completed construction activities and (b) the best predictor model of future performance (Everett and Farghal 1994). The solver function of MS Excel (version 2010) has been used in conjunction with the least squares method, so as to determine the optimum learning curve models parameters.

Stage A: Assessment of Best Fit Model with Historical Productivity Data

The analysis is conducted for both unit and cumulative data. The least square method is used in order to determine the optimum fitting curve. Pearson's coefficient of determination (R^2) is the preferred metric for the evaluation of each model's robustness and fluctuates from 0 to 1.00. The closer the R^2 values to 1.00, the better the correlation of the fitted data to the selected model.

Stage B: Assessment of Best Prediction Model for Future Performance

The analysis is confined to the unit data. As proposed by Everett and Farghal (1994), productivity data are divided in half, so as for the first 17 caissons to become the "historical data" and the next 17 caissons to be the future data. As before, the least squares method is used in conjunction with the Pearson's coefficient of determination for the estimation of the first 17 caissons (R^2_{1-17}). Subsequently, the computed learning curves (1–17 caissons) are extended from the 17th to the 34th caisson. Taking into account that Pearson's coefficient of determination (R^2) is not valid for correlating points with best-fit curves outside the range of points used to determine the best-fit curve, a new metric is used as follows (Everett and Farghal 1994):

$$Ef = \left(\sum \left\{ \left| y'_{m+i} - y_{m+i} \right| / y_{m+i} \right\} * 100 \right) / k, \quad \text{for } i = 1 \text{ to } i = k$$

where: m = the number of caissons to be fitted; k = the number of caissons to be predicted, y'_{m+i} = the value found on the extension of the best-fit curve; y_{m+i} =

the actual measured values; E*f* = average percentage error, which ranges from 0% indicating a perfect correlation between the extended best-fit curve and the actual data to large positive values indicating no correlation.

4 Results

Stage A: Assessment of Best Fit Model with Historical Productivity Data

Table 2 summarizes each model's performance, while Figs. 3 and 4 give a graphical representation of the results. There is a clear indication that the Cubic model demonstrates the best fitting results for unit data relating to the total caisson construction process. The Exponential model gives the least favorable adjustment, without being unacceptable, though, in absolute terms. These results enhance previous research and denote that the best fit model depends on the location and the nature of each project. For the cumulative data, again the Cubic model gives the best predictions. In fact, the cubic learning curve almost coincides with the real data. The other three models give a correlation coefficient very close to 1.00 which denotes a generally satisfactory prediction capability for all learning curve models.

In principle, the correlations for the cumulative data are better than the equivalent ones for the unit data, since the former give a more smooth graphical representation

Table 2 Correlation (R^2) of learning curve models for historical productivity data

Data type	Learning curve models				
	Straight-line	Stanford "B"	Cubic	Piecewise	Exponential
Unit	0.9530	0.9327	0.9781	0.9573	0.9256
Cumulative	0.9940	0.9890	0.9985	0.9941	–

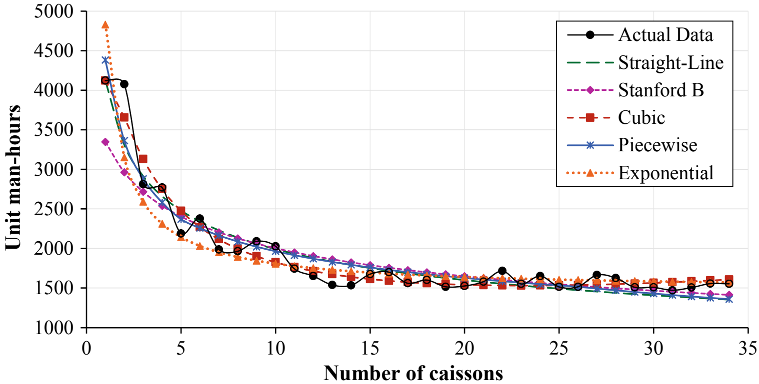

Fig. 3 Learning curves for historical data (Unit)

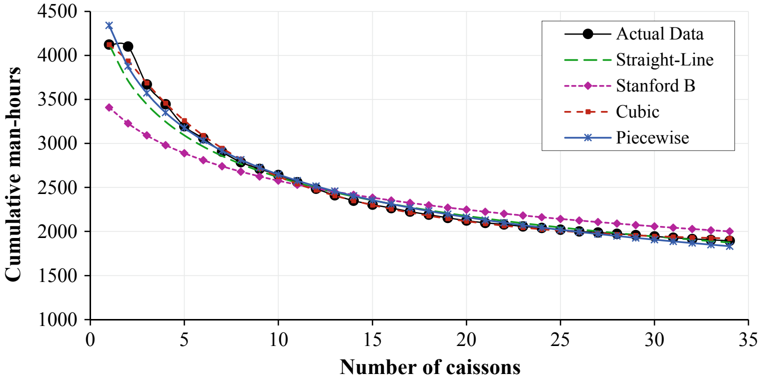

Fig. 4 Learning curves for historical data (Cumulative)

of the learning phenomenon. Comparing the Cubic and Piecewise models with the Straight-line model for the unit data there is a practically insignificant difference of 2.51% and 0.43% respectively ($p < 5\%$). The same results for the cumulative data range at the amount of 1.96% and 0.05% respectively ($p < 5\%$). This fact corroborates the tendency of the construction industry to characterize the Straight-line model as more "user-friendly" since (a) it yields similar results with the other LC models, (b) is much simpler in its implementation in terms of the required input data and parameters and (c) less assumptions are needed to be made.

Stage B: Assessment of Best Prediction Model for future performance

As depicted in Table 3, the best prediction model for future performance based on unit data is Stanford "B", since the average percentage error has a value of $Ef_{(18\text{–}34)} = 5.7\%$, which denotes good correlation between actual data and the extended curve. It is generally acceptable that Stanford "B" model simulates with acceptable accuracy complex construction processes, especially in large-scale projects. A graphical representation of the learning curve models' predictions is depicted in Fig. 5. The results for the Cubic and Piecewise models verify the findings of Everett and Farghal (1994), who claimed that these models are not a good predictor for future activities.

Table 3 Results of LC models for future performance prediction with unit data

LC Model	$R^2_{(1\text{–}17)}$ and $Ef_{(18\text{–}34)}$ values for learning curve (LC) models	
	$R^2_{(1\text{–}17)}$	$Ef_{(18\text{–}34)}$ (%)
Straight-line	0.9629	11.33
Stanford "B"	0.9626	5.75
Cubic	0.9767	17.42
Piecewise	0.9628	16.21
Exponential	0.9096	6.87

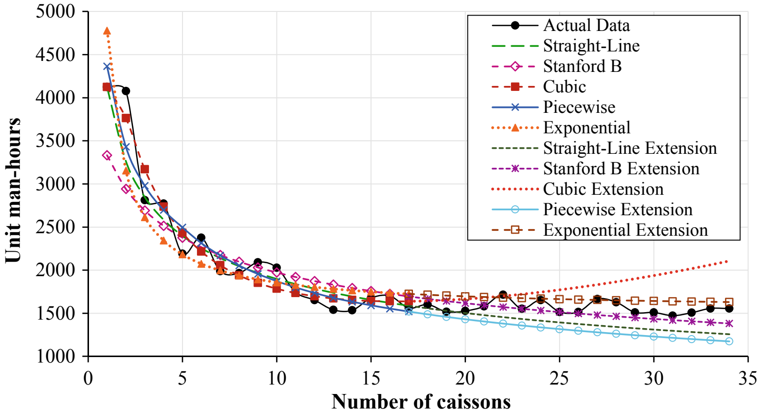

Fig. 5 Learning curves and learning curves extensions of models for unit data

More specifically, the Cubic model has the best value for $R^2_{(1-17)}$, but also presents the largest error margin of $Ef_{(18-34)} = 17.42$. Also note in Fig. 5, that the extension line of the Cubic model seems to increase significantly beyond the 25th caisson. A similar, but opposite trend is found for the Piecewise model as well, while it presents fairly equivalent error value ($Ef_{(18-34)} = 16.21$). Although, both models appear to be a reasonable predictor, these models deviate from the actual data for long-term prediction, since the extended curves continue upward or downward towards unrealistic values.

5 Conclusions

The conducted research demonstrated that the learning effect was intensely present in the studied project, which resulted in significant improvements in caissons construction productivity. All five (5) learning curve models were scrutinized for unit and cumulative historical productivity data and yielded a coefficient of $R^2 > 0.90$, which denotes a strong correlation to real data. The Cubic model has proven to be the best performer in terms of its adjustment capability to the historical data.

In terms of the future performance prediction capability, unit data was solely used for all learning curve models. Stanford “B” model was found to be the best predictor, with the Exponential and Straight-line model being quite close in terms of predictability. Therefore, it is beyond doubt that learning curve theory is an efficient and effective tool for assessing historical and predicting future productivity data in the case of caisson construction operations.

Possible research extensions could be developed in the area of future performance predictions, by adopting different data representation techniques such as (a) cumulative average data, (b) moving average data and (c) exponential weighted average. The research scope may be enhanced with the inclusion of other (non-classic) learning curve models (e.g. DeJong, Knecht, hyperbolic models), which were excluded from the current study due to brevity reasons. The enhancement of the already established historical project database with even more data covering similar activities is deemed necessary, so as to be able to structure a future performance prediction tool with inherent flexibility to simulate different work scenarios and feed project executives with valuable insights for informed decision making.

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Construction Project Manager (CPM) Contributions to Construction Health and Safety (H&S)

John Smallwood

Abstract The construction project manager (CPM) identity of work (IoW) records a range of H&S actions required of CPMs throughout the six stages of projects. Furthermore, CPMs as project leaders, are in a unique position to integrate H&S into the six stages of projects. Given the aforementioned, a study was conducted to determine the nature and extent of CPM contributions to construction H&S. A self-administered questionnaire survey delivered per e-mail, was conducted among a convenience sample stratum consisting of CPMs. The salient findings include that: seven project parameters are important to CPMs; CPMs consider/refer to H&S primarily during construction documentation and management, and tender documentation and procurement, in terms of project stages; CPMs generally undertake 'designing for construction H&S'-related actions relative to their projects/practices, and CPMs are knowledgeable with respect to project managing construction H&S, risk management, and constructability reviews, however, less so relative to the influence of design on construction H&S. The study concluded that CPMs consider/refer to H&S, there is more focus on H&S during procurement and construction, than design, and CPMs do understand and appreciate the need to integrate H&S into construction project management. The study indicates a need for enhanced integration of H&S into the first three stages of projects, and the upstream design aspects such as concept design.

Keywords Construction · Health and safety · Project managers

1 Introduction

The Construction Industry Development Board (cidb) (2009) highlighted the considerable number of accidents, fatalities, and other injuries that occur in the South African construction industry in their report 'Construction Health & Safety Status & Recommendations'. The construction industry experiences 0.98 disabling injuries

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_30

per 100 workers, which is referred to as the disabling injury incidence rate (DIIR), the all industry average being 0.78. The fatality rate (FR) is 25.5 per 100,000 workers, which does not compare favourably with international rates, the Australian construction industry FR for 2016 was 3.3 (Safe Work Australia 2017), and for the United Kingdom (UK), was 1.94 in 2015/2016 (Health & Safety Executive 2016). The severity rate (SR) in turn indicates the number of days lost due to accidents for every 1000 h worked. The South African construction industry SR 1.14 is the fourth highest, the all industry average being 0.59. Given that the average worker works 2000 h per year, if the SR is multiplied by 2, the average number of days lost per worker per year can be computed—the construction industry lost 2.28 working days per worker. This is equivalent to 1.0% of working time. A further aspect is that the total cost of accidents (COA) could have been between 4.3 and 5.4%, based upon the value of construction work completed in South Africa (cidb 2009). Therefore, the indirect motivation exists for CPMs to reduce project costs through improved H&S performance.

Given the differing interpretation of project management globally, it is important to define it within the context of South Africa, namely: "Construction project management is the management of projects within the built environment from conception to completion, including management of related professional services, and the CPM is the one point of responsibility in this regard." (South African Council for the Project and Construction Management Professions (SACPCMP) 2006). Therefore, CPMs manage design delivery, integrate design and construction, and manage the construction process indirectly.

The Australian Federal Safety Commissioner's best practice client H&S principles emphasise, inter alia, the inclusion of H&S as an integral aspect of project management, and that H&S should be afforded status equal to that afforded cost, quality, and time (Department of Education, Employment and Workplace Relations 2008). Lingard and Rowlinson (2005) emphasise the importance of a multi-stakeholder approach to H&S, and state that all parties to a project – clients, designers, specialist consultants, specialist subcontractors, and suppliers have a role to play in ensuring that H&S risks are controlled.

Clients, designers, quantity surveyors, principal contractors, and contractors have a range of H&S responsibilities in terms of the Construction Regulations, which constitute the primary regulations in terms of managing H&S in the South African construction industry (Republic of South Africa 2014). Although CPMs are not mentioned in the Construction Regulations, given the definition of construction project management and the requirements arising from the Construction Regulations, CPMs must ensure that H&S is integrated into the six stages of projects. Furthermore, integration implies that CPMs must ensure that H&S is a 'value' during projects.

A substantial period has elapsed since previous 'CPM H&S-related' studies were conducted in South Africa (Smallwood 1996; Smallwood and Venter 2002). Furthermore, the Construction Regulations were only promulgated in 2003, and amended in 2014, the CPM identity of work (IoW) was only finalised in 2006, and the cidb 'Construction Health & Safety Status & Recommendations' report was published in 2009. The Construction Regulations introduced major H&S requirements for clients and designers. The CPM IoW identified six stages of projects, and then the range of interventions and outputs per stage, H&S included. The cidb report cited the high-level of non-compliance with H&S legislative requirements, which the cidb contends is indicative of a deficiency of effective management and supervision of H&S on construction sites, as well as planning from the inception/conception of projects within the context of project management. Given the status of H&S in South African construction, the requirements of H&S legislation, the research gap identified in the previous paragraph, and the CPM identity of work (IoW), a study was conducted, the aim of which was to evaluate the contribution of CPMs to construction H&S, and identify interventions that can contribute to improving H&S performance. The objectives of the study were to determine, inter alia, the:

- importance of project parameters to respondents' practices;
- frequency at which respondents' practices consider/refer to H&S during the six stages of projects;
- frequency at which respondents' practices undertake 'designing for construction H&S' actions relative to projects/their practices, and
- respondents' rating of their knowledge relative to six construction H&S-related aspects.

2 Review of the Literature

2.1 Previous South African CPM and Construction H&S Studies

The first South African 'CPM and H&S' study (Smallwood 1996) addressed a range of issues, and the findings are summarised as follows. H&S is negatively affected by short project periods, primarily due to general pressure, and by competitive tendering. Cost, environment, productivity, quality, schedule, and client perception are negatively affected by inadequate H&S. There should be H&S prequalification, and a provisional sum for H&S.

Evaluating constructability, and preparing project documentation predominate in terms of the occasions CPMs deliberate H&S. Method of fixing, and design predominate in terms of aspects CPMs consider when deliberating constructability relative to H&S. Site meetings, and site inspections predominate in terms of the occasions CPMs refer to H&S. 95.8% of respondents indicated that inadequate or the lack of H&S increases project risk.

The second South African 'CPM and H&S' study (Smallwood and Venter 2002) addressed more issues, and the details relative to the influence of designers on construction H&S, based upon recently completed 'The influence of architects on construction H&S', and 'The influence of engineers on construction H&S' studies. The findings are summarised as follows. In terms of the importance of project parameters, client satisfaction predominated, followed by the traditional project parameters of quality, cost, and time – project H&S and public H&S achieved rankings of fifth and sixth respectively. Quality predominated in terms of the importance of contractor H&S, labour productivity, and quality to CPMs. Site meetings, site handover, and site inspections/discussions predominate, followed by constructability reviews, pre-tender meeting, and pre-qualifying contractors in terms of the frequency at which CPMs consider or refer to construction H&S on fourteen occasions. Specification, type of structural frame, method of fixing, and position of components predominate in terms of the frequency at which CPMs consider or refer to construction H&S relative to sixteen design related aspects. Clients revise their requirements, and competitive tendering predominate in terms of the frequency at which CPMs achieve/encounter/use eight procurement related situations/interventions. Project specific plan for H&S and quality, designer prioritisation/consideration, and constructability reviews by designers, predominate in terms of the potential of thirteen aspects/actions to contribute to an improvement in H&S performance. Labour productivity predominates in terms of the extent to which inadequate or the lack of H&S negatively affects seven other project parameters. 93.3% of CPMs responded that inadequate H&S increased overall project risk, and 63.3% of CPMs responded that H&S should be afforded status equal to that of the traditional project parameters of cost, quality, and time.

2.2 The Implications of the Client and Designer Responsibilities for CPMs

The South African Construction Regulations (Republic of South Africa 2014) schedule a range of responsibilities for clients, and designers, which have implications for CPMs in their capacity as project leaders.

Clients are required to, inter alia, conduct a baseline risk assessment (BRA), which provides the basis for the H&S specification, which must then be provided to designers. Designers in turn are required to, inter alia, consider the H&S specification, and in response, submit a report to the client before tender stage that includes all the relevant H&S information about the design that may affect the pricing of the work, the geotechnical-science aspects, and the loading that the structure is designed to withstand. Designers are also required to: inform the client of any known or anticipated dangers or hazards relating to the construction work; make available all relevant information required for the safe execution of the work upon being designed or when the design is changed; modify the design or make use of substitute materials where the design necessitates the use of dangerous procedures or materials hazardous to H&S, and consider hazards relating to subsequent maintenance of the structure and make provision in the design for that work to be performed to minimise the risk. To mitigate design originated hazards, requires hazard identification and risk assessment (HIRA) and appropriate responses, which process should be structured and documented. Therefore, CPMs must effectively integrate H&S into the management of the design process.

Thereafter, clients must include the H&S specification in the tender documentation, which in theory should have been revised to include any relevant H&S information included in the designer report. Thereafter, they must, inter alia: ensure that potential principal contractors (PCs) have made provision for the cost of H&S in their tenders; ensure that the PC to be appointed has the necessary competencies and resources; ensure that every PC is registered for workers' compensation insurance cover and in good standing in terms thereof; discuss and negotiate with the PC the contents of the PC's H&S plan and thereafter approve it; take reasonable steps to ensure that each contractor's H&S plan is implemented and maintained; ensure that periodic H&S audits and documentation verification are conducted at agreed intervals, but at least once every 30 days; ensure that the H&S file is kept and maintained by the PC, and appoint a competent person in writing as an agent when a construction work permit is required. Therefore, CPMs must effectively integrate H&S into the management of the procurement process, and the 'indirect' management of the construction process.

2.3 CPM Identity of Work (IoW)

The CPM IoW (SACPCMP 2006) is silent relative to stage 1 'project initiation and briefing' in terms of H&S. The interventions with respect to stages 2–6 are as follows. Stage 2 'concept and feasibility': Advise the client regarding the requirement to appoint an H&S consultant. Stage 3 'design development': Facilitate any input from the design consultants required by CM regarding constructability. Stage 4 'tender documentation and procurement': Facilitate and monitor the preparation by the H&S consultant of the H&S Specification for the project. Stage 5 'construction documentation and management': Monitor the auditing of the contractor's H&S plan by the H&S consultant, and monitor the production of the H&S File by the H&S consultant and contractors. Stage 6 'project close out': Manage the finalisation of the H&S File for submission to the client.

3 Research

3.1 Research Method and Sample Stratum

The quantitative study entailed a self-administered questionnaire survey delivered per e-mail. The questionnaire was based upon a previous study conducted among a range of designers in South Africa to determine their perceptions and practices with respect to construction H&S (Smallwood 2004). The questionnaire consisted of fourteen

Table 1 The importance of project parameters to respondents' practices

Parameter	Response (%)						MS	R
	Unsure	Not	………………………			Very		
		1	2	3	4	5		
Quality	0.0	0.0	0.0	7.1	7.1	85.7	4.79	1
Client satisfaction	2.4	0.0	0.0	2.4	11.9	83.3	4.71	2
Project H&S	2.4	0.0	2.4	2.4	11.9	81.0	4.64	3
Public H&S	2.4	0.0	2.4	2.4	14.3	78.6	4.62	4
Time	0.0	0.0	0.0	9.5	19.0	71.4	4.62	5
Productivity (contractor)	0.0	0.0	4.8	4.8	23.8	66.7	4.52	6
Cost	2.4	0.0	0.0	4.8	35.7	57.1	4.43	7

questions – thirteen closed – ended, and one open-ended. Seven of the close – ended questions were Likert scale type questions, and six were demographics related. A convenience sample survey consisting of CPMs was adopted for the national study. 43 Responses were included in the analysis of the data, which entailed the computation of frequencies, and a measure of central tendency in the form of a mean score (MS), to enable the interpretation of percentage responses to Likert point scale type questions, and the ranking of variables.

3.2 Research Results

Table 1 indicates the importance of project parameters to respondents' practices in terms of percentage responses to a scale of 1 (not important) to 5 (very important), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs are above the midpoint of 3.00, which indicates that in general, the respondents' practices perceive the project parameters to be more than important, as opposed to less than important. However, all the MSs are $> 4.20 \leq 5.00$ – between more than important to very important/very important. Quality predominates, followed by client satisfaction, and then the subjects of the study, namely project H&S and public H&S, which in turn are followed by time, productivity, and cost. It is notable that two of the three traditional project parameters, namely time and cost are ranked fifth and seventh respectively, while the third, namely quality, is ranked first.

Table 2 indicates the frequency at which respondents' practices consider/refer to H&S during the six stages of projects in terms of a scale of never to always, and a MS ranging between 1.00 and 5.00. It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general H&S can be deemed to be considered/referred to during the six stages frequently, as opposed to infrequently. However, it is notable that 3/6 (50%) of the MSs are $> 4.20 \leq 5.00$, and thus H&S can be deemed to be considered/referred to between often to always/always. Construction

Table 2 Frequency at which respondents' practices consider/refer to H&S during the six stages of projects

Stage	Response (%)						MS	R
	Unsure	Never	Rarely	Sometimes	Often	Always		
Construction documentation and management (S5)	0.0	0.0	0.0	0.0	9.4	90.6	4.91	1
Tender documentation and procurement (S4)	0.0	0.0	0.0	6.3	21.9	71.9	4.66	2
Design development (S3)	0.0	0.0	3.1	18.8	21.9	56.3	4.31	3
Project close out (S6)	3.1	3.1	0.0	18.8	34.4	40.6	4.13	4
Concept and feasibility (S2)	0.0	3.1	15.6	15.6	28.1	37.5	3.81	5
Project initiation and briefing (S1)	0.0	9.4	18.8	18.8	15.6	37.5	3.53	6

documentation and management predominates with a MS of 4.91, followed by tender documentation and procurement, and design development. The frequency relative to the latter is notable, as the opportunity to influence construction H&S is greater during the early than the latter stages.

Table 3 indicates the frequency at which respondents' practices undertake 'designing for construction H&S'-related actions relative to projects/their practices in terms of a scale of never to always, and a MS ranging between 1.00 and 5.00. The actions were derived from a previous study conducted among designers by the author (Smallwood 2016). It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general the 'designing for construction H&S' actions can be deemed to be undertaken relative to respondents' projects/practices, frequently as opposed to infrequently.

It is notable that 15/29 (51.7%) of the MSs are $> 4.20 \leq 5.00$, which indicates that the 'designing for construction H&S' actions can be deemed to be undertaken relative to respondents' projects/practices between often to always/always. It is notable that two of the top fifteen actions are H&S plan-related, three are H&S specification/information-related, seven are hazards and risk-related, one is H&S File-related, one is H&S Agent related, and one is design and construction method statement-related.

Table 3 Frequency at which respondents' practices undertake 'designing for construction H&S'-related actions relative to projects/their practices

Action	Response (%)						MS	R
	Unsure	Never	Rarely	Sometimes	Often	Always		
Monitor construction activities relative to the H&S plan	0.0	0.0	0.0	3.1	9.4	87.5	4.84	1
Review the construction phase H&S plan	0.0	0.0	0.0	3.1	15.6	81.3	4.78	2
Provide H&S information for tender documentation	0.0	0.0	0.0	0.0	22.6	77.4	4.77	3
Identify hazards	0.0	0.0	0.0	3.1	21.9	75.0	4.72	4
Review the client H&S specification	0.0	0.0	0.0	6.3	21.9	71.9	4.66	5
Conduct site risk assessments and actions/directions	0.0	0.0	6.7	6.7	3.3	83.3	4.63	6
Avoid/eliminate hazards	0.0	0.0	3.1	3.1	21.9	71.9	4.63	7
Monitor construction activities relative to design HIRAs	0.0	0.0	3.1	9.4	18.8	68.8	4.53	8
Maintain a register of project hazards and risk	0.0	6.3	3.1	3.1	12.5	75.0	4.47	9
Gather H&S information relative to projects	0.0	0.0	6.3	6.3	25.0	62.5	4.44	10
Assess/prioritise/investigate selected risks	3.1	0.0	0.0	18.8	18.8	59.4	4.42	11
Focus on significant/unusual/difficult risks	3.1	0.0	6.3	9.4	18.8	62.5	4.42	12
Monitor the development of/contribute to the H&S file	0.0	0.0	3.2	16.1	19.4	61.3	4.39	13
Assemble H&S expertise e.g. consult an H&S Agent	0.0	6.3	6.3	3.1	15.6	68.8	4.34	14
Prepare design and construction method statements or require same	3.1	0.0	6.3	12.5	21.9	56.3	4.32	15
Document the design HIRA process	9.4	0.0	6.3	15.6	25.0	43.8	4.17	16
Review the designer report(s) submitted to the client	6.3	0.0	6.3	21.9	15.6	50.0	4.17	17
Consider H&S during maintenance	0.0	3.1	9.4	18.8	9.4	59.4	4.13	18

(continued)

Table 3 (continued)

Action	Response (%)						MS	R
	Unsure	Never	Rarely	Sometimes	Often	Always		
Maintain a practice register of hazards and risk	0.0	12.5	3.1	9.4	15.6	59.4	4.06	19
Identify risks from residual hazards	6.3	0.0	9.4	18.8	25.0	40.6	4.03	20
Revisit the process if the design changes at any point	0.0	0.0	12.9	16.1	25.8	45.2	4.03	21
Amend designs or propose same	6.3	0.0	9.4	21.9	25.0	37.5	3.97	22
Prepare a 'design loop' for temporary works	12.9	3.2	9.7	16.1	19.4	38.7	3.93	23
Identify residual hazards or propose same	0.0	0.0	12.5	21.9	28.1	37.5	3.91	24
Amend details or propose same	9.4	0.0	12.5	18.8	28.1	31.3	3.86	25
Provide information on residual risks e.g. on drawings or require same	9.4	3.1	12.5	12.5	28.1	34.4	3.86	26
Prepare a 'designer report' (H&S) for clients or manage same	15.6	3.1	15.6	12.5	18.8	34.4	3.78	27
Compile a project H&S 'lessons learnt' report	3.1	9.4	9.4	21.9	12.5	43.8	3.74	28
Substitute materials or propose same	3.1	0.0	12.5	34.4	21.9	28.1	3.68	29

The remaining 14/29 (48.3%) of the MSs are >3.40 ≤ 4.20, which indicates that H&S can be deemed to be undertaken relative to respondents' projects/practices between sometimes to often/often. Eleven of the remaining fourteen actions are design HIRA or design HIRA process-related, and three are report-related.

Table 4 indicates the respondents' rating of their knowledge relative to six construction H&S-related aspects in terms of a scale of 1 (limited) to 5 (extensive), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general the respondents rate their knowledge as above average. However, it is notable that 2/6 (33.3%) of the MSs are > 4.20 ≤ 5.00, which indicates that the rating is between above average to extensive/extensive – project managing construction H&S, and risk management. A further 3/6 (50%) are > 3.40 ≤ 4.20. which indicates that the rating is average to above average/above average – constructability reviews, prevention through design (H&S), and designing for construction H&S. The MS of design HIRAs, which is ranked sixth, is 3.39, which is 0.01 below the lower limit of the upper range.

Table 4 Respondents' rating of their knowledge relative to six construction H&S-related aspects

Aspect	Response (%)						MS	R
	Unsure	Limited	…………………………			Extensive		
		1	2	3	4	5		
Project managing construction H&S	0.0	0.0	3.1	6.3	43.8	46.9	4.34	1
Risk management	0.0	0.0	0.0	9.4	50.0	40.6	4.31	2
Constructability reviews	0.0	0.0	3.1	21.9	46.9	28.1	4.00	3
Prevention through design (H&S)	0.0	0.0	9.4	37.5	34.4	18.8	3.63	4
Designing for construction H&S	0.0	0.0	15.6	37.5	31.3	15.6	3.47	5
Design HIRAs	3.1	0.0	18.8	34.4	31.3	12.5	3.39	6

4 Conclusions

Given that project H&S was ranked third, and public H&S fourth, in terms of the importance of seven project parameters, H&S can be deemed to be considered and viewed as a value by CPMs.

Given the frequency at which respondents' practices consider/refer to H&S during construction documentation and management (Stage 5), which was ranked first, followed by tender documentation and procurement (Stage 4), it can be concluded that CPMs focus on construction H&S more during the downstream and midstream stages than the upstream stages. However, given the frequency at which they consider/refer to design development (Stage 3), it can be concluded that CPMs understand and appreciate the role of design in construction H&S. Given that concept and feasibility (Stage 2), and project initiation and briefing (Stage 1) were the stages when H&S was considered/referred to least, it can be concluded that CPMs do not understand and appreciate the potential to influence construction H&S at these stages.

Given the frequency at which respondents' practices undertake 'designing for construction H&S' actions relative to projects/their practices, it can be concluded that CPMs project manage H&S in terms of H&S information, HIRA, construction planning therefor, and designing for construction H&S.

The respondents' rating of their knowledge relative to six construction H&S aspects leads to the conclusion that they are knowledgeable with respect to project managing construction H&S, risk management, and constructability reviews, however, less so relative to prevention through design (H&S), designing for construction H&S, and design HIRAs. This leads to a further conclusion, namely that they need enlightening with respect to the influence of design on construction H&S.

Finally, it is concluded that construction H&S is a multi-stakeholder issue.

5 Recommendations

CPMs should consider/refer to construction H&S more during project initiation and briefing (Stage 1), concept and feasibility (Stage 2), and design development (Stage 3). Project initiation and briefing (Stage 1) is a critical stage, as this is when client briefing occurs, and the opportunity exists to set a precedent in terms of H&S. Concept and feasibility (Stage 2), impacts on construction H&S primarily through concept design.

CPMs should focus more on temporary works, residual hazards and risks and the response thereto, 'designer reports', and project H&S 'lessons learnt' reports in terms of 'designing for construction H&S' actions relative to projects/their practices.

The CPM IoW should be reviewed to reflect 'better CPM H&S practice', which includes enhanced integration of H&S into projects during the six stages, and especially project initiation and briefing (Stage 1), relative to which it is silent.

Tertiary CPM education should address construction H&S in a comprehensive manner, as opposed to H&S legislation, and should be embedded in CPM programmes. The SACPCMP should ensure that the extent to which construction H&S is embedded in CPM programmes is interrogated during accreditation visits to tertiary institutions. The influence of design on construction H&S must be addressed.

The Association of Construction Project Managers (ACPM), and the SACPCMP should evolve 'CPM and construction H&S' practice notes and guidelines.

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The Role of Procurement in Construction Health and Safety

John Smallwood and Claire Deacon

Abstract Relative to other industries in South Africa and construction industries worldwide, the construction process generates a disproportionate number of fatalities, injuries, and disease and both the direct and indirect costs contribute to the cumulative cost of construction. Literature indicates that globally, procurement influences construction H&S, including issues such as pre-qualification, reference to construction H&S in conditions of contract and contract documentation, facilitation of financial provision for construction H&S, assessment thereof, and reporting thereon. A study was conducted among delegates attending a two-day summit to determine their perceptions relative to the role of procurement in construction H&S, and whether the summit had an impact, or not. The following constitute the salient findings. Delegates do have an understanding and appreciation of the role of procurement in construction H&S, and the multi-stakeholder nature of construction H&S. Furthermore, the summit did have an impact in terms of inducing a change in the delegates' culture. The paper concludes that: all stakeholders influence construction H&S; pre-qualification of all stakeholders in terms of construction H&S is important; construction H&S should be considered or referred to during all six project stages, in conditions of contract, contract documentation, and when deliberating project duration; financial provision for construction H&S should be facilitated and assessed; supply chain management within the context of construction H&S is critical; construction H&S performance should be assessed throughout projects, and be addressed in close out reports. Recommendations include: partnering as a process that includes H&S should be implemented on projects; multi-stakeholder project H&S plans should be compiled for projects, and more emphasis should be placed on construction H&S during the procurement process.

Keywords Construction · Health and safety · Procurement

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_31

1 Introduction

According to the Construction Industry Development Board (cidb) (2009), the South African construction industry experiences 0.98 disabling injuries per 100 workers, which is referred to as the disabling injury incidence rate (DIIR), the all industry average being 0.78. The fatality rate (FR) is 25.5 per 100,000 workers, which does not compare favourably with international rates, the Australian construction industry FR was for 2016 was 3.3 (Safe Work Australia 2017), and for the United Kingdom (UK), was 1.94 in 2015/2016 (Health and Safety Executive 2016). The severity rate (SR) in turn indicates the number of days lost due to accidents for every 1000 h worked. The South African construction industry SR 1.14 is the fourth highest, the all industry average being 0.59. Given that the average worker works 2000 h per year, if the SR is multiplied by 2, the average number of days lost per worker per year can be computed – the construction industry lost 2.28 working days per worker. This is equivalent to 1.0% of working time. A further aspect is that the total cost of accidents (COA) could have been between 4.3 and 5.4%, based upon the value of construction work completed in South Africa (cidb 2009).

Procurement is an integral aspect of, and a process in the built environment, and construction projects. The procurement process is not constrained to stage 4 ‘tender documentation and procurement’ of projects, as it involves all project stakeholders, and is thus a multi-stakeholder process that includes clients, construction project managers (CPMs), designers, quantity surveyors, principal contractors, subcontractors, and materials manufacturers and suppliers. The procurement process is framed and influenced by legislation, standards, and the general environment.

Aspects such as the type of procurement system adopted, standard conditions of contract, project duration relative to the nature and scope of the project, reference to construction H&S in contract documentation, mechanisms to facilitate financial provision for H&S, However, the development of construction projects is fragmented as each stakeholder has its own priorities. The need is thus for all stakeholders to improve the methods of procurement, as well as ensuring cost-based strategies, and the adoption of a systematic and strategic approach. The principles of efficiency, accountability, and appropriate transfer of risk are some of the elements required to maximise the value and sustainability of construction activities (Alharthi et al. 2014).

2 Review of the Literature

2.1 Legislation

The Construction Regulations require a range of ‘procurement’ related interventions (Republic of South Africa 2014).

Clients are required to conduct a baseline risk assessment (BRA), and then prepare an H&S specification based on the BRA, which is then provided to the designers who must take it into account during design. The designers in turn must provide the client with a 'designer' report' in response thereto. The client must include the H&S specification in the tender documents, and ensure that potential PCs have made provision for the cost of H&S in their tenders, and ensure that the PC to be appointed has the necessary competencies and resources.

Thereafter clients must ensure that every PC is registered for workers' compensation insurance cover and in good standing, appoint every PC in writing, discuss and negotiate with the PC the contents of the PC's H&S plan and thereafter approve it, and take reasonable steps to ensure cooperation between all contractors appointed by the client. However, clients are required to conduct follow up interventions: ensure that each contractor's H&S plan is implemented and maintained, and ensure that periodic H&S audits and documentation verification are conducted at least monthly.

Where a construction work permit is required, a client must appoint a competent person in writing as an agent, which agent must manage the H&S on a construction project. However, the agent must be registered with a statutory body.

PCs in turn are required to: provide subcontractors (SCs) who are tendering for the PC with the relevant sections of the H&S specification; ensure that potential SCs have made provision for the cost of H&S in their tenders; ensure that the SCs to be appointed have the necessary competencies and resources; ensure that every SC is registered for workers' compensation insurance cover and in good standing; appoint every SC in writing; discuss and negotiate with the SC the contents of the SC's H&S plan and thereafter approve it; take reasonable steps to ensure cooperation between all SCs; ensure that each SC's H&S plan is implemented and maintained, and ensure that periodic H&S audits and documentation verification are conducted at least monthly.

2.2 Identities of Work (IoW)

Built Environment Professionals (BEPs) within the South African built environment, are required to register with their respective statutory body. There are six statutory councils that register seven broad categories of BEPs: architects; construction managers; construction project managers (CPMs); engineers; landscape architects; property valuers, and quantity surveyors (QSs). Each of the six Built Environment Professional Councils (BEPCs) developed a scope of work, or what is known as the 'Identity of Work' (IoW), which documents the interventions relative to the six stages of projects. Table 1 presents the extent to which the seven IoW refer to construction H&S interventions per stage (Deacon 2016).

Table 1 Extent to which the seven identities of work refer to construction H&S interventions

Stage	%
Stage 1: Project initiation and briefing	0.0
Stage 2: Concept and feasibility	66.7
Stage 3: Design and development	57.1
Stage 4: Tender documentation and procurement	28.6
Stage 5: Construction documentation and management	71.4
Stage 6: Project close-out	28.6

2.3 Standard Conditions of Contract

The cidb Standard for Uniformity in Construction Procurement recommends the use of the following standard forms of contract for construction works' contracts in South Africa (cidb 2009): General Conditions of Contract (GCC) for civil engineering construction; International Federation of Consulting Engineers (FIDIC) for building and civil engineering construction; Joint Building Contracts Committee (JBCC) Principal Building or Minor Works Agreement for building construction, and the NEC3 Engineering and Construction Contracts, as published by the Institution of Civil Engineers for civil engineering construction.

All the standard forms of contract make explicit or implicit reference to the fact that the forms of contract are subject to the laws of the land and therefore to South African legislation impacting on construction H&S. However, in terms of specific reference to H&S, the: GCC includes the requirement 'reporting of accidents'; JBCC does not, and FIDIC and NEC do, although in some cases the terminology or referencing does not fully align with South African H&S legislation and regulations.

Wells and Hawkins (2009) state that many contracts make vague and general reference to H&S. However, without clear benchmarks and definitions the terms used such as 'reasonable precautions' tend to be ignored.

Clearly, scope exists for the standard forms of contract to include more direct reference to construction H&S, the Construction Regulations, and the obligations of contractors as well as providing for additional client driven H&S requirements.

2.4 Tendering Practices

The practice of contracting is noted as having the potential to intensify project risk. The increased risk is because of economic pressure and competitive tendering, where those that take H&S into consideration are penalised due to higher tender pricing (Wells and Hawkins 2009; Zou and Sunindijo 2015). Most contracts are awarded through competitive tendering, with the lowest tenderer being awarded the contract (Rowlinson 2004; Wells and Hawkins 2009). Rowlinson (2004) states that this form of tendering has been identified as the cause of a vicious cycle of cost cutting and claims generation. Other factors include a negative impact in terms of cost, H&S, quality, and time, with H&S most likely to suffer first due to budget cuts.

According to Smallwood (2011), due to competitive tendering, contractors need to limit costs, and consequently, the winning tender is unlikely to make adequate provision for H&S equipment, welfare facilities, and a healthy and safe working environment.

2.5 Challenges with Respect to Financial Provision for H&S

Smallwood and Emuze (2014) required respondents to a study to indicate their concurrence with respect to a range of statements. A mean score (MS) between 1.00 and 5.00 is recorded in parentheses after the statements: competitive tendering without reference to H&S marginalises H&S (4.09); contractors are afforded the opportunity to price H&S on an equitable basis (2.36), and contractors are afforded the opportunity to price items included in H&S specifications on an equitable basis (2.36).

Wells and Hawkins (2009) state that to avoid misunderstanding of what is required and to facilitate the checking of contractors' financial provision for H&S, it is recommended that H&S items that can be separately priced be listed as prime cost items, provisional sums, or the use of another form of pricing mechanism.

The study conducted by Smallwood and Emuze (2014) determined the concurrence with respect to a further range of statements: contract document enabled financial provision for H&S promotes H&S (4.36); a detailed H&S section should be included in the Preliminaries (4.27), and a provisional sum should be provided for H&S in the preliminaries (3.64).

3 Research

3.1 Sample Stratum and Method

The survey entailed the administration of a thirty-one-question questionnaire, at an ACHASM two-day Summit, at the inception and upon the closure, to determine whether the summit, which had a 'procurement' theme had an impact on delegates perceptions, and if so, the extent. The questionnaire required respondents to indicate their degree of concurrence with statements in terms of a five-point Likert Scale 'strongly disagree' to 'strongly agree'. An additional 'unsure' response was provided.

41 No. Responses were included in the analysis of the data, which entailed the computation of frequencies and a measure of central tendency in the form of a MS to interpret the percentage responses to six points of the scale.

4 Results

Table 2 provides a comparison of pre-assessment and post-assessment agreement with 31 statements related to the role of procurement in construction H&S in terms of a pre- and post-MS, and a percentage variance in terms of the percentage by which the post-MS is greater than the pre-MS.

29/31 Statements are true (T), which should have attracted agreement, and 2/31 are false (F), which should have attracted disagreement.

It is notable that 20/31 (64.5%) pre-MSs are $> 4.20 \leq 5.00$, and 26/31 (83.9%) post-MSs are $> 4.20 \leq 5.00$, which indicates concurrence between agree to strongly agree/strongly agree.

The biggest percentage differences between post-MSs relative to pre-MSs are: cost, quality, and time are more important than H&S (F) (−20.8%); procurement influences H&S (T) (12.1%); designers can influence H&S (T) (9.3%); construction project managers' H&S competencies should be a criterion for appointment (T) (9.3%), and quantity surveyors can influence H&S (T) (8.5%).

It is notable that 'H&S should be addressed during all six stages of projects' (T) has the highest pre- (4.63) and post-MS (4.68), which amplifies the requirements of the Construction Regulations, and the respective identities of work, and correlates with international research findings. 'H&S is a multi-stakeholder issue' (T) registered the second highest post-MS (4.63) along with two other statements' post-MSs, which reflects the realisation that construction H&S is no longer the contractor's problem. Furthermore, it reinforces the statement 'H&S should be addressed during all six stages of projects (T)'. 'Designers can influence H&S' (T), which recorded a further second highest post-MS (4.63), reinforces the contention that (and statement) 'H&S is a multi-stakeholder issue' (T). This result is complemented by the following post-MSs, which reflect concurrence between agree to strongly agree/strongly agree: 'clients can influence H&S' (T) (4.56); 'construction project managers can influence H&S' (T) (4.50); 'CHSAs can influence H&S' (T) (4.47); 'principal contractors can influence H&S' (T) (4.41); 'quantity surveyors can influence H&S' (T) (4.28), and 'subcontractors can influence H&S' (T) (4.25).

The statement 'Project duration should consider H&S realities' (T), which recorded a further second highest post-MS (4.63), reinforces the contention that in terms of H&S, project durations should consider the nature, scope, and complexity of the work to be undertaken.

The post-MS (4.61) of the statement 'CHSAs' competencies and resources should be a criterion for appointment' (T) is notable as the Construction Regulations only refer to these issues relative to PCs and SCs. However, it is logical, in that only competent and sufficiently resourced CHSAs should be appointed. Although the registration process assesses competencies, it is not concerned with resources. This finding is complemented by the post-MSs relative to 'construction project managers' H&S competencies should be a criterion for appointment' (T) (4.44).

Table 2 Comparison of pre-assessment and post-assessment agreement with statements related to the role of procurement in construction H&S

Statement	MS		
	Pre	Post	Post > Pre (%)
H&S should be addressed during all six stages of projects (T)	4.63	4.68	1.2
H&S is a multi-stakeholder issue (T)	4.44	4.63	5.7
Designers can influence H&S (T)	4.32	4.63	9.3
Project duration should consider H&S realities (T)	4.37	4.63	7.7
CHSAs' competencies and resources should be a criterion for appointment (T)	4.50	4.61	3.2
Clients can influence H&S (T)	4.36	4.56	6.1
Procurement influences H&S (T)	4.15	4.53	12.1
Construction project managers can influence H&S (T)	4.41	4.50	2.5
Contract documentation should include detailed H&S preliminaries items (T)	4.44	4.50	1.8
Principal contractors' ability to manage their supply chain e.g. subcontractors, plant hire, and suppliers, is critical for H&S (T)	4.34	4.50	4.7
Project close out reports should include H&S (T)	4.41	4.50	2.5
CHSAs can influence H&S (T)	4.25	4.47	6.7
Principal contractors should be pre-qualified in terms of H&S (T)	4.39	4.47	2.3
Construction project managers' H&S competencies should be a criterion for appointment (T)	4.15	4.44	9.3
Project performance assessment should include H&S (T)	4.39	4.44	1.4
Conditions of contract should refer to H&S (T)	4.39	4.42	0.9
Principal contractors can influence H&S (T)	4.32	4.41	2.7
Project progress assessment should include H&S (T)	4.44	4.41	(1.0)
Subcontractors should be pre-qualified in terms of H&S (T)	4.34	4.38	1.0
Separation of design and construction marginalises H&S (T)	4.10	4.36	8.2
Ensuring adequate provision for H&S is assessed during tender adjudication (T)	4.53	4.34	(5.1)
Quantity surveyors can influence H&S (T)	4.02	4.28	8.5
Partnering as a process that includes H&S should be implemented on projects (T)	4.30	4.28	(0.6)
H&S can be influenced more during the early stages than latter stages of projects (T)	4.37	4.26	(3.2)
Subcontractors can influence H&S (T)	4.13	4.25	4.0

(continued)

Table 2 (continued)

Statement	MS		
	Pre	Post	Post > Pre (%)
Pre-tender H&S plans should be a requirement of the Construction Regulations (T)	4.10	4.25	4.8
Multi-stakeholder project H&S plans should be compiled for projects (T)	4.15	4.16	0.2
CHSAs should be appointed by clients, not other stakeholders (T)	3.98	4.06	2.9
CHSAs can price appropriately for H&S services (F)	3.64	3.79	5.8
H&S is more important than cost, quality, and time (T)	3.30	3.28	(0.9)
Cost, quality, and time are more important than H&S (F)	2.03	1.81	(20.8)

In a similar vein to competencies and resources, the post-MSs relative to the statements 'principal contractors should be pre-qualified in terms of H&S' (T) (4.47), and 'sub-contractors should be pre-qualified in terms of H&S' (T) (4.38).

The statement encapsulating the study, namely 'Procurement influences H&S' (T) recorded the sixth highest post-MS (4.53). It also represents the greatest difference between post- and pre-MSs, which indicates a shift in understanding and appreciation of the role of procurement in H&S.

The post-MSs of the statements 'contract documentation should include detailed H&S preliminaries items' (T) (4.50), and 'ensuring adequate provision for H&S is assessed during tender adjudication' (T) (4.34) support the argument that contract documentation should promote and facilitate adequate financial provision for H&S, and in the case of the latter, the requirements of clients and PCs in terms of the Construction Regulations. A related issue is that of explicit and detailed reference to H&S in standard conditions of contract as referred to by the cidb (2009), which is amplified by the post-MS (4.42) relative to 'conditions of contract should refer to H&S' (T).

Construction is fragmented in terms of contributors, both during design and construction. Consequently, the integration of contributions, especially within the context of H&S is critical. The aforementioned are reinforced by the post-MS (4.50) relative to 'principal contractors' ability to manage their supply chain e.g. subcontractors, plant hire, and suppliers, is critical for H&S'.

The argument to afford H&S status equal to the other project parameters, and include it as a project 'value', is supported by the post-MSs relative to: 'project close out reports should include H&S' (T) (4.50); 'project performance assessment should include H&S' (T) (4.44), and 'project progress assessment should include H&S' (T) (4.41).

The case for integration in terms of advancing the cause of H&S is supported by the post-MSs relative to: 'separation of design and construction marginalises H&S' (T) (4.36), and 'partnering as a process that includes H&S should be implemented on projects' (T) (4.28). In the case of the latter, partnering complements

H&S as it includes the primary project stakeholders, and focuses on the development of common project goals, H&S included, and the necessary strategy, tactics, and interventions to achieve them.

The Construction Regulations only require project H&S plans, and then relative to PCs and SCs. However, such plans are provided after the PCs and SCs have been appointed, and they may only commence work on site when such plans are approved. Non-approval of such plans results in delays. Ideally, PCs and SCs should submit pre-tender H&S plans, which can be reviewed pre-appointment, and then relative to the 'financial provision for H&S'. Furthermore, ideally, overall project H&S plans, which include all stakeholders, would enable an integrated and focused H&S effort on the part of all stakeholders. The post-MSs of the statements relative to these two issues support the contentions: 'pre-tender H&S plans should be a requirement of the Construction Regulations (T)' (4.25), and 'multi-stakeholder project H&S plans should be compiled for projects' (T) (4.16).

'H&S can be influenced more during the early stages than latter stages of projects' (T) (post-MS = 4.26) reinforces the findings of previous research studies, and highlights that H&S should be addressed during all six stages of projects, and that construction H&S is a multi-stakeholder process. It is during the early stages of projects that clients, CPMs, CHSAs, and designers can exert optimum influence with respect to construction H&S.

The two statements 'CHSAs should be appointed by clients, not other stakeholders' (T) (post-MS = 4.06), and 'CHSAs can price appropriately for H&S services' (F) (post-MS = 3.79) are related. The Construction Regulations require direct appointment of CHSAs by clients, however, in many cases CHSAs are appointed on an indirect basis via other consultants such as architects and engineers. The latter often results in pressure on CHSAs to reduce their fees. Furthermore, based upon anecdotal evidence, CHSAs cannot price appropriately as there is no accepted fee scale, and therefore, the statement is deemed false. It is notable that although it was deemed false, the concurrence is between neutral to agree/agree.

The statements 'H&S is more important than cost, quality, and time' (T) (post-MS = 3.28), and 'cost, quality, and time are more important than H&S' (F) (post-MS = 1.81) are related. In reality, H&S is more important than cost, quality, and time, as it is a 'life an death' issue. It is notable that the false statement attracted a low level of concurrence, whereas the true statement.

5 Conclusions

Construction H&S is a multi-stakeholder issue, and not solely the contractor's problem, and therefore it must be considered during all six project stages. Clients, CPMs, CHSAs, designers, QSs, PCs, and SCs influence construction H&S, which amplifies the aforementioned conclusions.

Given that construction H&S can be influenced more during the early stages of contracts, it should be focused on during client briefing (stage 1), and ideally CHSAs should be appointed during stage 1. There is recognition for the need to integrate design and construction, which promotes construction H&S, and which is facilitated by procurement systems such as design-build.

Procurement clearly influences construction H&S as a process, and as the link between design, and construction, fulfills a major role, especially given that it entails the identification and appointment of the construction stakeholders, which have implications in terms of competencies and resources. Issues such as inclusion of construction H&S in standard conditions of contract, and documentation, facilitating financial provision for construction H&S are important in terms of promoting construction H&S. There is support for pre-qualification of PCs and SCs in terms of construction H&S, multi-stakeholder project H&S plans, and contractor pre-tender H&S plans. However, procurement is an issue relative to the appointment of CPMs, CHSAs, designers, and QSs by clients.

Construction H&S should be afforded status equal to that afforded to cost, quality, and time, and therefore should be reported on, and assessed throughout a project.

6 Recommendations

The BE statutory councils' respective IOW should be reviewed to determine whether the construction H&S interventions relative to their disciplines are adequate.

Upon the revision of standard conditions of contract, construction H&S should be embedded therein to reflect the requirements of the Construction Regulations.

H&S preliminaries should be included in BoQs to facilitate equitable financial provision for construction H&S.

The Construction Regulations should be amended to require multi-stakeholder project H&S plans, and pre-tender H&S plans relative to PCs and SCs.

Professional associations and statutory councils should evolve construction H&S guidelines for their respective disciplines and promote and/or provide construction H&S CPD. The guidelines and CPD should include the 'role of procurement in construction H&S'. The aforementioned approach should be followed by employer associations relative to their members.

Construction H&S should be embedded in tertiary BE education programmes, and statutory councils and professional associations should interrogate the extent to which it is embedded, during accreditation visits.

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Evaluating a Collaborative Cost Management Framework with Lean Construction Experts

Godfrey Monyane, Fidelis Emuze, Bankole Awuzie and Gerrit Crafford

Abstract The pervasiveness of in public sector projects running over budget is a call to all stakeholders to address cost performance issues in the construction industry. This paper proposes a framework for addressing construction cost performance issues that bedevil the public sector. The framework is intended to aid mitigation strategies required to overcome established cost management challenges. The framework was developed through the analysis of data from a qualitative multiple case study research design. Projects and associated interviewees were purposively selected to ensure data alignment to the subject matter; cost management and lean construction. Projects experienced excessive cost overruns and there is a need for a more collaborative solution to managing costs. The data from the interviews were compared with the evidence from project-related documents to develop a framework that was validated through expert interviews conducted among lean construction experts. Excessive cost overruns were experienced from all case studies analysed. Thus indicating a continuous problem. Data support the need for a collaborative cost management framework to improve the performance of public sector projects. The collaborative practices and lean tools mentioned for improvement include the 5 Whys, the big room, target value design, and the integration of design and construction. Experts agree that the CCMF demand for professionals to really collaborate and hold them accountable for project delivery success.

Keywords Construction · Cost · Collaborative costing · Cost management · TVD

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_32

1 Introduction

According to Fulford and Standing (2014), the construction industry is habitually infamous for its sluggishness to adapt, and the obsolete practice remains the most used project delivery method. The increase in productivity in construction has been much lower than that of other industries. The same can be said of the public sector, since in many cases it has no competitor for the services it provides, and it is a supplier-led sector without much incentive to change (Bhatia and Drew 2006). Adapting to new ways of doing business in the public sector is constrained by the rules and regulations related to the operational system, and this hinders any continuous improvement. Moreover, is value to the end user a factor frequently considered especially the public sector? Innovative ways of solving this problem, such as lean, provide an opportunity for the South African construction industry to deepen its understanding of the challenges, to evolve realistic solutions. The construction project is an inter-organisational process, which entails that all stakeholders contribute to accomplishing the objective of successfully concluding the project within the agreed constraints. Howell and Ballard (1998) describe lean as a value-seeking process that maximises value and continually redefines perfection. Lean has been applied to the construction industry abroad, and it has provided tremendous value in improving overall project performance (Ballard 2009; Ballard and Reiser 2004; Ballard and Rybkowski 2009; Nicolini et al. 2000; Zimina et al. 2012).

In brief, existing practices in use in South African construction are failing to ensure cost performance certainty and completion of projects on time. To attempt a remedy, using the principles underpinned by lean construction, as advocated by several authors (Ballard and Reiser 2004; Forbes and Ahmed 2010; Macomber et al. 2007; Nicolini et al. 2000), is the idea espoused in this study to demonstrate how lean would have remedied the challenges of traditional methods of cost management and assist in shifting to a more developed thinking for public sector projects.

2 The Lean Project Delivery System

According to Womack and Jones (2003), waste is defined as "specifically any human activity which absorbs resources but creates no value". Waste impacts negatively on the social, economic and environmental well-being of society, by taking in inputs without providing beneficial outputs. Corfe (2013) contends that 'waste' assumes a wider meaning when discussed in the context of 'lean'; it has a specific meaning that is wider than material waste alone. The process of achieving a task or project can be seen in three ways. There are the value-adding activities that the customer or end-user is prepared to pay for. Then there are the value supporting activities such as inspections, often referred to as essential activities, to make value happen. Lastly, there is 'waste', which is the activities that are carried out with adverse effects on cost, time, quality, or sustainability, and that add no specific value to the process (non-value adding activities). Lean is a process that "eliminates waste through delivering continuous improvement in a collaborative way, where the principles can be directed at sustainability objectives to good effect" Corfe (2013). Waste can occur at any stage of the production process/value stream. Waste includes time, energy, resources, whole-life cost, and physical waste, among others. In conceptualising the phenomenon of waste, the acronym "TIMWOOD" has been developed for easy identification of the seven common lean wastes (transportation, inventory, motion, waiting, overproduction, over processing, and defects) in the construction industry in relation to the associated sustainability benefits of removing them (Corfe 2013).

2.1 Traditional Costing Versus Collaborative Costing

The management of costs in a project is a common thread running through the entire life of a project. Cost management in construction projects seem to be failing to offer improvement interventions Nguyen et al. (2008) during the design stage in terms of responsive approaches to better designs. Pre-contract cost management is an advisory service provided by a consultant to a client on the price to design and construct a project (Towey 2013; Ashworth et al. 2013). This practice of assigning cost management duties to a cost planner provide a succinct picture of a fragmented nature of dealing with cost planning in a project leading to a dented image of the industry through several adversaries (Latham 1994; Egan 1998). The traditional costing management employs the cost planner's role within a design team appointed by a client who either is the end user or will pay for the works with the contractor required to construct the works appointed separately (Towey 2013). This kind of practice lack collaboration and has brought a divorce between the phases of design and production (Namadi et al. 2017). Moreover, Doloi (2011) affirm that the designers, consultants and the supply chain have continued to work in silos even in the current cost planning process, where the norm is to design-estimate-redesign, with the gaps and disconnects that lead to project delays, conflicts, ambiguities and value loss. The inclusion of the contractor in the design/costing development comes very late and deep into the technical stage, and as the responsible partner to construct the works has to deal with all the risks transferred to the construction stage. Early collaboration for project stakeholders is necessary within the lean concept. The aim of the collaborative cost management is to ensure that the design process is waste free steering design to cost, fully collaborating down to production as well as clearly defining the owner project requirements and value streams to achieve the success requirements of the project (Namadi et al. 2017). Moreover, the lean thinking and practices such as lean project delivery system, building information modelling, big rooms, pull planning among others; have well integrated the idea of collaborative costing. Collaborative costing model has been used as a matured approach in collaborative costing that continue to strive and change cultural behaviours, identify values, and waste during cost management processes (Namadi et al. 2017).

3 Research Methodology

The study adopted a qualitative case study design. Multiple case studies were analysed to understand the key issues that led to the outcome recorded by the public sector projects. The research techniques seek to gain in-depth understanding of the research problem. Unstructured data from the qualitative approach employed tends to be comprehensive in content (Fellows and Liu 2015). According to Yin (2014), collection of data should be systematic and follow an analytical procedure, which would divulge patterns, insights or auspicious concepts. To rule out bias, the researcher requested the public sector official to randomly select projects executed by the Department of Public Works (DPW) in South Africa. Five cases were analysed from a list of projects undertaken between 2009 and 2018 to test a range of cross case propositions and boost literal and theoretical replications. The study conducted 15 semi-structured interviews with participants of the selected cases. Participants included construction project managers, quantity surveyors, architects and engineers. Leedy and Ormrod (2010) deemed number of Interviewees suitable following the suggestion of interviewees ranging from 5 to 25 individuals as appropriate. Express permission was sought from Interviewees and the sessions were recorded and subsequently transcribed for verbatim. Sessions lasted between 45 min to one hour, and thematic analysis was applied to make sense of the data (Kulatunga et al. 2007).

4 Findings and Discussion

Table 1 depicts the five case study projects. The projects were selected from the Public works Project Management System and were uniquely codified starting with case and then a number assigned to each project for identification. The DPW checks the requirements against state-owned properties and performs feasibility study of all possible options for going ahead with the project. The best option is then decided based on the outcome of the feasibility study. The decision to construct, refurbish, or lease is the outcome of the feasibility study. The projects in this section employed the traditional method of procurement such as design-bid-build system. It is notable that the projects failed to achieve the intended outcomes in terms of both cost and time expected by the client. Lack of communication, continuous variation orders, and fragmentation of the design and construction contributed to the project not achieving the success initially intended. There is a gap between the planning and construction phase of the project and early involvement of contractor was missing. The projects followed an appointment of a cost or a Quantity Surveyor with the design team of Architects and Engineers separately before a contractor is appointed. Similarly, the design team carries out the costing and designs of the project without any of the constructors present. At this stage, a reporting system on each design update provides the design team with financial advice to enable a decision to be made whether to proceed or amend the design to any budget constraints prior going out to

Table 1 Project case 1–5

Project 1		*Project 2*	
Date contractor appointed	24 February 2012	Date contractor appointed	17 April 2012
Site hand over date	23 March 2012	Site hand over date	9 May 2012
Practical completion date	23 July 2014	Practical completion date	26 November 2014
Actual completion date	3 August 2015	Actual completion date	30 November 2015
Contract amount	R458,000,000	Contract amount	R98,800,000
Final amount	R643,000,000	Final amount	R141,200,000
Overrun amount	R185,000,000	Overrun amount	R42,400,000
Project 3		*Project 4*	
Date contractor appointed	08 January 2013	Date contractor appointed	27 August 2008
Site hand over date	17 January 2013	Site hand over date	22 October 2008
Practical completion date	16 January 2015	Practical completion date	22 April 2011
Actual completion date	30 June 2017	Actual completion date	30 November 2015
Contract amount	R117,000,000	Contract amount	R374,300,000
Final amount	R243,000,000	Final amount	R437,600,000
Overrun amount	R126,000,000	Overrun amount	R42,400,000
Project 5			
Date contractor appointed	08 November 2013		
Site hand over date	25 November 2013		
Practical completion date	09 April 2015		
Actual completion date	Contract terminated due to non-performance		
Contract amount	R27,000,000		
Final amount	R31,000,000		
Overrun amount	R4,000,000 at the time of termination of contract		

tender. Post contract cost management utilises cost reporting to update the client on progress.

Figure 1 indicates the results concerning the performance of public projects in terms of cost. Project case data from project 1 to project 5 elaborate on the time performance, which is dissatisfactory as well. All projects were general building projects from the DPW, ranging from various buildings such as offices etc. In amounts, they ranged from R27,000.00 to R458,000,000.00 in original tender amounts, and the

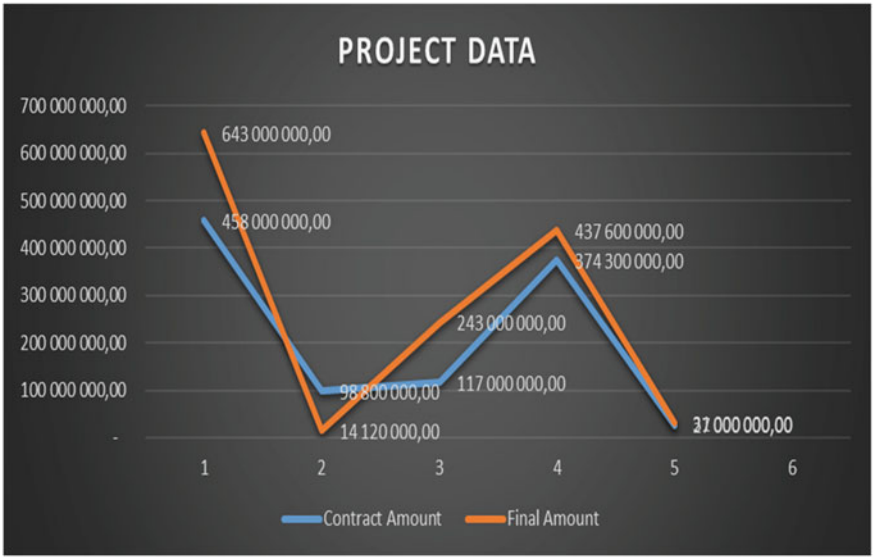

Fig. 1 Performance outcome for public sector projects

durations were from 12 to 24 months, excluding extension of time. The figure shows that overruns ranged from 15 to 40% of the original contract sum agreed initially. The reasons cited in the projects were additional work request by the client, extension of time, re-measurements and variations. Moreover, none of the remedial measures was applied to the projects.

4.1 Discussion and the Effects of Implementing Lean Tools and Behaviours

For identifying the root causes, the technique '5 Whys' is used (Ohno 1988). 5 Why's is a problem solving technique that asks "WHY" five times to get to the root cause of a problem (Basu 2009). It helps to avoid putting band aid solutions in place that will only be a temporary fix. Technique was applied with the project participants for obtaining their opinions on the different causes and effects underlying each reason under analysis. The following 5 Why's analysis for over budget:

(1) Why—poor coordination of design development, (2) Why—so many design changes, (3) Why poor communication, (4) Why—poor cost management of project, (5) Why—interface of design and construction misunderstood. The five questions posed to project participants assisted in gathering causes relating to planning, management and coordination in the category of processes applied to cost management of the selected project cases. Reasons obtained are used to propose a collaborative cost management framework for the public sector projects in South Africa.

Figure 2 is a proposed collaborative cost management framework for the public sector projects after discussion of the 5 Why's analysis. Table 2 beneath is findings of the 5 Why to analyse and find the root cause of cost overruns in construction projects.

The culture emanating from the construction industry was outlined by interviewees as barrier for improving the cost management of construction projects. Interviewee number 1 mentioned lack of accountability by professionals as the leading cause of cost overruns in projects. However, interviewee number 2 asserts that fragmentation is majorly causing the continuing cost overruns in construction projects as the cases clearly demonstrates this phenomenon. Interviewee number four opines that cost overruns and delays seems to be accepted as part of the construction projects, thus such performance does not trigger warning signs to the rest of the project team. Further interviews were conducted with the project participants as described in the method section to gauge their perception of the proposed framework. From Fig. 2, a proper owner project requirement have to be outlined regarding the success criteria that could improve the communication between designers. Instead of the cost management being the responsibility of the quantity surveyor alone, early contractor involvement contributes to cost improvement through clusters and integrated design development. Team selection is key to success of the project (high performing team). Big room meeting would encourage and force all stakeholders to work together and would collaborate during the design phase by conducting several meetings with both the designer and owner to discuss design details without having to use tedious requests for information (or RFIs). To limit variations set based design and target value design would have improved commitment of the design early to avoid changes during construction. According to Al Hattab and Hamzeh (2013) the approach can also be achieved through Building Information Modelling (BIM). The cost overruns experienced by all the projects could have been prevented by target costing (Ballard 2008). In the views of (Hamzeh et al. 2016) a suggested solution that could have helped in reducing the construction and design delays, predicting upcoming challenges and eliminating wastes would be implementing the Last Planner System (LPS). Consulting all stakeholders early and involving them in the design phase would have produced innovative ideas. The involvement of different stakeholders in the design phase not only guarantees enhanced communication and better understanding but also ensures quality, cost and time efficiencies. Collaboration of various parties and the alignment of interests of the shareholders is the basis of lean construction. All interviewees agreed that the collaborative cost management framework could improve the current cost management of public sector projects with the right political support of the public sector. Moreover, all agreed that bringing in all stakeholders early and signing of a manifesto is a great idea for encouraging commitment. However, policy changes is required and contract changes are also necessary to effect such a system in construction. Similar studies Namadi et al. (2017) have proposed collaborative cost management, however, the study was purely a literature review. This study proposes a collaborative cost management as a subsequent study to the initial studies Monyane et al. (2018a, b) to have first identified challenges hindering effective cost management during project delivery in the public sector projects

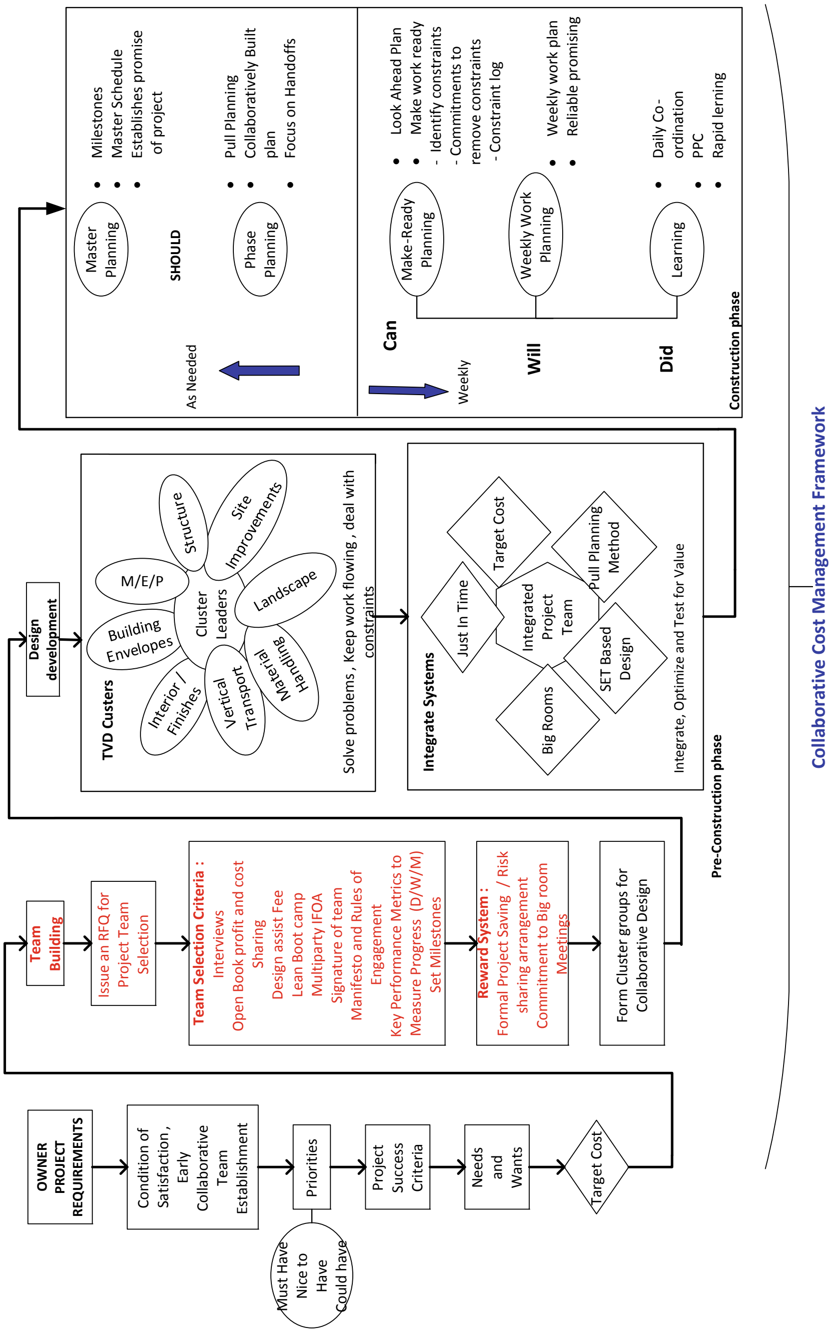

Fig. 2 Lean led collaborative cost management framework

Table 2 5 Why's analysis of project cases

5 Why's questions for projects running over budget	Probable cause
Why is there poor coordination of design development	Design development is done in isolation by various designers and taken form the architectural preliminary sketches, specialised brought in late for fixing errors
Why are there so many design changes	Client involvement is minimal and mostly done by non-technical staff hence constant change of designs, unclear owner project requirement, and no project success criteria
Why do poor communication persist in construction	No proper communication platform that allows all to see changes as and when they happen, waiting too long for feedback from client owner
Why do poor cost management persist in construction	Culture of assigning cost to QS alone, contractor not part of the design, non-collaboration of project teams, contractor profit driven, blame game, safeguarding of interests by consultants, risk transferred to contractor
Why is the interface between design and construction misunderstood	Procurement without best value, contractor not appointed early, lack of trust between consultants and contractor, cost management in construction phase is reactive and has no control of costs, delays contributing to cost overruns. No reward system for early completion

and the study provided a vignette that will enable an identification of the said challenges, and secondly identifying lean opportunities in a South African public sector projects. This study builds from the latter to propose and validates the framework for collaborative cost management for the construction industry in South Africa.

5 Conclusion and Further Research

Selected case studies above, clearly demonstrated that traditional project management practices have not improved at all and still leads to poor performance of infrastructure projects in South Africa. This study considered traditional cost management process within South Africa and an exemplar of collaborative cost management, and presented a framework that portray the difference within the two approaches. The proposed framework would assist practitioners on how to enhance and improve the current process of cost managing projects to achieve the intended outcome of the projects. Collaborative costing/design and construction of projects was missing from the case studies analysed. This fragmentation is evident that it contributed to the projects performing poorly and such could be avoided in future projects by early involvement of all stakeholders. A shift in planning management is needed and a number of lean management processes are required to build the culture of continuous improvement. Project participants are encouraged to use a proper sharing of information and data (less tedious RFIs, enhanced communications) between the different stakeholders in order to help achieve value, explore different alternatives to come up with the most suitable in order to avoid rework or maintenance problems and apply global instead of local optimization. Future research could align the process with the professional consultant services agreement (PROCSA) stages of construction to assist professionals with the performance and claiming of fees for the projects.

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Safety Leadership Functions Using Complexity Science

John Ojuola, Sherif Mostafa and Sherif Mohamed

Abstract In order to put a proactive approach in place with regards to the prevention of workplace injuries, there is a lean towards the main determinants of safety; e.g. leadership. As a result of their vital role in organisations, leaders are seen as prime players in the creation of safe work environments. However, leadership is a complex, multi-phased concept which advocates that various leadership styles affect the outcome of safety in diverse ways. Therefore, this paper highlighted that complex systems predominantly focus on the relationship amongst teams, behavioural patterns and the interdependencies within an evolving system. Thus, applying the same concept to safety and leadership provided direction in practice and presented an unorthodox leadership construct that would enable managers to imbibe leadership apt for the twenty-first century. The aim of this paper was to develop a framework for safety leadership functions using complexity science. This study was centred on literature review based on the following themes—leadership style, complexity leadership theory and safety leadership. Discussions on the study carried out was presented, followed by a framework for safety leadership. This paper concluded that complexity science supports the flexibility, innovative and dynamism of leadership; not as a set of capabilities or standards innate in any one person.

Keywords Complexity leadership theory · Leadership style · Safety leadership

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_33

1 Introduction

In order to put a proactive approach in place with regards to the prevention of workplace injuries, there is a lean towards the main determinants of safety; e.g. leadership. As a result of their vital role in organisations, leaders are seen as prime players in the creation of safe work environments (Flin and Yule 2004). While research on the link connecting leadership and safety has evolved significantly, conventional leadership models are not dynamic enough to garner the concept of centralised organisational structures and its need in safety-critical organisations (Christian et al. 2009; Nahrgang et al. 2011). For instance, the transformational leadership which highlights safety has been associated to increased safety behaviour in organisations (e.g., Barling et al. 2002; Conchie and Donald 2009). Several positive outcomes have been linked to transformational and transactional leadership; these include better safety climate, improved safety behaviours, and reduction in accidents and injuries (Hoffmeister et al. 2014). However, leadership is a complex, multi-phased concept which advocates that various leadership styles affect the outcome of safety in diverse ways.

2 Research Methodology

The aim of this paper was to develop a framework for safety leadership functions using complexity science. To achieve this, qualitative data on leadership style, complexity leadership theory and safety leadership was used. This research was designed in three stages:

- Stage 1: Reviewed related literature on leadership style, complexity leadership theory and safety leadership,
- Stage 2: Researched findings and analyses on safety and leadership, and
- Stage 3: Developed a framework for safety leadership in safety-critical organisations.

3 Leadership and Safety

The importance leaders place on safety and health in the work environment is reflected in their behaviour. Invariably, workers see these behaviours and can easily construe them to create standards with respect to how these leaders place safety in the workplace (Zohar and Tenne-Gazit 2008; Zohar 2014). Hence, it can be concluded that leaders play a key role in the creation of a safe work environment. This in-turn motivates workers to increase their safety behaviours; thus, reducing accidents and injuries (e.g., Barling et al. 2002). The connection between leadership and safety is mutually theoretically rational and empirically buttressed (Christian et al. 2009; Nahrgang et al. 2011).

3.1 Leadership and Safety Climate

Zohar (1980) defined safety climate as employees' perceptions with regards to the way an organisation values safety. Lewin et al. (1939) recognised that leaders create climates through their actions; which invariably provide the principles for how employees should act and relate with their work environment, team mates, and managers.

3.2 Leadership and Safety Behaviours

Griffin and Neal (2000) characterised employee safety behaviours by two forms: safety compliance and safety participation. Safety compliance means adhering to safety policies and practices and engaging in stipulated safety behaviours. Safety participation is shown when workers take the lead to be safe, assist other co-workers and deliberately work at creating a safe work environment (Neal et al. 2000). When leaders choose to be role models and act in a safe manner at work, their employees are very likely to emulate them (Hofmann and Morgeson 2004).

4 Transactional and Transformational Safety Leadership

To further develop the theoretical concepts of safety leadership, researchers have tried to explain effective safety leadership in terms of various leadership styles studied in leadership literature. Transformational and transactional leadership are the two most frequently cited (Clarke 2013; Inness et al. 2010; Zohar and Tenne-Gazit 2008). Transactional and transformational leadership are well-grounded theories in leadership literature (Bass 1985), providing a conceptual foundation for all leadership (Flin and Yule 2004).

According to Bass's (1985) model, transactional leadership encompasses three components. The first component is contingent reward, which means leaders set expectations and reward followers for meeting expectations. The second component is management-by-exception active; which means leaders monitor followers' performance and correct the actions preceding the occurrence of severe problems. The third component is management-by-exception passive; in which leaders monitor their followers' performance and corrects them when the need arises. Bass argued that this transactional relationship between leaders and subordinates is likely to create expected performance because this relationship sets goals and creates aspirations. Leaders generally portray various transactional attributes in their day-to-day interactions with their subordinates; nonetheless, only top performing leaders demonstrate both transformational and transactional behaviours (Bass 1985).

Transformational leadership consists of four dimensions. First, individualized consideration takes place when leaders pay attention to the personal and professional development of their subordinates and listen to their needs cum concerns. Second, idealized influence; this ensues as leaders portray themselves in admirable ways which lead subordinates to believe that they can be understood by their leaders. The third dimension is inspirational motivation, which denotes that leaders motivate others towards goals, provide meaning, and articulate visions that sound attractive and inspirational to others. Finally, intellectual stimulation takes place when leaders challenge norms and charge others to tackle confrontations in unusual ways.

As shown in Fig. 1, transformational leadership improves on the lone effectiveness of transactional leadership through a process called augmentation effect. The introduction of transformational leadership can stimulate subordinates in a workplace to aspire to achieve higher goals and to make additional effort to accomplish them. As a

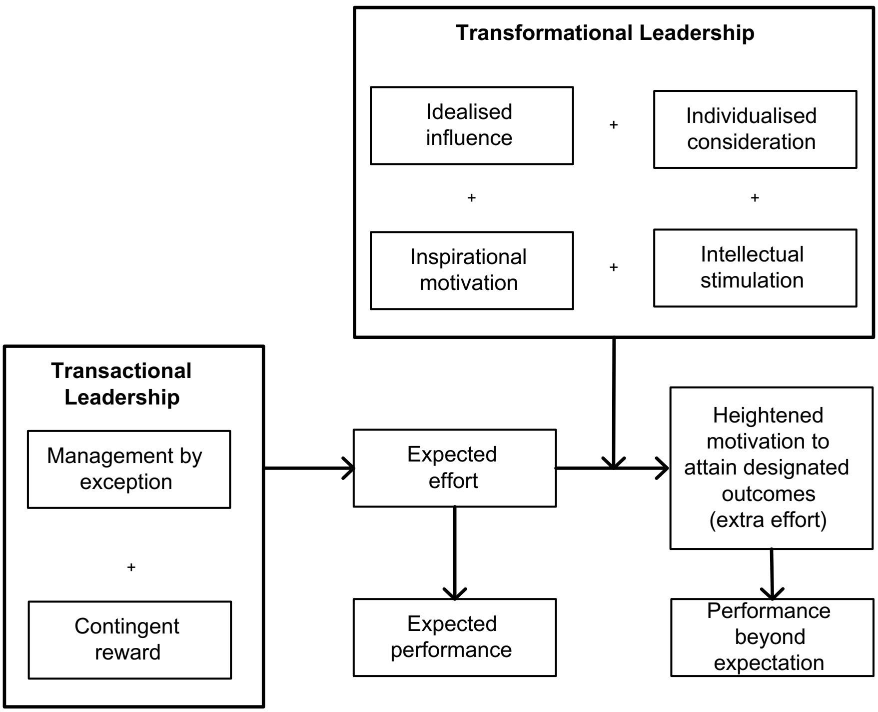

Fig. 1 Augmented effect of transformational leadership on transactional leadership. Adapted from Bass et al. (2003)

Table 1 Safety leadership behaviours

Safety leadership behaviours		
	Transactional	Transformational
Supervisors	Examining and ensuring that employees behave safely Contributing to workers' safety activities (this can also be regarded as transformational)	Encouraging of programmes designed to improve safety Enforcing that employees participate in safety programmes
Middle managers	Participating in safety initiatives (this can also be regarded as transformational)	Stressing safety over productivity Embracing a distributed style Communicating the company's concept of safety to managers
Senior managers	Maintaining a high level of adherence to regulatory standards Providing funds for a wide-range of safety programmes	Demonstrating obvious and continuous devotion to safety Displaying empathy for others Emphasising the participation of all supervisors Setting aside quality time towards safety

Adapted from Flin and Yale (2004)

result, transformational leadership can help to improve performance beyond expected levels. In other words, transformational leadership can explain the distinctive variation in extraordinary performance in addition to what transactional leadership can do.

Safety leadership is mostly explained in terms of the effects of transactional and transformational leadership. Flin and Yule (2004) categorised safety leadership behaviours in terms of transactional and transformation leadership as shown in Table 1.

By using transactional and transformational leadership to explain safety leadership, researchers have examined how these two types of leadership style may relate to different safety behaviours and outcomes. For instance, Zohar and Tenne-Gazit (2008) establish that transformational leadership was a predictor of safety climate. Inness et al. (2010) concluded that transformational leadership is positively related to safety participation, as transformational leaders are good at encouraging subordinates to partake in safety activities. Zohar (2002) reported that transactional leadership was associated with lower accident rates. Clarke (2013) carried out a meta-analytic review of 103 safety studies and found that transactional leadership was central to safety compliance, whereas transformational leadership was important to safety participation. Hoffmeister et al. (2014) investigated how each dimension of transactional and transformational leadership influenced five safety outcomes (SO): safety climate, safety compliance, safety participation, injury and pain. The results showed that the dimension of idealized attributes and behaviours under transformational leadership led for the most variance across all SO, whereas active management-by-exception under transactional leadership consistently accounted for the least number of variances. This could imply that transformational leadership is more predictive than transactional in leadership for driving better SO.

5 Safety-Specific Transformational Leadership

With the growing volume of safety literature revealing the importance of transformational leadership on safety performance, Barling et al. (2002) established a concept called safety-specific transformational leadership (SSTL) to capture the variance in SO beyond the variance noted for by general transformational leadership (Barling et al. 2002). In particular, SSTL consists of five components: idealized influence, inspirational motivation, intellectual stimulation, individualized consideration and contingent reward. The first four components are from transformational leadership, whereas the last component, contingent reward, is from transactional leadership. Contingent reward was included in the construct because a statistical factor analysis suggested that contingent reward consistently loads collectively with the four components of transformational leadership.

In SSTL, leaders with high ‘idealized influence’ demonstrate their own particular obligation to safety, thus enabling higher levels of follower-trust that management considers safety important. Leaders demonstrate ‘inspirational motivation’ when they challenge followers to go beyond their personal needs for the collective well-being. For instance, leaders convince their followers to achieve high levels of safety standards, using tales to clarify their mission. By using ‘intellectual stimulation’, leaders task their followers to question long-held traditions and motivate them to think about creative ways that could improve occupational safety. In addition, leaders manifesting ‘individualized consideration’ express an active interest in their followers’ welfare; including their work safety. Leaders make use of ‘contingent reward’ to encourage and reinforce followers’ safety behaviours.

Numerous studies have found a strong and positive association between SSTL and SO. For example, de Koster et al. (2011) found that SSTL is negatively associated with accident rate. Conchie and Donald (2009) suggested that SSTL has a considerable effect on subordinates’ safety citizenship behaviour. Mullen and Kelloway (2009) reported that SSTL is positively related to safety climate. Kelloway et al. (2006) found that SSTL is positively associated with safety climate and safety consciousness.

6 Limitations of Current Leadership Theories

Most theories on leadership are intended for rational goals attainment, even as they are managerial practices. Barnard (1938) noted that leadership means putting together organisational goals and individual principles for leading. On the subject of leadership, Selznick (1948) observed that unreasonable inclinations, collaborations and informal arrangements could destroy stipulated organisational goals. In this perspective, Conner (1998) stressed the effect of leaders in a prototype dominated by leadership theories which is dependent on other members in the context of predefined goals and constructs. This construct comprises of methods that encourage employees to attain organisational goals and provides motivation to increase the effectiveness of goods/services generated by employees (Burpo 2006). Micro theories are designed around the charismatic and visionary roles of leaders from top to bottom constructs (Castells 2003), while macro theories like "Executive Leadership" lay emphasis on inflexible configurations (Cilliers 2005). Conventional leadership is hinged on research in human relationships in the social sciences, rather than studies on organisational top-bottom distributed structures (Baltaci and Balci 2017). Despite the need for specific leadership for safety-critical organisations (SCOs) such as the construction industry, conventional leadership theories are largely built on the rigid patterns defined for the "Industrial Age". This form of leadership is centred around a framework which is essentially built on defined control mechanisms (Baltaci and Balci 2017).

These control mechanisms incorporated in traditional bureaucratic structures instinctively limit the extent to which conventional leadership theories can be applied to SCOs. Failure to progress beyond the form of leaders and control predominantly in conventional bureaucratic approaches restricts the applicability of conventional leadership concepts for SCOs. Lichtenstein et al. (2006) summarised that available conventional leadership concepts are not dynamic enough to be adapted for centralised organisations and the leadership requirements in SCOs.

7 Complexity Theory

Uhl-Bien et al. (2007) described traditional leadership constructs as products of top-down, bureaucratic prototypes, which although effective for economies, is centred on effectiveness of physical productivity; which are not suitable for the more knowledge-based economies of today. A distinctive paradigm for leadership is required; where leadership is portrayed as a complex and flexible construct leading to adaptive results (e.g., knowledge acquisition, creativity and adaptability)—emanating as complex leadership theory. This theory indicates a leadership model where people work together to collectively find highly efficient solutions to difficult problems, and in this, adjust to the ever-evolving system (Uhl-Bien et al. 2007).

The science behind complexity theory is centred on how work structures interact complexly (Marion and Uhl-Bien 2001). Coveney (2003) defined complexity theory as the study of the behaviour of several assemblages of unique, interrelating components, capable of changing with time. This theory is about: (1) interactions which are dynamic within several connected agents, and (2) how emergent events—such as creativity, knowledge acquisition or flexibility—emanate from these relationships (Marion 2008).

The terms 'complexity' and 'complicated' do not share the same meaning. A system is referred to as complex when the interaction of its structures cannot be expounded by simply analysing its components. The human brain, which is dynamic and evolving, is a complex system. On the other hand, a system can be described as complicated when each of its individual parts can be analysed. For example, computers are referred to as complicated systems (Cilliers 1999; Snowden and Boone 2007).

7.1 Safety Leadership Framework

Instead of seeking 'one true theory' of leadership, contemporary thinking has investigated the idea of leadership from a totally distinctive perspective, thus giving birth to complexity leadership theory (Ojuola et al. 2018). Complexity leadership theory is a construct which permits knowledge acquisition, flexibility, and adaptive capability of complex adaptive systems (CAS) in organisations. The framework for complexity leadership theory (as shown in the bottom part of Fig. 2) shows three leadership functions that is referred to as administrative, enabling and adaptive.

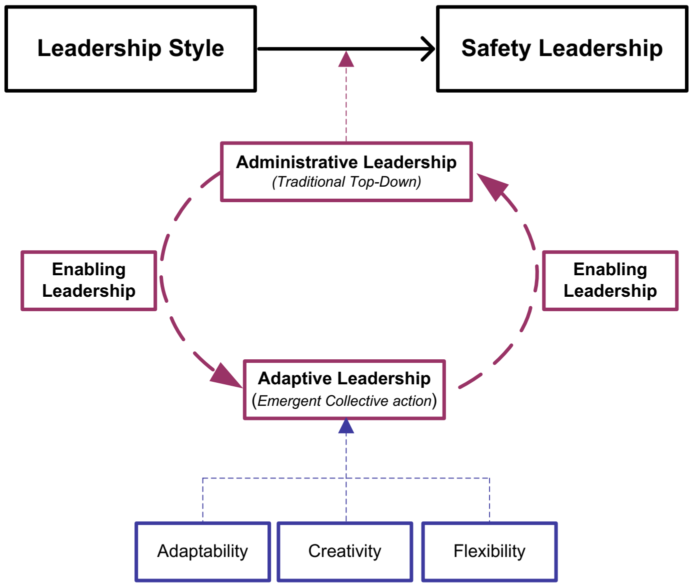

Fig. 2 Safety leadership framework

Mumford et al. (2008) noted that administrative leadership structures charges, employs planning, creates vision, assigns resources to attain goals, manages challenges, and manages organisational strategy. Administrative leadership emphases positioning cum control which is characterised by the hierarchical and bureaucratic modalities of the organisation. Adaptive leadership refers to dynamic, flexible and knowledge acquiring actions which arise as a result of the interactions of CAS as they attempt to adapt to changes (e.g., limitations or perturbations). Adaptive activity can occur anywhere; it is an informal emergent activity which occurs among interactive agents (CAS)—not with the aim to dominate. Enabling leadership acts to enhancement how adaptive leadership can succeed. It also manages a process called entanglement—interaction between the administrative and adaptive leadership roles. The following functions are required in the management of entanglement: creating conducive environments within the organisation to promote efficient adaptive leadership in situations where flexibility is required; and ensuring that there is a flow of knowledge and creativity from adaptive to administrative structures. Enabling leadership takes place at all levels of the organisation, though the characteristics of this role will differ within hierarchical level and position. Kontopoulos (2006) mentioned that entanglement is the interweaving of leadership functions as described in complexity leadership theory above.

The safety leadership framework presented in Fig. 2 depicts the relationships connecting the constructs of this study. Leadership style acts as the independent variable and has a positive impact on safety leadership (dependent variable). While the complexity leadership theory acts as a moderating variable demonstrating the strength of the relationship between leadership style and safety leadership.

8 Conclusion

With the increase in demand for leadership that understands high levels of interactivity suitable for complex systems, strategies to nurture such leaders are likely to be more appropriate as compared to conventional hierarchical approach; as the traditional approaches are incongruent with organisational behaviour. This paper highlights that complex systems predominantly focus on the relationship amongst teams, behavioural patterns and the interdependencies within an evolving system. In essence, complexity science supports the flexibility, innovative and dynamism of leadership; not as a set of capabilities or standards innate in any one person. Thus, applying the same concept to safety and leadership provided direction in practice and presented an unorthodox leadership construct that would enable managers to imbibe leadership apt for the twenty-first century.

Finally, as this paper has discussed safety leadership in the context of complexity science, further research may be implemented to the developed model to perform comparative analyses in different fields; to see if comparable results can be reached and give the proposed model greater generalisability.

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Proposed Risk Management Decision Support Methodology for Oil and Gas Construction Projects

Mohammed K. Al Mhdawi

Abstract Oil and gas construction projects are complex and risky due to their dynamic nature and environment, as they involve a considerable number of stakeholders. The contracting companies in Iraq find many challenges when managing the risky events in an environment that categorized with poor supplies, security threats, unskilled workforce and logistics difficulties. Evidence in the literature indicates that there is a lack of unified methodology for project management and especially for risk management in Iraq. Also, the rise in the global energy demand increases the need for a workable, effective and efficient risk management methodology for such projects. Thus, the purpose of this research is to develop an integrated decision support methodology for managing the risk factors in oil and gas construction projects in Iraq. The proposed methodology has been developed to support the local and international contracting companies working in Iraqi oil and gas fields when making decisions regarding the risk factors during the project life cycle. The proposed methodology consists of the following phases: risk planning, risk identification using documentation review and expert interviews, risk analysis using a multi-criteria risk analysis model based on fuzzy set theory, risk effect prediction on project time and cost using artificial neural network (ANN), selection of risk response actions using Gravitational Search Algorithm (GSA) optimization technique and finally, designing an integrated web-based risk management decision support platform. The adopted methodology will enable decision makers to assess the oil and gas projects risky events, support their decision during planning and work implementation stages, gain experience in risk management through exercising and implementing risk management on scientific and documented bases; organize and document the knowledge-based information for decision makers.

Keywords Oil and gas · Project management · Risk management · Decision support system

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_34

1 Introduction

Energy demand is rising, and it is expected that global investment in the energy-related sectors will reach 38 trillion through 2035 (Accenture 2012; Jayaraman et al. 2015). Oil and Gas industry considered to be as a backbone of any country's economy (Mubin and Ghaffar 2008). All construction projects are usually confronted by many types of risk factors. There is always some sort of uncertainty in meeting construction project objectives (time, cost and quality). These objectives are risky due to several factors such as: the complexity of the construction projects and the unique nature that makes them scientifically different from other similar projects (Kendrick 2015; Seddeeq et al. 2019; Salas 2014). The construction risks facing oil and gas construction projects can be social, political, financial, and technical in nature, as well as related to the natural disasters and natural environment (Aven et al. 2007; Zhao et al. 2012). Recognizing and Understanding the risk factors associate with energy sector is not only a construction market need, but also it is essential to the upstream and downstream oil and gas industry sub-sectors (De Maere d'Aertrycke et al. 2017). Construction projects at the oil and gas fields play a significant role in the sustainable supply chain and processing (Hong et al. 2016). Because to this importance, governments of developing countries are under pressure to ensure that construction projects will be completed on time within the estimated budgets and least amount of uncertainties and risks (Dehdasht et al. 2015). The continues need to ensure that construction projects are managed effectively led both of the academia and industry emphasising on the development of reliable methodologies for managing projects risks (Elhoush and Kalafungin 2017). Project risk management (PRM) has been known as a strong factor in need of careful assessment to ensure project risks are minimized (Carvalho and Rabechini 2015; Salazar-Aramayo et al. 2013). Unfortunately, the construction industry is not as advanced at assessing and analysing risk factors in comparison with other industries (Laryea 2008; Taroun 2008). Lack of risk management methodology during oil and gas construction projects will not always leads to cost overrun and delays but it also can be crucial for pricing the energy policies (AL-Zwainy et al. 2016). The challenge is when the project moves from design stage into site production stage. The management team are so stretched with everyday challenges that they often fail to keep the risk register up to date and fail to recognize the interdependence of the risky events. It is therefore the aim of this research is to propose a risk management methodology for supporting decision makers when managing the construction risks at the oil and gas field in Iraq. This theoretical work illustrates the integration of risk management phases and analytical approaches for supporting risk decision making.

2 Literature Review

2.1 Oil and Gas Industry in Iraq

Iraq has become the 4th largest oil producer in the world after Russia, Saudi Arabia and USA (World Bank 2017) and the 2nd largest oil producer in OPEC (EIA 2017) with a total oil production of 4.5 million bpd in 2016 (BP 2017). Iraq considered to be one of the few regions left where vast oil reserves, proven and unknown, have hardly discovered (Donovan 2013). The Oil reserves of Iraq are enormous, it considered to be the 5nd largest reserves in the World with around 142.8 Billion bpd. Iraq natural gas production reached 189.4 billion m^3 in 2015 with a total proven reserve of 3.7 trillion m^3 for the same year (BP 2017). The energy sector in Iraq is heavily depends on petroleum production (Maniruzzaman and AL-Saleem 2017), with around (90%) of its energy requirements met with petroleum (Balanchard 2018). Iraqi oil and gas industry contribute for most of the Gross Domestic Product (GDP), foreign exchange earnings and public revenues (IEITI 2015). It is, therefore, central to the country finical position and critical to the vitality of the country economy and the ongoing reconstruction efforts of the country, particularly with regard to oil, gas infrastructure and development (IEITI 2015). According to the World Bank report in 2017, the Oil and Gas fields in Iraq contributes to around 65% of its gross domestic product (GPD), and over 90% of the public income and most of its foreign exchange revenue (World bank group 2018), while the non-oil sector non-productive as the oil and gas sector due to weak service delivery, corruption and insecurity situation (Balanchard 2018). Iraq has (22) major oil and gas fields separated mainly in the south, middle and north.

2.2 Project Risk Management

In the construction industry risk is defines as a variable, condition or uncertain event that if occurred it will have an impact on at least one of the project objectives (Jin et al. 2017). Numbers of researchers dated the origin of the modern risk management to be between the 1950s and 1960s (Crockford 1982; Arthur and Richard 1995; Scott and Gregory 2003). The first two scientific books were published by Mehr and Hedges (1963) and Scott and Gregory (1964) were they covered pure risk management fundamentals and principals. Project risk management was practised in the mid of 1980s (Rezakhani 2012), it falls inside the nine knowledge areas of the project management institute's project management body of knowledge (PMI 2008). Risk management is defined as the proactive, constant and organized system to manage, realize and communicate risk events (Hutchins 2016). Risk management in construction projects usually has two main goals: to avoid threats and to exploit the opportunities (Smith et al. 2013). An effective risk management depends on previous historical data then looking forward to thorough planning to narrow future risks area where future failures can be avoided (Kendrick 2015). Effective management of risks does not only concentrate on minimizing risk consequences, but it gives sufficient support to the activities that adopt innovation, so greater benefits can be achieved. According to the authors, risk management cannot be utilized as a tool to predict the future. Instead, it facilitates the project to make proper decisions depending on related information in which the decision that depends on insufficient information can be neglected in which it will lead to efficient project performance. Risk management assures that almost all project problems are discovered in the early project stages without overpassing the project budget or missing the project schedule (Tamak and Bindal 2013). Understanding the risks confronting a construction project helps the project team to meet the project parties' expectations more effectively. The assessment of these risks withdraws the decision makers attention to the difficulties that might be faced in order to fulfil the project objectives and the enterprise overall expectations (WSDOT 2014). Therefore, risk management is considered as an integration of decision making and good management at all levels of the organization (Berg 2010). The proper implementation of risk management aimed at providing sensible assurance as to the successful accomplishment of the project objectives and helps the company financial goals. The Key benefits of applying systematic risk management can be summarized below as it described by Dinu (2012), Siang and Ali (2012), and Shad and Lain (2015). It reduces threats and increases their opportunities, so it maximizes the probability of accomplishing objectives, it provides effective management that maximizes the work effectiveness and efficiency by minimizing stress and waste, it helps in providing proactive management of threats which have an important effect on the whole project objectives, it fills strategic gaps by shaping and updating the risk culture at all management level, it decreases the instability of the construction activities and discourages the acceptance of financially unsound projects and it protects credibility and reputation of the company.

3 Research Problem

Studies about risk management have been presented since the 1950s (Crockford 1982; Arthur and Richard 1995; Scott and Gregory 2003). Risk management process steps and characteristics based on several risk management international and professional standards such as: British Standards Institution (BS6079-3: 2000), Institute of Risk Management (IRM: 2002), Standards Australia/Standards New Zealand (AS/NZS 4360: 2004), the international organization for standards (ISO 31000: 2009), International Electrotechnical Commission (IEC 31010: 2009), Canadian Standards Association (CAN/CSA Q850: 2009), National Institute of Standards and Technology (NIST800-30: 2012), Project management body of knowledge project management institute (PMBOK-PMI: 2013), American Management Association Handbook (AMA: 2014) which are sharing the same crucial steps despite the existence of some differences in some of risk management steps details. These steps are risk planning, risk identification, risk analysis, risk response and risk monitoring and controlling. However, the risk related information gathered from any project phase is different from the other phases, in another meaning, in each phase, the project has its risk characteristics. Also, the extent of how the decision makers assess the relevant risks becomes different at each phase of the project life cycle. In addition, risk factors of oil and gas construction projects are complex, interrelated and varied. Therefore, the traditional approaches of risk management have limitations and barriers of applicability to such complex projects. The construction projects in Iraq have always been plagued with implementation problems and weak outcomes (Abdulsattar 2017). Iraqi contracting companies find a big number of challenges to mitigate risk events in an environment with poor supplies, security threats, unskilled workforce and logistics difficulties. Also, there were some downsides due to the unstable country economy and political issues. Besides, there is a lack of the adoption of a unified methodology for project management in the Iraqi construction industry (AL-Zwainy et al. 2016) and lack of information and data regarding the construction risk management processes in Iraq.

Based on the issues stated above, there is a need to develop a risk management decision support system methodology for oil and gas construction projects in Iraq.

4 Research Methodology

The nature of the study takes up a qualitative approach as it based on literature review and documents analysis which used for knowledge acquisition to develop a formalised risk management methodology. The investigation began by reviewing the related literature to determine the gaps in the relevant literature and to establish the proposed system requirement in which it helped to identify the most effective techniques to achieve the research aim. Documentation analysis in this research includes risk data, risk behaviour, causes of project failure and adopted strategies for decision making when managing risks at the oil and gas construction project for the local and international oil and gas companies working in Iraqi oil and gas sector.

5 Proposed Risk Management Decision Support Methodology

The proposed risk management decision support methodology is defined by six phases which can be illustrated by Fig. 1.

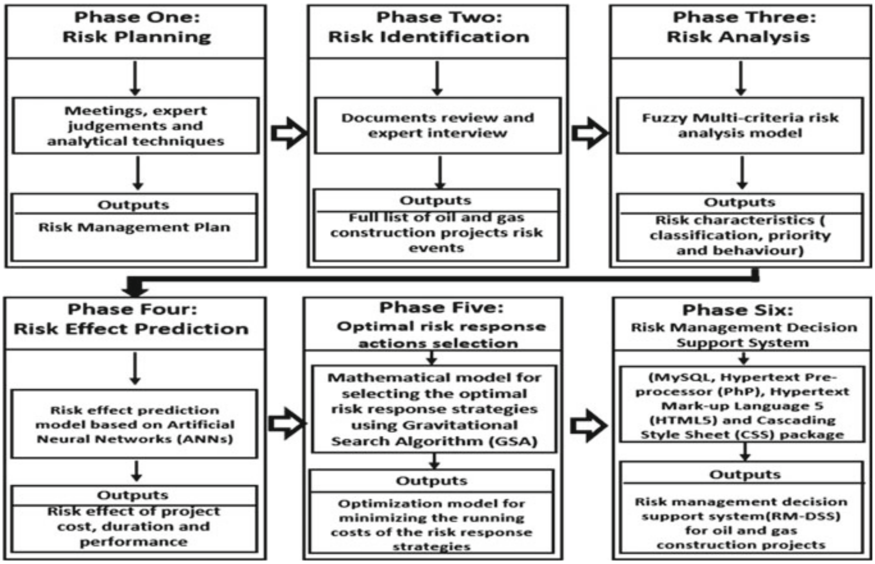

Fig. 1 The proposed risk management decision support system structure

5.1 Phase One: Risk Management Planning

Risk management planning is a systematic approach of deciding how to plan and implement the risk management activities throughout the project life cycle. The development of risk management plan is considered to be one of the most important activities in the risk management process, because it establishes and organize the activities of the project management team when dealing with project risks and uncertainties.

In this Phase, the operations that need to be accomplished by the risk management team are described in detail. It includes defining and scheduling all the activities and procedures needed to observe, evaluate and document the risk factors associated with the project. The outcome of this step is known as risk management plan which has an essential role in (Burek 2007; Nicholas and Steyn 2011): updating the project risk management strategy, finding out the most effective approaches to implement the risk management strategy and nominating the appropriate parties to get the job done. In order to build up a successful risk management plan, enough data must be collected through the project work breakdown structure (WBS) in addition to the project performance standards, cost plan and schedule. Previous effective strategies in similar achieved projects must also be present. Risk management planning activities can be summarized into the following: identifying appropriate cost-risk team, determining the workshops types and durations, establishing risk communication approach, determining the risk identification methods depending on project characteristics, determining the level of risk assessment, scheduling risk assessment activities, implementation of risk treatment actions, initiating monitoring for risk treatment actions, updating risk management plan and performing post mitigation analysis and report.

5.2 Phase Two: Risk Identification

Risk identification is considered as the most significant step in the risk management process where the risk assessment and response actions cannot be applied only on the risks that been identified and recognized (Burek 2007). According to Giannakos and Louis (2011), risk identification is the essential step for detecting the risk factors that affecting the project objectives. Any failure in identifying any risk factor will lead to the ill implementation of the whole process, which can in turn critically affect the organization's resources. It is also considered as an essential step in constructing all risks profiles. Risk identification is said to be of two phases. The first is the initial identification phase which is usually conducted by firms that have not already identified their risk factors in a structured way or by new firms or projects. The second is the continual risk identification phase which aims at identifying new risk factors never occurred before (Ana-Maria and Doina 2012). Risk identification, classification and risk breakdown structure helps to comprehensively identify all risk. Risk Identification techniques in the proposed methodology are documentation review and expert interview. In order to collect the primary data, two techniques will be carried out: documents review and expert interviews with construction experts.

5.2.1 Documents Review

A traditional and basic technique that involves reviewing reports, drawings, plans, estimates, schedules contracts and other stored information in either hard copy or electronic formats in which the pre-identified opportunities and threats are investigated for signs of potential risk situations. According to Myers (2009), the analysis of documentary data and records is important to identify statements made by key persons in an organization which can be utilized as inputs to the interview guides. The causes of projects failures will be analysed from published reports produced by construction companies working at Iraqi's oil and gas fields which are located in Basra governorate. These report record information such as into risk status records, project sum, project duration, time extensions, variation orders project failure, causes of project failure and their response actions.

5.2.2 Expert Interviews

It is a very effective tool of obtaining rich data from the participants which is crucial for explaining or exploring phenomena or complicated situations. Based on Knight and Ruddock (2008), a good interview is the art of exploring the beliefs and opinions of the participants and the subject knowledge. This technique is known as a resource-intensive technique because of the organizational time and resource requirement. Interviews are conducted with project managers, contractors, consultants and key stakeholders, where it could be conducted one-on-one or within a group setting which can be utilized to discuss existing concerns, identify any risky event and recommend what measures need to be taken when dealing with such risks. In order to make the interviews with the key personnel more efficient, a set of questions need to be prepared prior to the interviews. Besides being an effective technique for risk identification, the challenges come when interpreting the information obtained from the interviews and to classify the developed risky event properly. In order to obtain the proposed system requirement, interviews with experts are needed; to identify risk factors in oil and gas projects where no documentary data are available; to investigate the risk management current practice, adopted methodologies and challenges in the Iraqi oil and gas construction projects and its impacts on the project outcome; to collect some information needed for the design of the questionnaire surveys such as risk analysis criteria and the effective response strategies.

5.3 Phase Three: Risk Analysis

Risk analysis is the process of defining, analysing and prioritizing the risk factors based on their importance (El-Sayegh and Mansour 2015). The objective of risk analysis is to have a clear understanding of the risk circumstances and consequences then to sort risks according priorities based on a definite risk management strategy. Risk analysis aims at realizing the significance of each risk and the appropriate management path needed. The assessment process should be performed periodically to identify and risky event that should have positive or negative impact on the project objectives (time, cost and quality). The selection of the analysis approach is mainly depending on the level of risk, management experience and project level. Based on that a multi-criteria risk analysis model using fuzzy set theory is proposed to carry out the analysis phase of the identified risks. A multi-criteria risk analysis model based on fuzzy set theory and fuzzy analytic hierarchy method is proposed in this research through literature review and expert interviews. The model intends to achieve systematic and structured analyses of projects risks. According to Muhammad and Mhdhav (2016) and Roghanian and Mojibian (2015); Fuzzy logic is an effective management technique for risk management and for dealing with uncertainties in human decision making. It is an appropriate tool to deal with subjective judgement (Nieto-Morote and Ruz-Vila 2011). It can be employed to develop a model on the base of qualitative data (expert judgment) or quantitative values (Subramanyan et al. 2012). Fuzzy logic formulation and computation is applicable to a large number of engineering fields which ranging from risk assessment to risk pricing algorithm (EL Khalek et al. 2016). The development of the risk analysing model can be achieved through establishing the risk analysing criteria of the proposed model by analysing the limitation of the traditional multi-criteria analysing models and by taking into consideration the expert interviews outcomes regarding the effective analysing criteria, evaluating the fuzzy language set which depends on the risk analysing criteria, evaluating the failure mode by a triangular fuzzy number depending on the fuzzy set, determining the weights of the proposed criteria model using the fuzzy analytic hierarchy Process and determining each risk rank and importance. The outcomes of this phase are prioritized risk parameters obtained from conducting the questionnaire survey and processed using the proposed fuzzy multi-analysing criteria.

5.4 Phase Four: Risk Effect Prediction

This phase involves the development of a risk effect prediction model based on Artificial Neural Networks (ANNs) which can predict the effect of each risk factor on the project cost and duration. According to Lazarevska et al. (2012), ANNs are a computational mechanism which can analyses, and process data obtained from numerical analysis or experiments. ANNs has been usefully applied for cost estimation and construction scheduling. It is can be successfully utilized to solve problems related to cost estimation, decision making, optimizations and schedule predications in the field of construction engineering and management (Waziri et al. 2017). In this research ANNs will be utilized to determine and predict the duration needed to overcome each risk factor based on the project duration and risk importance obtained from risk analysis phase by Fuzzy set theory and also to predict the total cost needed to treat each risk factor based on the project total cost and each risk importance based on the fuzzy analysis phase in which it will allow a reasonable logical assessment away from randomization when determining the project schedule activities (duration contingencies) and cost of contingencies.

Based on Sang et al. (2014), the Steps for applying ANNs can be summarized as: identifying inputs variables, data collection and encoding, determining the output variables, Ann's architecture design, ANNs training and testing and ANNs validating. Despite the existence of several methods for estimating and predicting the risk effect on project time and cost, such as Analytic Hierarchy Process (AHP), Monte Carlo simulation and expert evaluation, these methods are subjected to personal judgement in which it may led to inaccurate prediction of the failure effect which will have an impact on the risk management decision making. Also, the traditional risk effect deterministic methods may neglect the factors that might have a significant influence on expected prediction values. However, artificial neural networks have been shown ability of solving different prediction problems in construction management field. In this research a back propagation neural network which based on back ward propagation of errors algorithm will be adopted. It considered being one of the most common types of neural networks and the most widely used especially in engineering applications.

The neurons or the nodes activation functions in this type of networks are similar to each other in each layer. The system requirement is represented by two sets of variables. In order to build the prediction model, two types of variables are defined. Independent and dependent variables. The independent variables are the impact of the risky events on the project time and cost which represented as the risks qualitative assessment using fuzzy multi-criteria risk analysis mode. While the dependent variables are the percentage of risk impact on the total project cost and duration. The system architecture consists of three layers. Input, middle and output layers. The number of the nodes located in the inputs and outputs layer is linked to the known and unknown facts of the problem. While the middle layer is determined based in the previous experience (historical data) (Haykin 2018). The ANN prediction model consists of two sets of groups. The first set is the training data set which used to the development of the model based on the historical data of achieved construction projects. While the second group is the testing data set which will be used to evaluate the performance of the ANN prediction mode. The Back-propagation (BP) method is chosen to train the applied artificial neutral network due to number of advantages such as high efficiency and simplicity. The outcomes after training the ANN is the prediction of each risk impact on the project cost and time.

5.5 *Phase Five: Optimization Model for Selection the Optimal Risk Response Strategy*

The most significant stage within the risk management process is risk response stage, where decision about the risky event is taken (Motaleb and Kishk 2012). This step designates strategy to manage a certain risk in the most efficient, appropriate and safe manner (Mubin and Mannan 2013). Risk response actions depend upon the type of risks if it a downs side risk (negative risk) or upside risk (opportunity). However, risk response planning stage is almost ignored part of the project risk management (Syedhosini et al. 2009). Literature investigation shows a limited research is carried out on the relation between risks and their response actions (Smith et al. 2014; Zhan 2016). According to most of the previous work in what concerning risk response actions have focused on human resources, experience and attitude factors and their relations to the binary variables (Cheraghi et al. 2017). Therefore, a mathematical model for selecting the optimal risk response strategies using Gravitational Search Algorithm (GSA) is proposed. The optimization model is to construct a mathematical model that considers the interaction between risks and relation between response actions in order to select an effective and efficient response action. The objective function in the model is to minimize the implementation costs of the response actions by taking into consideration time and cost constrains.

5.6 *Phase Six: Risk Management Decision Support System*

This phase will involve in the development of the proposed DSS computerized parts using (visual basic application software). This will include testing and validating the model to ensure its efficacy to the end users. To facilitate the process an interactive web-based decision support platform will be developed using the outcomes of the processed data. The online tool will be achieved using the following package:

(a) MySQL which is an open-source relational database management system. MySQL will be used for storing the primary data after being analysed. The stored data considered to be the core of the decision support system.
(b) The Hypertext Pre-processor (PhP) is a programming language together with Hypertext Mark-up Language 5 (HTML5) and Cascading Style Sheet (CSS) will be used for designing the user interface and functions of the decision support system.

According to Lam et al. (2007); the use of MySQL, PhP, HTML5 and CSS can provide the following benefits: the simplicity of using, data security, and the developer community is large in which it can extend their cooperation easily. They are open source content management programs. Therefore, it is not needed to pay for licenses as well as issues concern about the intellectual property when the decision support system comes into implementation. Therefore, using this package can provides a powerful decision support system development environment (Adam and Humphreys 2008). The designed DSS will enable decision makers to assess the oil and gas projects risky events; support their decision during planning and work implementation stages; gain experience in RM through exercising and implementing RM on scientific and documented bases; organize and document the knowledge-based information for subsequent generation of the oil and gas construction projects decision makers.

6 Conclusions

Oil and gas industry are an essential engine for economic in the developing countries. The construction projects in this sector are characterised as complex and risky due to their unique nature, dynamic environment, complex technology and numerous stakeholders. Oil and gas construction projects play a significant role in the sustainable supply chain and processing. Because of this importance, governments of developing countries are under pressure to ensure that construction projects will be completed on time within the estimated budget and the least amount of uncertainties and risks. However, the practice of construction risk management has not got the required attention in developing countries such as Iraq. The purpose of this research is to present an integrated methodology for managing construction risks in oil and gas fields in Iraq by focusing on analytical models to formalize and deal with human knowledge, risk impression and characteristics that are inherent. Also, to provide a clear differentiation between different risks and methods of understanding the interdependence between risks. This paper concludes that establishing a structured methodology for managing construction projects risks for oil and gas projects will increase the effectiveness of projects risk management and improve project performance within the Iraqi oil and gas sector. In order to verify the proposed methodology, the next stage involves the use of documentary reviews, expert interviews and questionnaire survey for primary data collection (system requirement) and risk rating. Also, the feedback of the construction experts working in Iraqi oil and gas constriction projects will be used to validate the efficacy of the proposed research methodology. The design process of the risk analysis model, risk effect prediction and response action optimization model will be developed and tested based on real projects case studies in the mentioned area.

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Assessment of Risk Management Practices in Construction Industry

Mohammed K. Al Mhdawi, Ibrahim Motawa and Hatem A. Rasheed

Abstract The construction industry is globally known as a risky industry because construction projects usually accompanied with high uncertainty in achieving their final objectives (time, cost and quality). The main purpose of this research is to investigate the current practices and methodologies of risk management for the construction industry in Iraq. A mixed research method that involves both qualitative and quantitative approaches is adopted in this research to collect and analyses the primary data. A comprehensive review of the available literature of risk management at the international and local construction projects is conducted followed by interviewing experts and carrying out a questionnaire survey with construction professionals in Iraq. The assessment focuses on the following levels: Project management team awareness and understanding of risk management tools and techniques, methods used to identify risks, currently used risk analysis and ranking techniques, risk management monitoring and controlling procedures, the status of risk management for each project phase, contractors role in applying risk management process, and the relation between risk management and project success. It has been found that the use of risk management techniques in building construction in Iraq is low. Most of contracting companies in Iraq are applying qualitative methods when identifying and analyzing the risky events over quantitative methods. The absence of the risk management team within the project management culture, weak risk planning, the lack of risk management training and knowledge within the construction firm were found to be the main barriers preventing the execution of effective risk management process.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_35

Keywords Construction projects · Risk management

1 Introduction

Risks in the construction industry are perceived as events that effects project objectives. Some of the risky events associated with construction processes are predictable; others may be unforeseen (Ahmed and Azhar 2004). The scope and level of the risks are different from project to another depending on the project characteristics (Davis and Prichard 2000). An effective approach for managing risks is to understand how to manage all types of risks facing the construing project during its different phases (Taroun 2014). The main challenge of applying effective risk management is to explore the unknown risks and turn them into known risks by applying creative risk management steps (Hosny et al. 2018). Generally, the main objectives or risk management are to decrease threats (negative risks) and increase the opportunities (the positive risks) (Mulcahy 2009). For many years' construction firms in the developing countries have approached risk management using a self of insufficient practices which produce poor outcomes at most of the time (Serpell et al. 2014). This can be observed in both public and private contracting companies. To measure the capabilities of the construction organisations of performing effective and efficient risk management requires an investigation of the risk management current practices and methodologies. Thus, the aim of this research is to assess the existing construction risk management practices in the Iraqi construction industry.

2 Literature Review

According to the Project Management Institute (PMI 2008), Project risk is defined as an uncertain condition or event, if occurs, it will have a negative or positive impact on the project objectives (time, cost and quality). while, the International Standards Organization (ISO) defines the risk as the effect of the uncertainty on the project objectives (ISO 2009).

Risk management in construction projects usually has two main goals: to avoid threats and to exploit the opportunities (Smith et al. 2013). Effective risk management depends on previous historical data then looking forward to thorough planning to narrow future risks area where future failures can be avoided (Kendrick 2015). Effective management of risks does not only concentrate on minimising risk consequences, but it gives enough support to the activities that adopt an innovation, so more significant benefits can be achieved. Risk management process is a systematic approach to planning for evaluating, treating and monitoring the risky events of the project. It involves a set of tools and techniques that will assist the management team to minimise the likelihood and the impact of the adverse events and maximise the opportunities of the positive events. It defines the essential parameters within which

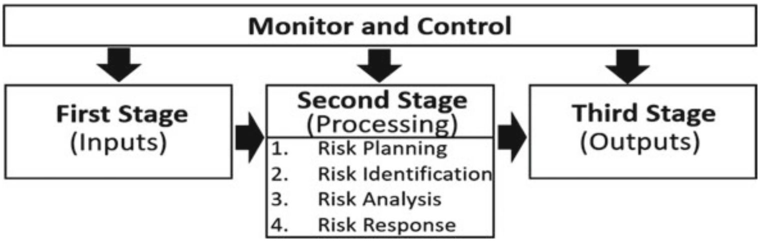

Fig. 1 Risk management stages

the risky events should be managed and outline the plans for the rest of the management process of the risks by defining the internal and external environment of the organization, develop criteria and define the structure. To ensure applying effective risk management, its three main stages must be performed successfully. Those three stages are; inputs, processing and outputs as shown in Fig. 1 which illustrated in the coming paragraphs.

2.1 First Stage: Inputs

In this stage, all the basic information about the construction project must be assembled and kept updated. Such information must include the following items: overall and detailed scope of work; overall and detailed project schedule; Overall and detailed project cost; overall and detailed methods of construction; overall and detailed contractual obligations; overall and detailed quality assurance plan; overall and detailed health and safety plans and previous risk analysis (historical data) if any (PMI 2013).

2.2 Second Stage: Processing

This stage of risk management includes conducting the operations of planning, identification, analysis, response actions and control. The objectives of these operations are to increase the likelihood and impact of positive events and decrease the probability and the effect of adverse events expected to happen in the project.

2.2.1 Planning

In this step, the operations that need to be accomplished by the risk management team are described in detail. It includes defining and scheduling all the activities and procedures required to observe, evaluate and document the risk factors associated with the project. The outcome of this step is known as risk management plan which has an essential role in Kendrick (2015): updating the project risk management strategy; finding out the most effective approaches to implement the risk management strategy; nominating the appropriate parties to get the job done. To build up a successful risk management plan, enough data must be collected through the project work breakdown structure (WBS) in addition to the project performance standards, cost plan and schedule. Previous effective strategies in similar finished projects must also be present. All this information is helpful to realise the project requirements and difficulties which can also be used for cost and schedule re-planning and to predict the final product of the project.

2.2.2 Risk Identification

Risk identification is considered as the most significant step in the risk management process. Any failure in identifying any risk factor will lead to the ill implementation of the whole process. It is also considered as an essential step in constructing all risks profiles. Risk identification is said to be of two phases. The first is the initial identification phase which is usually conducted by firms that have not already identified their risk factors in a structured way or by new firms or projects. The second is the continual risk identification phase which aims at identifying new risk factors never occurred before (Ana-Maria and Doina 2012).

2.2.3 Risk Analysis

The objective of risk analysis is to have a clear understanding of the risk circumstances and consequences then to sort risks according to priorities based on a certain risk management strategy. Risk analysis aims at realising the significance of each risk and the appropriate management path needed. Realising the importance of risks in construction projects can be done using two different approaches; Qualitative and Quantitative risk analysis (Keith et al. 2010).

2.2.4 Response Actions

The aim of this step is to develop response actions according to the risk management strategy in order to reduce threats to the project objectives. The risk management team must ensure that each risk and response is closely monitored even when the response action is delegated to others. Response actions are generally classified into four types of actions as follows: Avoid, Mitigate, Transfer and Accept.

2.3 Third Stage: Outputs

At this stage, an effective project risk management plan will be available in the form of a detailed risk register which is generated from the outputs of the operations stage. The risk register is a document that contains a full list of the identified risk factors, risk analysis methods and results and response actions (PMI 2013). As a result of the monitoring and control operation, the risk management plan is concurrently updated.

2.4 Monitoring and Control

To assure a successful implementation of risk management, it is essential to apply firm monitoring and control on all operations. Various risk factors may require different monitoring approaches at different time frames by different individuals (Peter and Pail 2005). Monitoring and control must systematically track and assess the efficiency of all adopted risk response actions. The findings of this process provide a baseline to add new response actions or to develop the existing strategies. The main success factor of minoring and control is to set technical performance, schedule and cost key indicators which can be used to assess the status of implementation (El-Sayegh 2014; Górecki and Bizon-Górecka 2017).

3 Problem Statement

The construction industry is highly linked to risks due to its complex nature, environment, technology, activities, processes and organization (Mani et al. 2017). The risk factors facing the construction cab be minimized, transferred, accepted or neglected (Burtonshaw-Gunn 2016). Since it is impossible to eliminate all the risks facing the projects, a successful project can be accomplished when identifying the risk factors at early stages and manage them. On the other hand a lack of proper consideration and assessment of the construction project risks are the lead cause to poor quality, delays and cost overruns (Taillandier et al. 2015). The previous literature regarding risk management indicated that there is a lack of risk management knowledge in term of published work and application in real projects (Howard and Serpell 2012). Construction projects today are subjected to more risks and uncertainties due to social concerns, climatic and environmental factors, economic and political statutory regulation, planning and design complexity (Thuyet and Ogunlana 2007). The construction industry has a poor reputation in coping with risks as many projects fail to meet deadlines and cost targets. Clients, contractors, the public and others have suffered as a result (Zavadskas et al. 2012). Thus, construction business is related to high risk, which affects each of its participant; while effective analysis and management of construction associated risks remain a big challenge to practitioners of the industry. In Iraq, most of the construction contractors are having lack of knowledge in applying risk management in their projects. This can be due to lack of researches and applied knowledge regarding risk management in the construction projects in Iraq. Also, the limited influence of construction industry revenue towards the country economy as it depends significantly on the production of oil and gas. Therefore, there is a need to investigate the current practices of risk management in the Iraqi construction industry to diagnose the root of management problems, monitoring the existing performance and supporting decision making.

4 Methodology

A mixed-methods approach that involves both qualitative and quantitative data was adopted for this research to assess the risk management current practice in the Iraqi construction projects and its impacts on the project outcomes. The outcome of one method assist to commence the questions on the next method and the results of both methods can be applied side by side to reinforce each other (Khan and Gul 2017). The decision of the selected research methods depends on the study nature, purpose of the research, research objectives, the availability of the resources and previous literature.

Direct structured interviews were conducted first with (30) Iraqi construction experts followed by carrying out (50) questionnaire survey. The interview questions are designed based on the existing literature while the questionnaire survey designed depending on the previous literature and expert opinions. Those experts were senior engineers with not less than (20) years of experience in the contracting companies, consulting centres and other directorates of the Ministry of Construction and Housing and Municipalities and public works. The assessment of the current practices focused on the following levels: Project management team awareness and understanding of risk management tools and techniques, methods used to identify risks, currently used risk analysis and ranking techniques, risk management monitoring and controlling procedures, the status of risk management for each project phase, contractors role in applying risk management process, and the relation between risk management and project success.

5 Analysis of Results and Discussion

In order to make the analysis process easier to be understood. Statistical interpretations were indicating how responses varied and distributed. The analysis of the gathered data from expert interviews and questionnaire survey was used to assess the current practices and methodologies adopted for risk management in Iraq.

5.1 Findings of the Expert Interviews

- Most of the construction project managers in Iraq do not apply a formal approach for managing risks.
- Most of the construction project managers in Iraq are uncertain at the project inception that they will meet the time and budget frames.
- The current practice of risk management in Iraq is to take actions when the risk do occur having no plans in advance.
- Recently most of the contracts in Iraq were breached because of mal planning for risk management.
- Absence of any risk management team in the culture of project management in Iraq.
- Estimating contingencies depends solely on the estimator's personal judgment.
- Absence of any documentation system for historical risk data.
- The Public Sector does not exercise its role in training junior engineers in the field of the risk management.
- The bid evaluation and analysis process do not consider how successful the contractor was in his previous works.

5.2 Findings of the Questionnaire Survey

The questionnaire survey includes 21 questions which were grouped into four sections. The description of these sections is as following; sections one: sample characteristics; section two: risk management current practices in Iraq; section three: methods used to identify risks; section four: methods used for risk analyses. A total of (50) questionnaire forms were distributed and (46) forms were received with a response percentage of 94%. Table 1 lists the affiliation of the respondents and their

Table 1 Number of respondents and their organizations

No	The respondents organizations	No. of respondents
1	National center for engineering consultations/ministry of construction and housing and municipalities	10
2	State commission for roads and bridges/ministry of construction and housing and municipalities	10
3	Al-Rasheed contracting company/ministry of construction and housing and municipalities	9
4	Hammurabi contracting company/ministry of construction and housing and municipalities	9
5	Al-Mansour contracting company/ministry of construction and housing and municipalities	8

Table 2 Quintet rating scale

Class mid.	Class boundaries	Class rank
10	0–20	Almost never
30	20–40	Rarely
50	40–60	Sometimes
70	60–80	Often
90	80–100	Almost always

number in each organization. A quintet rating scale was adopted in the questionnaire form in order to facilitate the statistical analysis of the respondents' answers as shown in Table 2. The questionnaire survey outcomes were analysed using e statistical software package (SPSS).

5.2.1 Sample Characteristics

The closed questionnaire was directed to engineers working in the Public sector. They fill the jobs of Project Managers, Consultants, Site Engineers, Design Engineers and Safety Engineers. Some of them hold Ph.D. or M.Sc. degrees. Their fields of practice vary from civil, architectural, mechanical and electrical to others. Figures 2, 3, 4 and 5 show the respondents' characteristics.

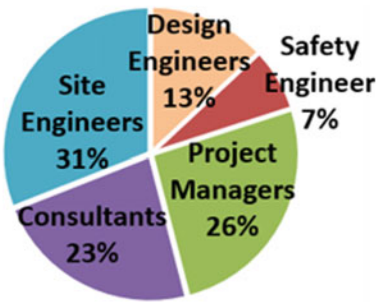

Fig. 2 Respondents' jobs

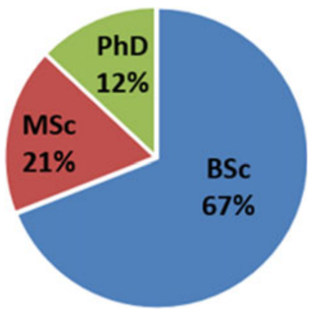

Fig. 3 Education degrees of the respondents

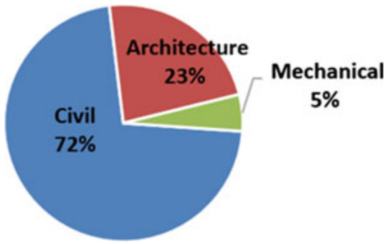

Fig. 4 Specialization of the respondents

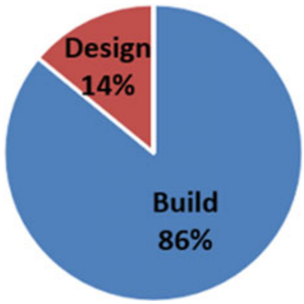

Fig. 5 Field of experience of the respondents

5.2.2 Current Practices in Risk Management

The main objective of this section is to investigate the current practice of risk management and how it is planned for in Iraq. It was found that:

- According to (73%) of the respondents, contractors are rarely or almost never preparing a risk management plan and/or take preventive actions.
- According to (68%) of the respondents, the contractor rarely or almost never explains the expected work hazard to his manpower.
- According to (86%) of the respondents, the existence of an investigation program for the accidents occurred in the site with reporting to the appropriate parties is almost always or often done.
- According to (74%) of the respondents, conducting meetings between the contractor and a person to be in charge of running a risk management program is sometimes or often done.
- According to (70%) of the respondents, the potential risks are rarely or almost never be taken into consideration by the contractor prior to submitting his bid.
- According to (46%) of the respondents, the periodic monitoring (weekly, biweekly or at any specific periods) is sometimes or rarely done.
- According to (75%) of the respondents, the project risk factors are rarely or almost never taken into consideration when preparing the contract form.
- According to (61%) of the respondents, the project risks are rarely or sometimes taken into consideration in the design phase.

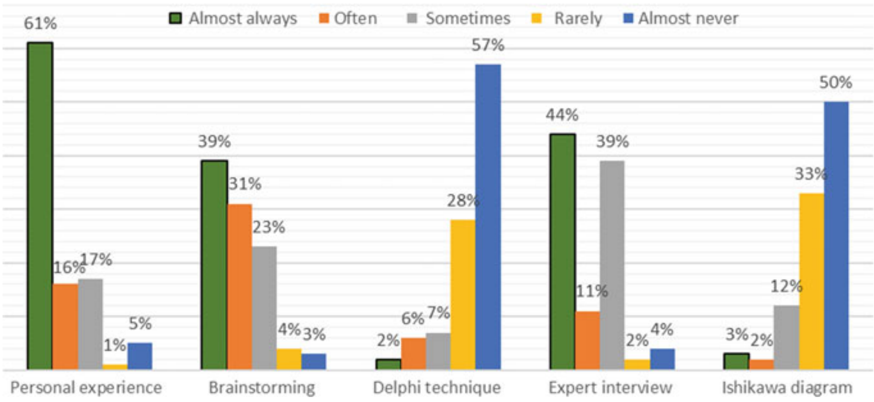

Fig. 6 Current methods used for identifying risks

- According to (50%) of the respondents, the project cost estimator sometimes or rarely takes into consideration the potential risk factors when estimating contingencies.
- According to (73%) of the respondents, the inexperienced contractor who does not take into consideration all potential risk factors in bid pricing is often or sometime lose the contract.

5.2.3 Methods Currently Used to Identify Risks

This section investigates the methods currently used to identify the construction projects risk factors in Iraq. Figure 6 show the results of this section. It was found that 77% of respondents are often or almost always rely on personal experience to identify risk factors. However, 70% of the respondents stated that the brainstorming technique is almost always or often used to identify risks. On the contrary, over 50% of the respondents stated that interviews with experts are almost always or often used to identify risks. Finally, the use of Delphi technique and Ishikawa diagrams are considered by 85% and 83% respectively as almost never or rarely used to identify risks.

5.2.4 Methods Currently Used to Analyse Risks

This section investigates the most common risk analysis methods used in the current risk management practice in Iraq. Figure 7 show the results of this section. It was found that 57% of the respondents answered that the quantitative analysis approach is rarely or almost never used to analyse risks. Whereas, most of the respondents (72%) are often or sometimes use qualitative approaches for risk analysis. Respectively,

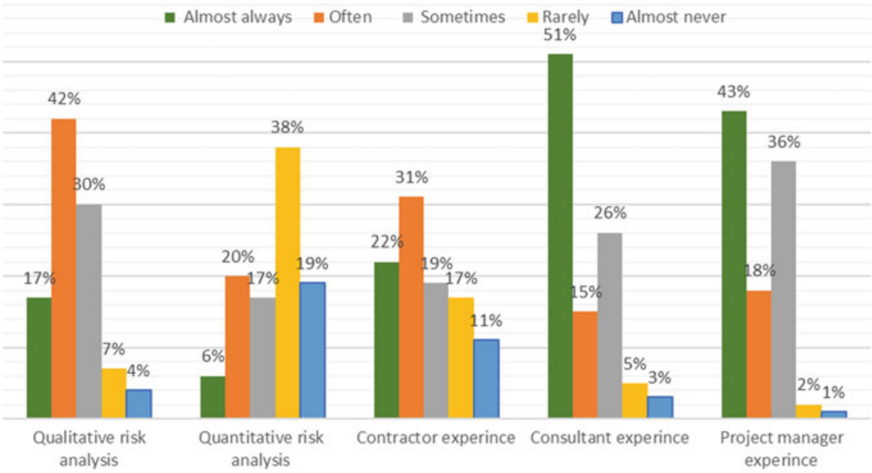

Fig. 7 Analysis methods for the construction projects risk factors

53% of the respondents stated that contractors experience is often or almost always used to analyse risks. Furthermore, consultants and project managers experience are almost always or often used to analyse risks by 66% and 61% respectively of the respondent's answers.

6 Conclusions

Investigating the current level of risk management of the construction companies in Iraq included the adopted tools and techniques when identifying, analyzing, responding and monitoring the risky events. This has helped in diagnosing the roots of the current management problems that are facing this critical sector in Iraq, establishing a basis for priority settings and planning for future work plans, assisting in monitoring the existing performance, identifying and setting the targets for improvement and judging the progress towards those targets.

Expert interviews indicate that the current practices of risk management are mainly reacting when risk happens with no adoption of a formal risk management approach. Also, the absence of risk management team within the project culture, weak risk planning, the absence of any documentation systems for historical risk data and lack of contractor's selection criteria are found to be the main barriers towards applying effective risk management approach.

The results of the questionnaire survey indicated that the use of subjective judgement is applied by construction professionals over the objective methods. Brainstorming and expert interviews are found to be the most popular risk identification techniques in use while the use of Delphi and Ishikawa (fishbone diagram) are rarely used for this purpose.

For risk analysis, it has been found that the use of qualitative approaches presented by expert personal experience is a preferred technique for risk analysis while the use of software's and mathematical models are rarely or never used for risk analysis.

The main conclusion of this paper is that risk management practices in the construction projects in Iraq are weak which characterized with lack of risk management knowledge, training and parodic meetings, the absence of formal approach of managing risks and relying on subjective judgement when analyzing risks. These subjective approaches are based on the assumption of the randomness and ignoring the necessary and essential information regarding the correlations among risks rather than using more structured and modern methods that formalize and deal with human knowledge, risk impressions and characteristics.

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Improving Formwork Design Using Lean Thinking

Chien-Ho Ko

Abstract Formwork is one of major engineering works in reinforced concrete projects. Its performance affects project success and therefore profitability. Formwork engineering could be divided into design and construction phases. Conventional formwork engineering involves unnecessary non-value-adding activities, such as change orders and material movement. The objective of this study is to applying lean thinking in formwork design to reduce unnecessary waste, increase design reliability, and enhance construability. A lean thinking formwork design process is proposed to achieve the goal. Concurrent design and Building Information Modeling (BIM) ideas are used in the process to improve visibility. Design reliability is improved using design correctness reviewed by project stakeholders. Thus, a continuous learning culture is developed. A real building project is used to validate the feasibility of the proposed method. Analysis results demonstrate that the proposed approach could be used to increase design reliability and enhance construability, thus reduce unnecessary waste in formwork design.

Keywords Building information modeling · Concurrent design · Design correctness · Formwork design · System dynamics

1 Introduction

Formwork expenditure, including material and labor, occupies approximately 15% cost in reinforced concrete structures; it is one key operation affecting project success (Peng 1992; Santilli et al. 2011). Design quality may directly impact construction quality. Improper formwork design may lead to low constructability and even formwork collapse, resulting in unnecessary waste which is regarded as a barrier to increase profits (Kikolski and Ko 2018; Ko and Kuo 2019). Traditional formwork design primarily completed by the general contractor. This practice may induce design flaws and, therefore, affect project delivery (Ko et al. 2011).

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_36

Lean manufacturing, derived from the Toyota Production System (TPS), has been successfully applied to improve construction performances. Eriksson (2010) adopted lean thinking to improve construction supply chain collaboration and performance. The author found that lean thinking could be implemented in various aspects and can have a positive effect upon supply chain systems and construction performances (Ko 2016). Nahmens and Ikuma (2012) applied the lean philosophy in homebuilding industry. According to their study, one barrier to popularize the sustainable homebuilding is the high initial costs to the learning curve of workers with new tools and ideas. Nahmens and Ikuma's (2012) analysis shows that lean construction could reduce material waste by 64% and reducing production hours by 31%. Bajjou et al. (2017) compared the lean construction and the traditional production system. The comparative study demonstrates that lean ideas such as creating value and eliminating waste, planning and mutual coordination, and site organization could improve the traditional production system through waste reduction.

Although previous studies have deeply discussed the potential of applying lean ideas to improve project performances, a complete formwork design process has not been fully discovered yet. To remove unnecessary waste in the formwork engineering, the objective of this study is to develop a formwork design process using lean thinking.

2 Lean Formwork Design Process

2.1 Design Value

The value of formwork design lies in completing correct formwork design in accordance with customer requirements. This study improves design value through the design correctness rate. The design correctness rate, defined in this study, is an indicator for reviewing if the design contents comply with requirements by project participants.

This study applies the concept of concurrent design in the formwork planning phase. The site manager integrates formwork subcontractor together with other related subcontractors carrying out the formwork engineering in the project level. As far as requirements of project participants are concerned, the formwork subcontractors, structural engineers, and related subcontractors (e.g. scaffold, rebar, electromechanical, and concrete engineering) can be integrated. The purpose of allowing project participants to take part in planning and design of formwork at the beginning is to take factors that should be considered by formwork engineering into account at the beginning, and to solve problems that may occur in the construction phase at an earlier time.

2.2 Value Stream Analysis

A product cannot generate its value until it has been manufactured. If the product value or market competitiveness is lowered due to poor design, it can be viewed as a waste (Ohno 1988). In other words, poor design itself is a waste that causes change order and defective products. Problems that molds cannot be assembled based on shop drawing often occur during construction phase (Williams et al. 2011). The Lean Formwork Design Process is a production flow for enhancing customer value. During production, the value stream mapping is used for analyzing the non-value-adding activity and then improvement is made such that customer value is gradually improved. While designing the formwork, if problems are hidden in the drawing, waste such as change order and rework are produced in the construction phase. The general contractor shall help the formwork subcontractor to carry out the concurrent design. Moreover, the formwork subcontractor also shall appropriately use organizational learning to continuously analyze the design stream value so as to enhance the formwork design value.

2.3 Design Flow

Traditional formwork engineering is outsourced in the form of labor and materials. Formwork is traditionally designed by the general contractor and then delivered to the formwork subcontractor for assembly. However, since formwork subcontractor does not participate in the design process, problems such as design errors and poor constructability encounter in the construction phase. In order to make the design process smoother, turnkey, concurrent design, and organizational learning are used for enhancing design value in this paper. Turnkey of formwork engineering is that the general contractor subcontracts both formwork design and assembly to formwork subcontractor. Concurrent design is that the design team members collaboratively conduct design documents. Organizational learning is adopted primarily for increasing design reliability through the feedback of design correctness.

When the formwork subcontractor uses the concurrent design for formwork design, the general contractor helps the subcontractor to integrate the design team including owners and other formwork related subcontractors to ensure design results comply with customer requirements and other third parties. The design process consists of preliminary design and detailed design phases shown in Fig. 1 (Ko and Kuo 2019).

2.3.1 Preliminary Design

The main purpose in this phase is to correctly mark the building size on the drawing. The BIM is prepared by the general contractor. Formwork subcontractor designs the

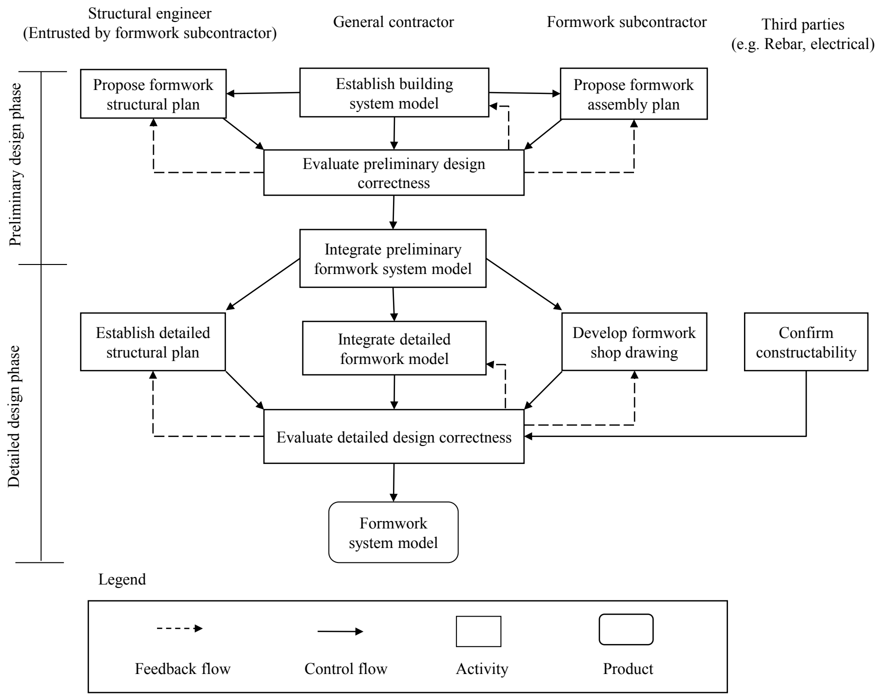


Fig. 1 Lean formwork design process

Table 1 Preliminary design correctness evaluation (partial contents only)

Evaluation item			Evaluation results					
			GC		Structural engineer		Formwork subcontractor	
			Yes	No	Yes	No	Yes	No
General contractor	Design conflictions	Concrete engineering						
		Scaffold engineering						
		Electromechanical engineering						
		Rebar engineering						
		Others						

prototype of formwork system. Structural engineers analyze mechanical behavior of formwork structure.

Design correctness in the preliminary design phase is evaluated using Table 1. The formwork team (general contractor, formwork subcontractor, and structural engineers) jointly review and discuss the design contents shown in Table 1. In case that any design contents are not described in detail, the responsible designer shall explain completely to reduce the recognition difference among professional fields. Any incorrect and improper design shall be returned to relevant designer for further modifications. The next design phase cannot be carried out until all design contents, including modifications, meet customer value. Table 1 provides no specific figures for grade evaluation but "Yes" and "No" for evaluating the correctness of the design contents. By using the table, the construction and design team members participate in and learn together to reveal problems and solve them as soon as they have been found.

2.3.2 Detailed Design

The main purpose in this phase is to develop shop drawing and 3D formwork system. The formwork system is perfected through the feedbacks of design correctness. Formwork design team members, Architectural/Engineering (A/E), and related subcontractors jointly evaluate the design results. Detailed structure plan, formwork detailed model, and formwork shop drawing are continuously improved until 100% design correctness has been reached. Detailed design correctness checking list is shown in Table 2.

3 Case Study

A real case, a university building situated in Neipu, Pingtung, is used to validate the proposed design Process. System Dynamics is applied to analyzed the effectiveness of the developed method. The structure of the studied case is reinforced concrete. This case study uses traditional formwork design method. The general contractor develops building system model required for formwork engineering. The formwork structure plan is prepared by the structural engineers. The general contractor formulates the formwork preliminary models. The structural engineers analyze the mechanical behavior of the formwork support system. The formwork assembly plan is responsible by the formwork subcontractor. The general contractor then integrates these artifacts into a formwork system model. Finally, formwork subcontractor assembles molds according to the formwork system model.

Table 2 Detailed design correctness evaluation (partial contents only)

Evaluation items			Evaluation results							
			Structural engineer		Formwork subcontractor		A/E		Third parties	
			Yes	No	Yes	No	Yes	No	Yes	No
Structural engineer	Seism-resistance structure									
	Formwork structure	Shop drawing								
		Support configuration								
	Material specifications									

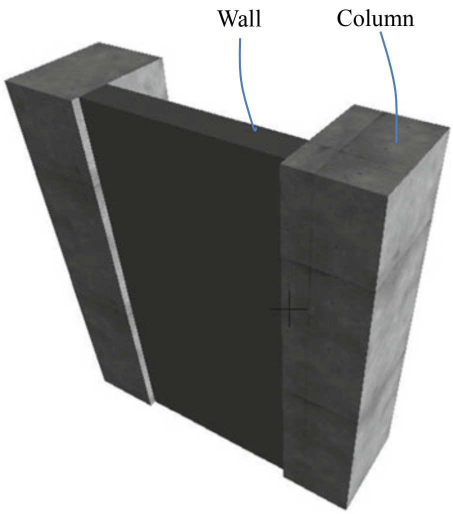


Fig. 2 Formwork design through BIM 3D model

3.1 Formwork Building Information Modeling

The Lean Formwork Design Process is applied to this case study to improve the formwork design process. The Lean Formwork Design Process employs the BIM as a platform for information sharing and communication. Formwork subcontractor leads formwork design through the general contractor's assistance. The general contractor coordinates requirements and prerequisite works of the formwork related subcontractors before assembling molds. In order to effectively bring every designer into communication, formwork is designed through BIM. The formwork assembly team can understand the building system through BIM 3D model. In addition, formwork related members can be integrated to jointly participate in design process. Design members are allowed to bring their specialties into the design and therefore establish the design drawing together and enhance design quality. The BIM formwork design is shown in Fig. 2.

3.2 System Dynamics Analysis

The effectiveness of the proposed Lean Formwork Design Process is analyzed using system dynamics. The stock-flow diagram shown in Fig. 3 is used to understand the influence and information flow in the design system. Detailed design can be launched when preliminary design correctness rate reaches 100%. The detailed design correctness rate is set as the stock. The auxiliary variables are detailed modification numbers and correctness rate of the integrated preliminary formwork model.

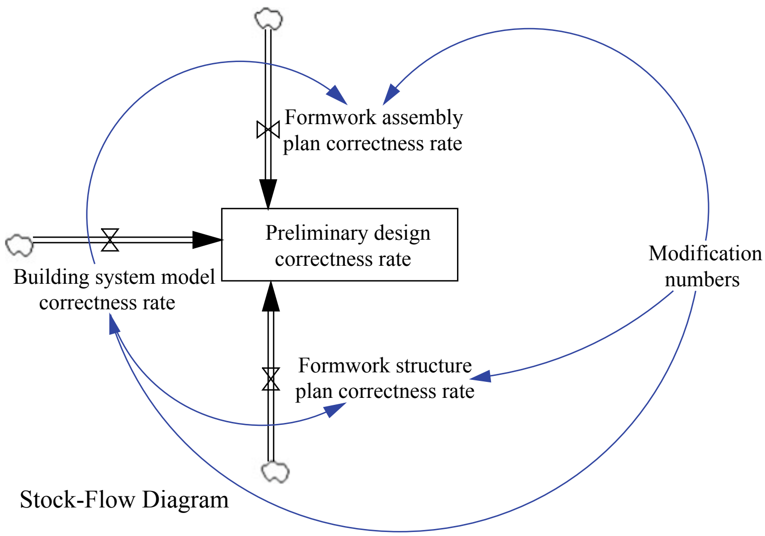
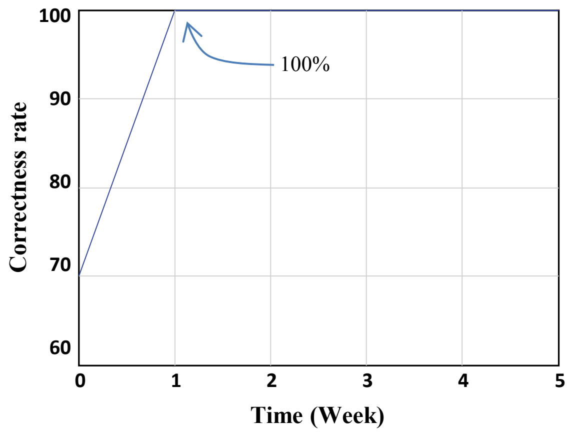


Fig. 3 Preliminary design stock-flow diagram

The preliminary design correctness rate analyzed using System Dynamics is shown in Fig. 4. The design correctness reaches 100% about a week with one time modification. The next phase of detailed design system is carried out once the preliminary design has no error can be found.

The detailed design correctness rate analyzed by the System Dynamics is shown in Fig. 5. In the organizational learning environment, the detailed design correctness rate reaches 97.12% in the first modification. However, due to the influence of constructability review, the rate reaches 99.04% at the second week. The 100% correctness can be achieved at the third modification.

Fig. 4 Preliminary design correctness rate



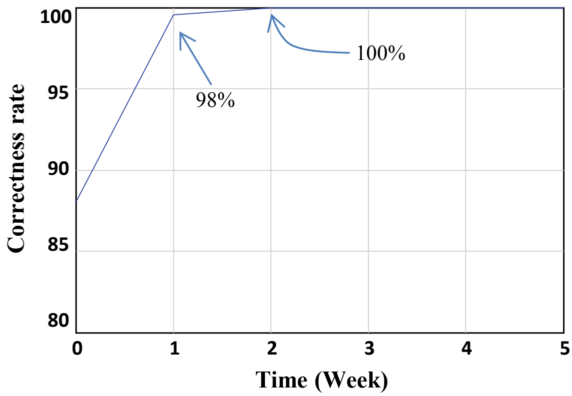


Fig. 5 Detailed design correctness rate

3.3 Discussions

Poor design frequently results change order and waste such as reworks during construction (Aleisa et al. 2011). When design errors found in the formwork assembly, most formwork subcontractors change the assembly method or add other materials on site as opposed to make change orders. The primary purpose to do so is to save the time required for change order. Therefore, the increase of formwork design correctness can reduce the waste for assembling and processing formwork.

"Weight of design category" is the proportion of design category. For example, formwork subcontractor is responsible for "propose formwork assembly plan" that account for 26.9% (7/26) evaluation items. The "establish building system model" is implemented by the general contractor, which occupy 26.9% evaluation items. The evaluation item for "propose formwork structure plan," responsible by structural engineers, account for 46.2% (12/26) items in the preliminary design evaluation table.

The design weight of formwork assembly and processing multiplies the manpower (140.5 labors) and value-adding time (1124 h), the "design-affected manpower" and "design-affected value time" can be obtained respectively. Note that the manpower (140.5 labors) and value-adding time (1124 h) are investigated in the construction site by this research. In the "propose formwork assembly plan," the design-affected manpower is 21.5 (15.3% * 140.5) and the design-affected value time is 171.7 h (15.3% * 1124). The influence of poor design is summarized in Table 3.

This case study designs the formwork system using traditional method that has no design correctness examination and organizational learning mechanism. However, in building projects, the rework cost due to design error is up to 35% (Choo 2008), which implies the formwork system may contain up to 35% design errors; manpower in mold assembly may involve up to 35% operational waste. The use of the Lean Formwork Design Process suggested in this paper can eliminate unnecessary waste in formwork assemble and processing, including 7.53 (21.5 * 35%) labors and 60.01 (171.7 * 35%) working hours.

Table 3 Poor design influence

Design phase	Design category	Design category weight (%)	Design-affected manpower (labor)	Assembly and processing design weight (%)
Preliminary	Propose formwork assembly plan	26.9	21.5	15.3
	Establish building system model	26.9	21.5	15.3
	Propose formwork structure plan	46.2	36.9	26.2
Detailed	Integrate formwork detailed model	14.3	11.4	8.1
	Establish detailed structure model	23.8	19.0	13.5
	Develop formwork shop drawing	57.1	45.6	32.4
	Verify constructability	4.8	3.8	2.7

4 Conclusions

A lean thinking formwork design process is developed in this study to reduce unnecessary waste occurred in formwork design phase. Design error is reduced using concurrent design ideas and a visual communication platform is constructed using BIM. Communication interface between formwork stakeholders, including formwork designer, assembly trade, rebar, and electrical subcontractors, are eliminated using a formwork turnkey contract. Since formwork stakeholders are reviewing design correctness and constructability concurrently through a visual communication platform, an organizational learning environment can be built. Finally, a real building project is used to validate effectiveness of the developed method using system dynamics.

In the current practice, formwork design and assembly are implemented by different parties, whereas general contractor is responsible for formwork design and formwork subcontractor for mold assembling. This practice leads to defective and low constructability formwork design. The proposed method, by the contrast, carries out the formwork design together with stakeholders in the formwork assembly phase, resulting reliable design artifacts. Moreover, since formwork assembly team participates early in design phase, they could help stakeholders identify potential problems as early as possible and thus improve design reliability and correctness.

This research has not taken into account cost effectiveness while implementing the proposed method. Future research may further analyze the cost that can be reduced using the proposed approach.

Acknowledgements This research was sponsor by Ministry of Science and Technology, Taiwan with grant number MOST 103-2221-E-020-027-MY2. Special thanks are due to graduate student Jiun-De Kuo who helped in data collection and data analysis.

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Lessons Learned from Managing the Design Process of a Large and Complex Construction Project Seen in a Lean Construction Perspective

Bo Terje Kalsaas, Anders Rullestad and Hanne S. Thorud

Abstract The construction project being studied is a government investment related to a relocation of a biomedical institute delivering research-based knowledge and contingency support in the fields of animal health, fish health and food safety. The project covers a total of 63,000 m^2 distributed over 10 buildings. The buildings have a very high degree of complexity due to a large proportion of special areas, great ambitions to the minimize environmental impact in addition to strict compliance to Infection Prevention and Control in order to achieve a world class product in its field. The project is procured as a design-bid-build project divided into 40 different execution contracts. The design alone has required 1 million hours and more than 100,000,000 Euro. The purpose of this article is to study the applied methodology for managing the detailed design to identify lessons learned from the project. The theory underlying the study is inspired by lean design management and design theory linked to design as phenomena, including reciprocal interdependencies, iteration, decomposition, design as a "wicked problem", learning, gradual maturation, etc. The article is based on an abductive research design and has been implemented as a case study where both qualitative and quantitative methods have been used. First, the study describes how the design process was managed. Furthermore, challenges that are revealed through interviews and a survey are presented. Uncovered are a widespread volume of negative iterations and waste, where reasons for the challenges are linked, among others, to the use of traditional management methodology, a long user process and late owner and user decisions. Finally, the key lessons learned from the case are further explored in how they could be solved by alternative management methodology.

Keywords AEC-industry · Complexity · Design · Lesson learned

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_37

1 Introduction

The concept of design in this paper includes both architectural and engineering design. While the design processes in construction make up a relatively small share of construction costs (about 10%), they are integral to the building's life cycle, including customer value, maintenance and operational costs (Evans et al. 1998; Gilbertson 2006). Koskela et al. (2013) regard the design-production as a chain of processes where "value is created as a potential in design, is embodied in production and is realised in the intended use by the client."

The management of the design process itself however, is more complicated than the management of the production phase due to characteristics such as iterations, gradual maturation, learning, reciprocal interdependencies and the often-fragmented design process involving several different consulting companies, the client and construction companies as well as their subcontractors (Kalsaas and Moum 2016). According to the Lean tradition, the management of design processes is often designated as Lean Design Management (LDM), e.g. Koskela et al. (1997) and Uusitalo et al. (2017).

In order to achieve efficient design management, we need knowledge of design as phenomena, structured work methodology and feasibility. This paper builds on a master thesis (Rullestad and Thorud 2019) and studies one of Norway's largest AEC projects, which has a high degree of complexity. The aim is to study the structure of the applied methodology in relation to design as phenomena regarding uncovering improvements and lessons learned. Thus, the problem can be stated as follows; *Which lessons can be identified from the process of designing a large and complex construction project seen in a lean construction perspective?*

2 Methodology

This research deals with a single project and therefore the most obvious research approach to choose is case study methodology as well as most appropriate. We were inspired by Sayer (1992) concerning critical realism (theoretically informed) case studies, then supplemented this with Yin (2014) using the case study method. The study is primarily a contextual analysis in relation to explaining obstacles in the design work (lessons learned). In terms of structure, it is in the incentives associated with the applied contract strategy (design-bid-build). We consider incentives as a structure that together with mechanisms can lead to certain outcomes, given certain conditions (Sayer 1992). Qualitative data collection was conducted using semi-structured interviews, of which two were with representatives from the client's project administration and eleven with the design team management. Quantitative data collection was conducted using a survey.

This paper has been organized in the following manner. Firstly, the researchers acquired relevant literature which worked as a foundation for further work, which is backed up by Creswell (2009) and Yin (2014). Then, an interview guide was established with specific topics of what the researchers wanted to obtain information about. Thereafter, semi-structured interviews with key actors and leaders were organized whereas the interviews were recorded. From there, the empirical data was combined and contrasted with acquired literature. Furthermore, the survey was conducted to ensure that the findings from the interviews were representative of a larger population.

3 Theory

The TFV theory (Koskela 2000) is a production theory related to lean production and lean construction. In this theory, production is seen as a flow of transformations that create value in the form of a product. Transformations are the traditional focus of production, while flow and value are the new perspectives. Koskela (2000) links value to the quality movement, where value is implied as customer value. If we go deeper, for example to the flow-section (Koskela 2000), its emphases include:

- remove waste
- reduce the lead time in the supply chain
- counteract variation
- simplify the supply chain (number of steps, parts, components and relations)
- increase flexibility
- increase transparency (visual management)
- continuous improvement.

The TFV theory has furthermore been a fundamental inspiration for the Last Planner System (Ballard 2000), a well-known method for production control in Lean Construction, which is based on five principles. These are highlighted by Ballard et al. (2010) as:

1. Plan with greater detail the closer you get to the specific execution
2. Plan with those who will do the work
3. Identify and remove obstacles for scheduled tasks in teams
4. Make reliable commitments for work to be carried out as agreed
5. Learn from cases where problems with the implementation occurs.

It is common in architecture and engineering to start with the client's specifications and then develop both conceptual and practical solutions throughout several distinct stages. This method of design analysis does not guarantee that a solution will be found. On the contrary, in design one must often return to the problem by trying to solve it in a different way, i.e. a new iteration. Koskela and Kagioglou (2006) refer to the concept of iteration arising as a new idea in the 1980's based on the observation that when working, designers jump between goals and means instead of following a linear path. Regarding the method aspect of project realization, a significant shift came with the arrival of agile methods in software development (Schwaber and Beedle 2002).

Ballard and Koskela (2013) link the works on rhetoric and design by Kaufer and Butler (1996) to the concept of "wicked problems" (Churchman 1967). Moreover, because of complex interdependencies, the effort to solve one aspect of a wicked problem may either reveal or create other problems. The phrase was originally used in social planning and is contrasted with "tame problems", which are more linear in nature, where the concept of cause and effect is well known. We may relate wicked problems to the Cynefin framework for complexity (Snowden 2000) to which the researchers relate wicked problems to the denoted "complex" and "chaotic" domains, where cause and effect is unknown.

4 Bridging Theory and the Case Study

Reciprocal dependencies are fundamental to understanding what kind of phenomenon design is. These often play out in one or, often, multiple iterations. Iterations can be linked to the Kolb's experiential learning cycle (1984), where each loop represents a test, observation and reflections before identifying needs or desires to make a new iteration. The coordination mechanism for reciprocal dependencies is mutual adjustment, but if we have reciprocal dependencies then there are always sequential dependencies present, which then begs the coordination method. Design in complex projects can be considered a wicked problem, and as such there is no logical end for when the design is finished as it always can be improved by additional iterations.

When we analyse the case in relation to lessons learned, we have chosen theory related to design as phenomenon and the TFV theory, which means trying to answer how the applied design management method pertains to:

- Transformation
- Flow, related to complexity with reference to the Cynefin framework, gradual maturity, constructability, learning and continuous improvement, interdependencies and coordination
- Value, linked to customer/user value.

5 The Case

The AEC project being studied is a conglomeration of a faculty of veterinary medicine and an independent biomedical research institute delivering research-based knowledge and contingency support in the fields of animal health, fish health and food safety. The construction project comprises 63,100 m^2, which is distributed between ten buildings. The buildings have a very high degree of complexity due to a large proportion of special areas, great ambitions to minimize environmental impact and strict compliance to Infection Prevention and Control in order to achieve world class classification in its field. The project costs are 7.1 billion plus 1 billion in user equipment. A government administrated company is the client of the project, and it is organized as Design-Bid-Build with a total of 40 execution contracts. In relation to the design process, there was a group of four consultant companies that won the contract together. Within the design team, there are coordinators, architects, landscape architects and discipline representatives from construction, electrical, Heating, Ventilation, and Air Conditioning, fire, acoustics and building physics, as well as 11 different special disciplines such as Infection Control, laboratory design and external environment. The project started in 2010, where the detailed design was carried out from 2013 until the start of 2019. About 200 architects and engineers have worked with design in total, whereas 120 worked simultaneously at the most. The planning group has been co-located since the start of the detailed design and moved to the construction site in August 2018. The construction period went in parallel with the design process, starting in 2013 and completion scheduled for 2020.

6 Empirical Findings

6.1 Detailed Design Before Bid

The design process was mainly managed according to traditional principles of management. There were organized weekly design meetings and the earned value method was used to measure progress, and a design plan was prepared in Gantt. Figure 1

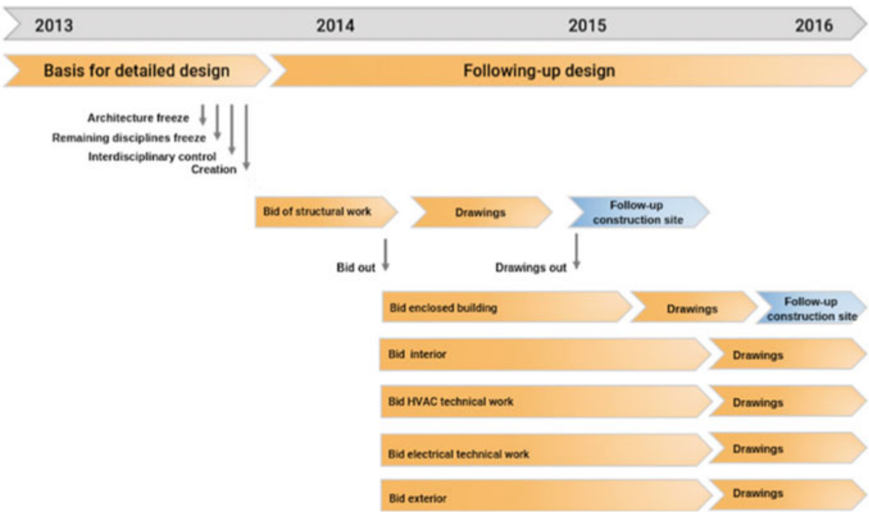

Fig. 1 Illustration of the strategic schedule for the design phase

shows how the design management in the case has presented the overall schedule for the design phase. In the context of progress, it was planned in detail longer than 6 months ahead. Because of an owner/client decision, the project had to reduce the area in several rounds at relatively early stages. It was reduced from 120,000 to 63,000 m^2. Although the project was cut in area, they did not compromise features. For design alone, it has required 1 million hours with a value of more than 100,000,000 Euro.

From start-up, to detailed design and until completion, it was planned according to area design. Each of the ten buildings in the project represented its own sub-schedule, led by its own area team and with its own administrator in addition to representatives from all the disciplines.

BIM has been actively used in the project, continuously for drawings, calculations and quantity extraction, and to achieve better task understanding, coordination and interface planning, reporting, communication, quality assurance and control. There has been an overall BIM coordinator for the project, in addition to a BIM coordinator for each of the disciplines.

The design team had little knowledge and experience with Lean beforehand. However, Lean processes were initiated in the detailed design phase, approximately half a year before the bidding, when a Lean influenced actor with Virtual Design and Construction (VDC) certification joined the design team. One of the measures introduced was Integrated Concurrent Engineering (ICE) meetings. These were held 1–2 times a week and lasted a maximum of 45 min. In addition, elements from Last Planner was applied on the last of the 10 buildings to be built, on the initiative of the same person.

6.2 Follow-up Design

In total, the project was divided into 40 different execution contracts. After the offers were picked up, the client chose to change the structure, and redesigned the hierarchy as a contracting organization. Most disciplines had between 1 and 5 contracts each, while HVAC had 16. The design team moved out to the construction site in August 2018 and redistributed the organization around six “fronts”. Each front represented one or more buildings, and within each front there was a leader in addition to representatives from both the design group, the client, the building management and the contractors. One of the purposes of the reorganization was to facilitate problem solving in design in interaction with those on the construction site. In summary, the design was first organized as site design for buildings, then it went over to contracts, and then it went back to being projected for buildings in the form of “fronts”.

7 Empirical Analysis

7.1 *Transformation*

The project mainly used traditional methods for management which are based on the waterfall model. Kalsaas (2020) claims that traditional methods are suitable for construction projects with a relatively high degree of predictability, but to a lesser extent for projects that are complex and unpredictable. The case study indicates that the methodology used is based on being in the single domain of the Cynefin framework and is not equipped to handle wicked problems. The methodology did not seem to capture all the reciprocal dependencies that emerged from the data. The design process requires a more agile design management that can capture the complexity of using alternative methodology. Eg. Last Planner as a planning method could have been combined with a structure for management based on Scrum, cf. Ballard (2000), and Kalsaas (2020). This could have contributed to better handling of reciprocal dependencies, breaking down complex work tasks into smaller work packages and having a more realistic schedule by planning in more detail the closer one comes to execution.

7.2 *Flow*

7.2.1 Complexity with Reference to the Cynefin Framework

It was pointed out by the design manager that "*this project is defined as one of the most complex construction projects in Norway ever (…), and there is very limited space for applying standardized solutions as few rooms are of same kind*". Several respondents pointed out that the project has been more complex than initially expected, and both the design team and the client underestimated the amount of work required for the design process. The project has, to a small extent, been able to transfer solutions from previous projects, as it is, especially nationally, only hospitals that can be compared.

The project has a total of 80 different ventilation systems, and several informants pointed out that the requirements for the HVAC installations have complicated the design process. Findings indicate that it was challenging to provide sufficient personnel who had experience from similar installations and also possessed the skillset to model well enough in relation to the technically complicated tasks that were presented. In cases where the progress of the design process was lagging, manpower was increased in the relevant disciplines. HVAC was heavily manned in 2015, and at one point six different HVAC companies worked on design at the same time. This meant that the progress was maintained, but it went beyond the continuity of solutions.

Several informants point out that design rules and design requirements should have been more clearly described, and that these should have been stored in a design manual. Beforehand there should have been examples of how things should be done, and prototypes should have been prepared for how the designer should work. It should have been specified and predefined which products should be used and how the different guides should be relative to each other for the different types of rooms, to ensure that everyone knows exactly how to do it on the project and that things are done equally. One informant points out that "*I think it could have been avoided frustration by those who project, if you had a blueprint*." This shows that coordination through a degree of standardization has failed.

7.2.2 Reciprocal Dependencies and Coordination

Findings indicate that handling the information flow in the project has been challenging based on the size of the project and the size of the project organization. The information flow between disciplines and interfaces has, by several informants, been described as "*challenging and chaotic*". The use of Last Planner could improve the information flow in the project and make it easier for the group to communicate needs and clarifications sequentially. Furthermore, in connection with decision making in the project, findings indicate that it might be challenging to get actors involved to make interdisciplinary decisions, and that the decision-making processes lasted longer than necessary. The data also indicates that it could be challenging to know who to deal with. This suggests that there has been inadequate coordination in relation to problem solving, which created waste in the form of resource focus.

Contrastingly, one factor that appears to have strengthened coordination and customer value is co-location of the design group. Many of the informants claimed that such a large and complex project would not have been possible without co-location. This has been an advantage for information and communication flows, as well as allowing ICE at times to be an effective way of dealing with reciprocal dependencies. Nevertheless, there is agreement that co-location to the construction site should have been done simultaneously with the client in 2016 and not in 2018.

7.2.3 Gradual Maturation

With respect to gradual maturation, findings show that the project lacked an efficient way to deal with this, and it was pointed out that it was mainly dealt with using "gut feeling" and previous experiences. Initially, a procedure was described for the design, where it was first architect freeze, then freeze for other subjects, and finally interdisciplinary control. However, due to scarce time in the project, the procedure has not been followed and the disciplines have had to work in parallel. When some disciplines lagged behind, other disciplines have continued with their own prerequisites that did not always turn out to be right, which contributed to inactivity in the design and waste of having to restart tasks. In addition, it was challenging to get disciplines to set the freeze status of objects in the BIM model. E.g. the architects claimed that they always worked further after the freeze. In conjunction with gradual maturation, LoD could have been used, cf. Grytting et al. (2017).

7.2.4 Constructability

In relation with constructability, findings show that achieving design solutions with good constructability has been a challenge. An influential factor was that it was cut down on areas without reducing the number of functions in the project, which affected areas that users did not use daily, such as shafts and technical rooms. Both the representatives from the design team and the construction management pointed out that it often happened that the design solutions were not possible to build, and they therefore had to restart. In addition, several informants stated that there have already been identified areas that will not be inaccessible, which lowers the customer value and which most likely will result in increased costs related to operation and maintenance.

Further, the crude building was completed before the technical disciplines had sent out the furnishings for tenders, which meant that many holes were taken at an early stage. As learning and maturing process increased throughout the project, and new and better solutions emerged, it was necessary to make changes. The later a change is made, the higher the cost and consequences of the change. Technical disciplines and entrepreneurs should therefore be involved earlier in the design process as this is where the influence and the value creation potential are strongest.

7.2.5 Learning and Continuous Improvement

Findings indicate that there have been few systematic processes for learning during the project. When informants were asked if the design team had a focus on evaluating during the process, an informant replied that: "*We could probably have been a little better at writing deviations when we do things wrong, so we get a better learning from the deviations during the planning. Here it has been a challenge not to make the same mistake several times*." Another informant argued that: "*It is common in "our world", that we should invent the wheel every time. We are not that good at evaluation.*" Furthermore, many in the staff have gone in and out of the project during the 10-year project period. For example, it emerged that the automation discipline has had seven replacements in management over an eight-year period. When people left the project, they also took valuable tacit knowledge and experience. Findings indicate that there was not enough focus on knowledge transfer in the design. An informant from the architectural discipline supports this with the statement: "*Lack of continuity has been one of the greatest challenges at all levels. Tacit knowledge disappears when someone leaves. Getting that knowledge transfer right has not been good enough.*"

The use of Last Planner and Scrum could facilitate learning and reflections, cf. Ballard (2000), and Kalsaas (2020). In addition, in order to build on and exploit the lessons from the project, it is important to gather and share the experiences, for example through the use of conducting seminars reflecting lessons after project completion.

8 Value

Customer value has been sought through extensive user processes. The design team has been dependent on input from users to understand the room functions, and since the sketch project phase there have been regular meetings with the users to clarify user needs and requests. However, it was used too long to establish the room-function-program. Optimally, this should have been completed before the start of detailed design rather than one month prior to the bidding, where an agreement on what needs to be built in relation to user needs can be established so that the design team could convert it to technical solutions. When technical solutions and functional needs were discussed simultaneously, it created resource demanding iteration processes.

Throughout the project, there has always been a desire for changes from the users' side, and it was noted that heavy user processes were still ongoing when things should have been frozen. This has greatly influenced the design process, and it has been pointed out that the user process has not been managed strictly enough from the client's perspective. In order to ensure customer value, the design team has therefore made many redesigns. An example was an area of 3000 m^2 that was drawn 19 times. This generates waste when each conversion takes 2–3 weeks. Furthermore, as technology developed during the project period, users often wanted to replace older designs with newer products, and these inputs could come as late as in the final phase of detailed design. The design team managed to handle the late user changes, but it resulted in inflated accrued hours and a sub-optimal process. The customer probably gets its functionality, but likely at an unnecessarily high cost. There are measures within target value design (Zimina et al. 2012) and choosing by advantage (Arroyo et al. 2016) that could have been used to increase customer value.

9 Conclusions

At a slightly more strategic level, the biggest challenge encountered in this case study is the need for a project model that captures the complexity of designing world class infection control buildings located in an important agricultural area. The large-scale nature of the project divided into many contracts with several organizations within the same discipline add to the complexity. A project model should be able to add frames and structure to capture the integration of both product, process and organization. Having an integrated information flow structure is an important part of this. For example, the data shows that the same message is given via multiple channels to different roles with tunnel vision and different departments are often blind to the information of other sectors. The substantiated material shows that traditional planning and management do not work as intended when dealing with the complexity of significant reciprocal dependencies. For the future, we propose a transition to more agile and flexible methods in combination with Last Planner and VDC. Gradual maturation in design must necessarily be handled in a structured way to reduce the extent of negative iterations, waste and processes that easily slip into a chaotic area characterized by "fire extinguishing" and "muddling through". We refer to LOD as an example of method for dealing with gradual maturation. Gradual maturation is further related to learning, and we have not been able to observe a systematic approach to learning and continuous improvement during implementation.

An important driver of uncertainty and waste has also been the lack of standardization of technical solutions for equal problems. It is obvious that it increases the complexity unnecessarily and has the potential to generate waste. The data furthermore shows that significant changes have been made by the owner and the client. This seems to be a driver which has generated many extra rounds of design. The user processes close to the detailed design are part of this waste.

In relation to the theoretical basis of the lean design management perspective, the identified lessons learned means that the process flow could have been considerably better by removing the causes of waste both in terms of the transformation (the actual design work) and in terms of the processes around it. There have been extensive user processes that ensure customer value, but as pointed out, these processes came temporally late, near the completion of the detailed design just before the bidding process.

We have not considered whether the project has been appropriately organized, including whether design-bid-build is an appropriate form of contract for such a large, complex project with high risk on both time, cost and quality. Future research is warranted to investigate this question.

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Feedback Loop—The Missing Link in Activity Analysis

Hasse H. Neve, Søren Wandahl and Jon Lerche

Abstract Construction productivity has been stagnating and declining for decades. Thus, developing continuous improvement processes is crucial. The aim of this research has been to explore if the 3rd step "analyse" in the 5-step activity analysis continuous improvement process could be further developed to, in one workflow, set targets, identify improvement areas, unveil root courses and create motivation for change in an integral way fitting the existing five-step process. An exploratory single case study was used to collect data through the methods of activity sampling, semi structured interviews and observations. The research showed that a workflow called the Feedback Loop, involving craftsmen, foremen and an activity analysis analyst, could set targets, identify improvement areas, unveil root causes and create motivation for change. This was done by empowering craftsmen and foremen, in collaboration with the activity analysis analyst, to analyse the activity sample in a 7-step Feedback Loop fitting the existing 3rd step "analyse". The implications of this research are that we could adjust the already well proven activity analysis continuous improvement process to improve future results. The conclusion is that the Feedback Loop worked in this project and trade, but further research is needed in other contexts.

Keywords Activity analysis · Work sampling · Continuous improvement · Productivity · Refurbishment

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_38

1 Introduction

The Intergovernmental Panel on Climate Change's report (IPPC 2018) has again emphasized the urgent need for radically reducing CO_2 emissions worldwide. Due to this long known climate challenge, EU, and hereby Denmark, aims at reducing CO_2 emissions by 80–95% in 2050 (Danish-Government 2014). Through 21 initiatives, Denmark will reach this goal and one of these initiatives is to reduce the energy consumption in existing buildings with 35% (ibid.). Lowering the energy use in existing buildings with 35% will have a significant impact since 40% of all energy used today is related to heating, cooling, ventilation, and running equipment in existing buildings (ibid.). The need for energy renovations have been a contributing factor to the fact that the biggest sub-sector in the Danish construction industry is refurbishment (Byggeri 2018). In addition, Ravetz (2008) shows that over 70% of all buildings that exist today will also exist in 2050, resulting in an increase in the demand for refurbishment in the future.

This trend emphasizes the need for innovation in the refurbishment sector to ensure that we can decrease CO_2 even further for the same or lower investment costs in the future. As an indication of where the biggest innovation potential is in refurbishment, LCICG (2012) has analyzed the four main areas in refurbishment projects and concludes that the biggest potential is within the build process. This seems plausible since labor productivity in construction has been declining for several decades (Farmer 2016). This creates an urgent need for research into labor productivity in construction and how it can be increased in refurbishment as well as in construction in general.

1.1 *Labor Productivity and Improvements*

Labor Productivity is a simple ratio between output and input where output is the value of a building, for example, and input is labor hours. This ratio only provides a number or index and provides no real insights into why the ratio has exactly this size, or how one could improve it (Thomas and Daily 1983). When targeting increased labor productivity, one must either increase output, decrease input or do both to achieve higher productivity. However, in the context of the construction industry, the total output is almost always contractually locked, which leaves one to optimize productivity by using less production factors, i.e. less labor hours.

To optimize labor usage, one must have deep insights into planning, operating and managing the focal activity. Activity analysis (AA) is a method (CII 2010; Gouett et al. 2011) that has proven its ability to create both insights and continuous improvements to the way construction workers' time is used (Gouett et al. 2011; Hwang et al. 2018). AA origins all the way back from the snap reading method (Tippet 1935) and gained momentum in the construction industry in the 1970s and early 1980s (Gong et al. 2011). Fundamentally, AA is a continuous improvement cycle similar to the Toyota PDCA cycle (Liker and Meier 2006). AA consists of five steps: (1) plan AA study; (2) activity sampling; (3) analyze activity sample; (4) plan improvements; and (5) implement improvements (CII 2010; Gouett et al. 2011).

The research of CII (2010), Gouett et al. (2011) and Hwang et al. (2018) provide great insights into how AA is applied and what results this method can create. However, it is found that step 3 "analyze" lacks a clear description of how targets are set, root causes are unveiled and improvement areas are identified in one workflow. In addition, it is not clear how to motivate change within the actual working context.

Previous research has shown that direct work rates go from 13% (Josephson and Björkman 2013) to around 30% (Gouett et al. 2011; Neve and Wandahl 2018; Shahtaheri 2012) reaching even above 60% (Christian and Hachey 1995; Da Silva 2006; Hajikazemi et al. 2017; Handa and Abdalla 1989; Kaming et al. 1997; Thune-Holm and Johansen 2006). Given the large variation, using other studies to set targets contains some challenges. Looking at the challenge of unveiling improvement areas and root causes, previous research proposes craftsmen and foremen as valid sources (Ballard 2000; CII 2010; Gouett et al. 2011; Neve and Wandahl 2018). Further, involving and empowering craftsmen and foremen in identifying improvement areas and root causes would probably motivate change.

Thus, it seems natural to let the craftsmen and foremen perform the analysis in cooperation with the analyst leading the AA. This analyst team should then bring improvement areas forward to management who will initiate step 4 plan improvement and step 5 implement improvement.

Not having a "one workflow" that can support the important step 3 analyze in AA is a challenge, and the literature review reveals a gap in the current body of knowledge on using AA for continuous improvements.

Thus, this research aimed to explore if a "one workflow" process can be designed for step 3 analyze to accommodate target setting, unveiling root causes, finding improvement areas and creating motivation for change, and whether it can fit into the existing framework of AA by answering the following question.

RQ: How can a "one workflow" with craftsmen, foremen and analyst in the 3rd step "analyze" set targets, identify improvement areas, unveil root causes and create motivation for change in an integral way, fitting the existing framework of activity analysis?

2 Method

To answer the research question, a demolition crew working on a Danish social housing refurbishment project was followed for a total of eight weeks. The research approach was an exploratory single case study using multiple methods to enable deeper understanding and secure both reliability and validity (Yin 2009). Using multiple methods was a necessity to answer the research question. The methods applied were: (1) the three first steps of AA amended by using a "one workflow" named Feedback Loop (FL) for the 3rd step "analyze" and (2) observations and interviews as part of the FL. First, the case and the crew are presented. Second, step (1) plan study and step (2) sample are presented along with the chosen categories, observation intervals and uncertainties. Third, the FL and its purpose are outlined.

2.1 The Case and the Crew

The focal case was built in the 1950s and was scheduled to go through a comprehensive refurbishment from 2017 to 2021. The general contractor's contract size was USD 31 million covering 291 apartments with a total of 22.800 m^2 going from basement to second floor. The refurbishment, being comprehensive, included total renovation of the building envelope, new installations and renovation or replacement of all interior. The managerial approach was very "old school" meaning that the use of modern construction management approaches such as the Last Planner System (LPS) (Ballard 2000) and Location Based Scheduling (LBS) (Kenley and Seppänen 2010) was very limited. Instead, a classical Gantt chart was applied as the main production control and management tool.

The subcontracted demolition crew in focus consisted of several craftsmen and a foreman daily on site but for this study only two craftsmen where observed. The subcontractor was often the first trade at any location since they had to demolish the existing parts of the building before other trades could start rebuilding. The demolition activities consisted of demolishing balconies, removing windows and doors, breaking down inside walls, removing interior, cleaning any asbestos and similar materials, etc.

2.2 Step 1 plan study and step 2 sample, as well as, categories

This research uses the activity sampling method to gather data using the approach by Terp et al. (1987). The activity sampling method is quantitative and based on direct observations (Terp et al. 1987). The research categories chosen for categorizing observations in this research is structured around three main and seven subcategories. The three main categories is inspired by the work of Kaplan and Cooper (1998) and Womack and Jones (1996) and creates an initial overview of the data. The seven chosen subcategories enable deeper analysis. The seven categories were defined through discussions with peers. The three main and seven subcategories are as follows: (1) direct work—production, (2) indirect work—talking, preparation and transport, and (3) waste—walking, gone and waiting. These categories have been used for describing refurbishment works in previous research (Neve and Wandahl 2018). Using the structure with three main and seven subcategories is also used by CII (2010). The seven subcategories are described in Table 1.

A peculiarity of demolition work that must be addressed is the topic of value adding work to which direct work (production) contribute. In demolition work, breaking

Table 1 Description of observation categories from Neve and Wandahl (2018)

Category	Description
Production	Activities that physically add value to the product, processing of materials or assembling of a kitchen element
Talking	The time used to discuss drawings or work at hand, conversations with persons outside the crew such as tenants or managers. There is no distinction between professional and private talk
Preparation	Non-value adding handling of materials and elements, adjustment and cleaning of machines and tools, looking for tools or materials and measuring and marking
Transport	Driving in a truck to move materials, carrying materials or tools from one place to another
Walking	Walking without carrying any tools or materials from one place to another
Gone	Time absent from the construction site such as visits to the toilet and smoking
Waiting	Time spent waiting for co-workers, information and materials

down existing parts of a building is value adding work from the perspective of the client and we thus categorize it this way.

2.3 Observation Intervals, Observations and Uncertainties

This research used fixed observation intervals like Josephson and Björkman (2013) instead of random intervals. "*Since almost all construction operations are stochastic in nature, sampling at fixed intervals, also referred to as systematic sampling is superior*" (Peer 1986). Observations were made every minute starting and stopping with the demolition crew's working day. The total number of required observations was based on Terp et al. (1987), and stabilization curves (ibid.) were used as a control mechanism (stabilization curves are left out due to the space constraints of this paper).

Even though the case and crew were followed for eight weeks, all activity sampling was done within one week. The remaining time on the case was, among other things, used to plan the study and build relationships and openness with the demolition crew, site management and foreman.

The authors' effort to build personal relations with people on site enabled the use of unexperienced observers with one of the authors acting as supervisor. Before starting observations, observer and crew were thoroughly introduced to the whole study so everybody knew what was going to happen.

An inherent uncertainty when doing activity sampling on site with pen and paper is the risk of incorrect categorization of observations. This is accommodated by having high numbers of observations and using stabilization curves.

2.4 Activity Analysis and the Missing Link of the Feedback Loop

The FL, as we choose to call it, is based on the semi-structured interview method (Ritchie et al. 2005). It is a novel approach to setting optimization targets, quantifying optimization potentials, unveiling root causes, finding improvements, and securing ownership of change by involving craftsmen and foremen in step 3 analyze. Making craftsmen and foremen an integral part of the feedback loop, instead of site management, seems natural since both CII (2010) and Gouett et al. (2011) recommend craftsmen's questionnaires and foremen delay surveys to unveil root causes. Further, the LPS which, even by name, asks for the people on site to be part of both planning and root cause analysis since they have the deepest insights.

The FL is thought to be an integral part of step 3 in activity analysis (CII 2010; Gouett et al. 2011) and due to the involvement of the people executing production, also an enabler for the later step 4 implement.

2.5 Step 3 analyze—using the FL

1. Analyst prepares activity sample data to reflect how each crew member's time is used in each category per day in both minutes and percent.
2. Analyst presents the activity sample data and discusses findings until both crew, foreman and analyst have same understanding of the results.
3. Analyst asks the crew and foreman how time would be distributed in each category if they had the perfect production conditions. This step is to identify potentials and set targets for each activity sample category (explanation of calculations are presented in the results section above Tables 3 and 4).
4. Analyst asks the crew and foremen what improvements that should be made to initiate the changes necessary to reach the targets and asks them to put either percentage or minutes to the improvements.
5. Analyst presents own observations and improvement ideas.
6. All discuss root causes to the potentials in each category until consensus is made.
7. Results from step 1 to 6 are presented to management and the best improvement ideas are taken to step 4 implement.

Uncertainties in the Feedback Loop are unavoidable regarding the quantification of potential (target setting) in each category and in quantifying the potential in each proposed improvement area. Thus, these identified targets must not be perceived as fixed values we aim to push, but as a vision that can be adjusted.

Table 2 Activity analysis sample baseline for the demolition crew

Demolition, N = 4641							
Work types	Direct	Indirect			Waste		
P (%)	18.6	41.5			39.9		
N	864	1927			1850		
Category	Prod.	Talk.	Prep.	Trans.	Walk.	Gone	Wait.
P (%)	18.6	26.2	9.6	5.7	9.9	12.7	17.3
N	864	1215	446	266	458	589	803

3 Results

The results from this study consist of an activity analysis sample baseline for the demolition crew, optimization potential in each sample category, an optimized future state for the demolition crew, root causes for the potential and quantified improvement areas.

3.1 *Activity Sampling Data Baseline for Demolition Crew*

Table 2 presents the activity analysis baseline for the demolition crew and outlines how time is being used in the three overall categories and the seven subcategories. It further shows the percentage (P) and number of observations (N) for all categories.

3.2 *Optimization Potential in Each Work Sampling Category Based on the Feedback Loop*

Table 3 presents the optimization potential identified by craftsmen and foremen in the Feedback Loop. The percentage given in Talk, for example, at 50% means that the time spent on talking can, in the context of the perfect day, be reduced by 50%.

Table 3 Optimization potential based on Feedback Loop

Category	Prod.	Talk.	Prep.	Trans.	Walk.	Gone	Wait.
P (%)	0	50	50	10	40	80	60

Table 4 Targets for demolition crew if potential is realized

Demolition, N = 4641							
Work types	Direct	Indirect			Waste		
P (%)	61.6	23.1			15.4		
N	2857	1070			714		
Category	Prod.	Talk.	Prep.	Trans.	Walk.	Gone	Wait.
P (%)	61.6	13.1	4.8	5.2	5.9	2.5	6.9
N	2857	608	223	239	275	118	321

3.3 Targets for Demolition Crew if Identified Potential Is Realized

Table 4 presents the targets calculated based on the crew's and foremen's own identified optimization potentials for each category and subcategory. The calculation procedure is as follows: reduce all categories (N)'s in indirect work and waste with the optimization potential identified by crew and foreman, take all the reduced (N)s and move them to direct work, then recalculate the percentages for all seven subcategories and later for the three overall categories.

The crew and foremen set the target for the direct work to be 61.6% which is a 230.7% potential. Previous studies show (though not on demolition works) that reaching direct work rates above 60% is possible (Alarcón 1993; Choy and Ruwanpura 2006; Christian and Hachey 1995; Da Silva 2006; Gong et al. 2011; Hajikazemi et al. 2017; Handa and Abdalla 1989; Kaming et al. 1997; Olomolaiye et al. 1987; Parker et al. 1987; Picard 2002; Thune-Holm and Johansen 2006; Winch and Carr 2001).

3.4 Root Causes for the Potential

The root causes for the potential in each category identified by the craftsmen, foremen and analyst (first author) are summed up below:

- Talking: The 50% potential is a direct consequence of the phenomenon known as Making-Do (Koskela 2004) where an activity is started without having all its preconditions ready. Making-Do causes change from plans and uncertainties, which often results in intensive talking (discussion and problem-solving).
- Preparation: The 10% potential comes from being asked to "put out fires", creating discontinued work, causing unnecessary preparation time for small jobs.
- Transport: The 10% potential comes from unnecessary movement of materials caused by "putting out fires" and ineffective site layout.
- Walking: The 40% potential in walking comes from Making-Do situations, "putting out fires" and ineffective site layout.

– Gone: The 80% potential mainly comes from starting late and having longer breaks than agreed upon.
– Waiting: The 60% potential comes from Making-Do situations, "firefighting" and lacking coordination between trades.

3.5 Improvement Areas

Three improvement areas were identified, two being straight forward and the third a general suggestion to the project management team.
Gone: The study showed that in average 33 min. everyday were wasted on starting late and taking too long breaks. This corresponds to 6.1% of the whole working day or approximately 50% of the time currently registered in the gone category. It was agreed that this would be improved, realizing 50% of the 80% potential identified (The 33 min. was identified by summing up gone time after each break and in the morning through the activity sample data registered every minute during the day).
Walking: Toilets were only found in the central container next to site management meaning an average walk of 6 min (back and forth) the two times a day people went to the toilet on average, besides during breaks. It was found possible to halve this walk if local toilet containers were set up on site, saving three min. This corresponds to 0.6% of the whole working day or approximately 10% of the time currently registered in the walking category. If site management set up these extra toilet containers, it would realize 25% of the 40% potential identified. The cost of doing so was estimated to be less than the potential savings.
All categories: All categories contained large optimization potentials related to the situations Making-Do, "putting out fires" and ineffective site layout, which the analyst team found to originate from a systematically inadequate approach to planning, management and leadership on site. For example, talking contained a 50% potential equaling 10.7% of the whole workday. Waiting contained a 60% potential equaling 6.9% of the whole workday. This fact was brought to the site management's attention who was both surprised and motivated to initiate improvements.

4 Discussion

The discussion will shed further light on the results and relate these to the existing body of knowledge in this topic. The discussion will be divided into four sections.

The result outlines that the analyst team of craftsmen, foremen and analyst has set targets, identified improvement areas, unveiled root causes and created motivation for change both for themselves and their managers.

Looking first at the targets, the analyst team finds that direct work contains an optimization potential of 230.7% going from 18.6 to 61.6%. Reaching direct work rates above 60% is possible (Christian and Hachey 1995; Da Silva 2006; Hajikazemi et al. 2017; Handa and Abdalla 1989; Kaming et al. 1997; Thune-Holm and Johansen 2006) but the referenced research is neither the same work or in the same context, thus only indicating that the 61.6% is realistic.

Second, the analyst team identified root causes for the potentials in the six subcategories of indirect work and waste. The root causes found are all well known within the lean construction (LC) community, which indicates validity. The root cause causing the biggest potential overall (waste) was the Making-Do situation represented in all categories except for gone. This matches the results of Neve and Wandahl (2018) who states that: "*Making-Do is highly likely to be the prevailing reason for the low productivity in refurbishment projects*". The very large potentials in all activity categories, and thereby in all work, indicate that a fundamentally wrong approach is used to manage the demolition crew. This makes sense considering the management's use of "old school" and insufficient ways of leading, managing and planning all construction work.

Third, three improvement areas were identified with two being instantly implementable and one naturally following from the insufficient approach to managing construction. Identifying the three improvement areas is important, but the way the improvement suggestions were received was more interesting. The first improvement area in gone (not working the agreed hours) was identified by the ones creating the problem, namely the craftsmen and foremen. They were very motivated to change what they called a bad habit since they themselves were part of finding the potential. The second improvement area (extra toilets) was also well received by both craftsmen, foremen and management since it was a simple action with a clear business case. The third which addressed the problem of insufficient leadership, management and planning of construction works was presented to the management. This improvement area contained the biggest potential and the management was especially surprised to see how much waste their management approach created in the talking and waiting category. Further, the quantified potential made them realize the need for change and they were motivated to begin the incremental changes necessary for reducing it. Enabling improvements and changes requires that the people who must change both understand why and how. This is in line with Ballard (2000) who shows that if people do not understand both the why and how of the LPS, change and improvements will be a very tough path to walk.

Fourth, although the results only present one cycle of AA using FL, the results strongly indicate that the FL can be integrated into the existing framework of AA.

5 Conclusion

The conclusions of this research and the main contributions to knowledge are firstly designing a workflow (Feedback Loop) that integrates into the existing framework of Activity Analysis in step 3 analyze, solving the challenge of setting targets, identifying improvement areas, unveiling root courses and creating ownership for change, and Secondly, testing the one workflow (Feedback Loop) on a demolition crew working on a refurbishment project and finally, showing that a team of craftsmen, foremen and an analyst can analyze the activity sample and create valid insights for improvements.

The conclusions of this research have been reached in a narrow context and further research must be conducted to understand if they can be generalized.

Acknowledgements This research is part of the REVALUE research project, a USD 3.4 million research project on refurbishment of social housing buildings sponsored by The Innovation Fund Denmark.

Furthermore, the support and openness from the case contractors and sub-contractors, and the help from engineering students to collect data have been highly valuable.

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The Effect of Perceived Safety on User Behaviour in the Holy Mosque

Kassim Gidado and Mohammed Alkhadim

Abstract The Holy Mosque in Makkah is claimed to be the largest and most used crowded open space building in the world. It is used by very large crowd reaching maximum capacity of up to 2 million users at a time especially during the Hajj period. In practice, facilities managers of such buildings always give a lot of emphasis to objective safety (normative and substantive), but researches have shown that subjective safety (perceived) is equally important and cannot be overlooked. This research theorised that a decline in perceived safety (PS) will have an influence on user behaviour (UB) that could result in a crowd disaster. Previous researchers have established that there are 10 key factors that could affect perceived safety in large space buildings, but no empirical study has yet been carried out to identify how significant is the effect of each of these factors on perceived safety and the consequent effect of perceived safety on user behaviour. This paper therefore presents the findings of an empirical study carried out by using the Holy Mosque as a case study. Data was collected using iPad devices via a group-administered questionnaire to 1940 pilgrims from 62 different nationalities during the Hajj period. The results were analysed using SPSS for descriptive analysis and AMOS 22 for Confirmatory Factor Analysis (CFA) and Structural Equation Modelling (SEM) to test the relationships between the factors and PS and between PS and UB by setting up a number of hypotheses. The findings revealed 7 out of the 10 factors have a significant influence on perceived safety and also established that perceived safety has a significant influence on the behaviour of the pilgrims as users.

Keywords Large space buildings · Perceived safety · Subjective safety · User behaviour

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_39

1 Introduction

Miller (2015) has reported several incidents during the Hajj that caused loss of thousands of lives. Still (2000) has established that the safety limit for crowd density is 40 people in 10 m^2 for a moving crowd and 47 for standing areas, but Alnabulsi and Drury (2014) confirmed that the crowd density in the Holy Mosque is often 6–8 people per m^2. This clearly exceeds the safety limit with an extremely high risk or potential of occurrence of a crowd disaster. Such peak capacities are often reached during the Hajj (annual pilgrimage to the city of Makkah by Muslims lasting 4–6 days that involves rituals in four holy places: Holy Mosque, Arafat, Muzdalifah and Mina) especially during the Tawaf (anticlockwise circumvallating movement of pilgrims in the Holy Mosque around the Kaaba repeated seven times) that is done on the 2nd day immediately after the first visit to Jamarat (ritual site situated at Mina). This type of crowd is classified by Berlonghi (1995) as "a dense or suffocating crowd" that could sweep people along with movement and compression, which could result in injuries and fatalities.

Sagun et al. (2008) states that the fundamental principle of safety in the built environment is ensuring the safety of occupants during both normal and emergency events. The Hajj Authorities have therefore invested heavily and are using strategies and systems to help mitigate the Health and Safety risks using objective safety considerations based on globally recognized best practices. Every effort is continuously made to expand the mosque, currently at 356,800 m^2, to help the situation, but there is also an annual increase in the number of pilgrims attending the Hajj from across the world. Although the emphasis on objective safety is appropriate, but research has shown that subjective safety (perceived) is equally important and cannot be overlooked. Dickie (1995) have reviewed some major past crowd disasters that occurred in Sunderland (1883, deaths 183), London (1943, 173 deaths), Bolton (1946, 33 deaths), Glasgow (1971, 66 deaths) and Sheffield (1989, 96 deaths) and concluded that a flaw of hazard and poor risk management during the event was one of the main reasons for these disasters, but issues associated with perception of the crowd and their actions or behaviour could not be eliminated from the reasons leading to the disastrous outcomes. Miller (2015) and Challenger et al. (2009) have reported notable stampedes and other failures during the Hajj of 2015, 2006, 2004, 2001, 1998, 1994 and 1990 resulting in thousands of lives lost and many more injured. Although none of these notable disasters have occurred in the Holy Mosque, but having these established facts, the potentiality of a crowd disaster is extremely high. This reveals the urgency to have a better understanding of the relationship between perceived safety and behaviour of pilgrims in the Holy Mosque.

Alkhadim et al. (2018) have adapted two theoretical frameworks, namely: FIST model developed by Fruin (1993); and the Six Dimensions and Loci model developed by Chukwuma and Kingsley (2014), to identify 10 critical factors of perceived safety in crowded large space buildings, namely: Perceived Force (PF), Perceived Poor Information (PPI), Perceived Insufficient Space (PIS), Perceived Poor Real Time Management (PPRTM), Perceived risk of Stampede (PRS), Perceived risk of Riot

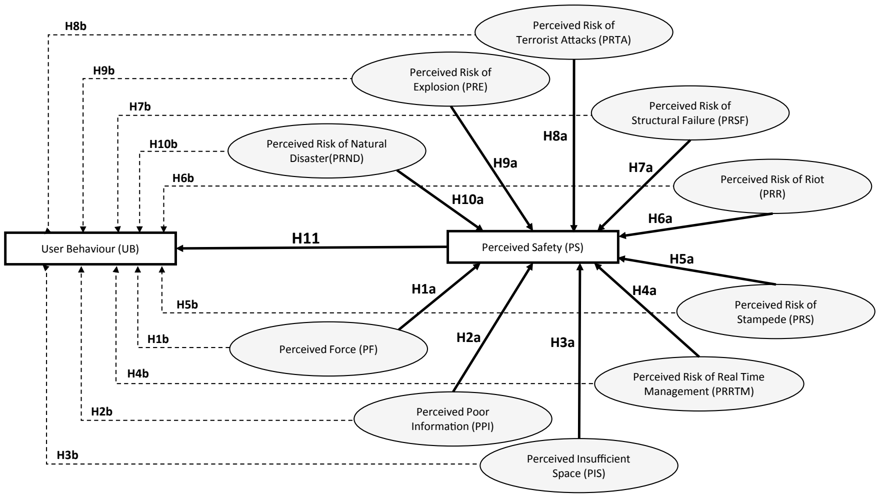

Fig. 1 The Subjective Crowd Safety Model (SCSM)

(PRR), Perceived risk of Structural Failure (PRSF), Perceived risk of Terrorist Attack (PRTA), Perceived risk of Explosion (PRE) and Perceived risk of Natural Disaster (PRND). They carried out a detailed confirmatory analysis of the 10 factors together with perceived safety and user behaviour to test the theoretical pattern of the variables loading on a developed construct to show how well they match reality. Based on these studies, a conceptual Subjective Crowd Safety Model (SCSM) is therefore developed to study the interrelationships between the variables. The SCSM model is illustrated in Fig. 1, which shows that there are 10 hypothesis (H1a to H10a) set to test the direct effect of each critical factor on perceived safety (PS) respectively; one hypothesis (H11) to test the direct effect of PS on user behaviour (UB); and 10 other hypothesis (H1b to H10b) to test the in-direct effect of each critical factor on UB respectively. The purpose of this paper therefore is to establish these direct and indirect effects by testing the 21 hypotheses depicted in the conceptual model.

2 Research Methodology

Primary data was collected using iPad devices via a group-administered questionnaire distributed to 1940 pilgrims of 62 different nationalities during the Hajj period using stratified sampling technique. The results were analysed using SPSS for descriptive analysis and AMOS 22 for Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM). Initially, secondary data was used to establish the items for each variable to guide the development of the questionnaire. The CFA analyses have established the 12 latent constructs, and the assessment of the model shows solid evidence of unidimensionality, convergent validity, discriminant validity, and reliability and therefore warrants the continuation to further analysis. 38 items were found with acceptable factor loading greater than 0.60. The descriptive and CFA analyses have been reported in Alkhadim et al. (2018).

SEM was chosen as a statistical technique for two main reasons: Firstly, the study aims to establish the interrelationship between the perceived safety and user behaviour in which latent variables are encountered that cannot be measured directly. Secondly, SEM is a powerful tool that can test the model fit to the data by taking into account any measurement error (unreliability) for each latent variable of the constructs being estimated.

3 Structural Equation Modeling (SEM)

The structural model as shown in Fig. 2 presents the interrelationship among the variables. It consists of 10 unobserved exogenous constructs (Perceived Force, Perceived Poor Information, Perceived Insufficient Space, Perceived Poor Real Time Management, Perceived risk of Stampede, Perceived risk of Riot, Perceived risk of

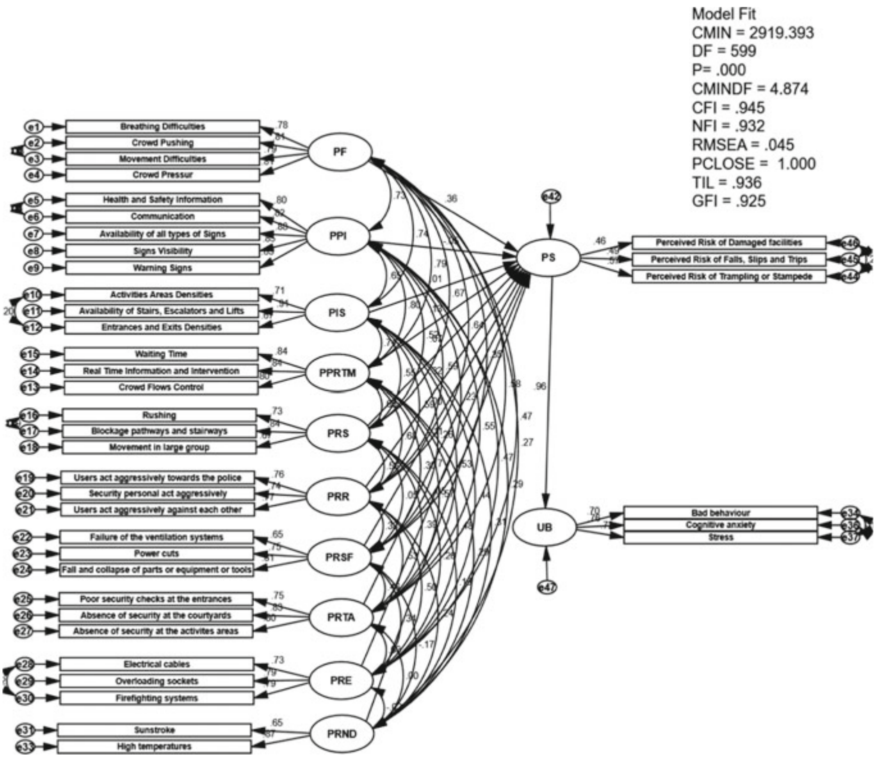

Fig. 2 The proposed structural model

Structural Failure, Perceived risk of Terrorist Attack, Perceived risk of Explosion and Perceived risk of Natural Disaster) and two unobserved endogenous constructs (Perceived Safety & Users Behaviour).

According to Awang (2015), a model that achieves fit indexes values of comparative fit index CFI ≥ 0.90, standardised root mean square residual SRMR ≤ 0.08, and the root mean square error of approximation RMSEA ≤ 0.06 should be considered an acceptable model fit. Based on these fit indexes, the model illustrated in Fig. 2 is therefore a good fit because the CFI = 0.979, SRMR = 0.032, and RMSEA = 0.043. Consequently, the model became accepted for further analysis in testing the 21 different hypotheses identified in Fig. 1.

4 Testing Direct Effects

The results of the analyses are summarised in Table 1 that shows each path and its estimate for path coefficient weight, standard errors, coefficient regression composite reliability and p-value as well as the significance for that particular path. It presents the effect of each exogenous construct on the respective endogenous construct.

The results reveal that all the independent variables have a significant effect on perceived safety except three: PPI perceived poor information ($p = 0.207$), PIS perceived insufficient space ($p = 0.882$), and PRSF perceived risk of structural failure ($p = 0.925$). It means hypotheses H2a, H3a and H7a are **rejected**.

Making reference to Table 1, the hypothesis **H2a** (*Perceived Poor Information* (*PPI*) *has a significant direct influence on Perceived Safety* (*PS*)), the results showed that the path coefficient of PPI on PS is at −0.026 with a $p < 0.207$, which is not significant. This value indicates that for every one-unit increase in the PPI, its effect on PS would even decrease by 0.207 units. It means that PPI does not have a significant

Table 1 The significant effect among the constructs

	Constructs		Estimate β	S.E.	C.R.	p	Result
PS	←	PF	0.229	0.031	7.507	***	Significant
PS	←	PPI	−0.026	0.021	−1.263	0.207	Not Significant
PS	←	PIS	0.003	0.019	0.148	0.882	Not Significant
PS	←	PPRTM	0.076	0.03	2.543	0.011	Significant
PS	←	PRS	0.035	0.017	2.068	0.039	Significant
PS	←	PRR	0.19	0.021	8.976	***	Significant
PS	←	PRSF	−0.002	0.019	−0.095	0.925	Not Significant
PS	←	PRTA	0.073	0.021	3.442	***	Significant
PS	←	PRE	0.116	0.02	5.847	***	Significant
PS	←	PRND	0.048	0.022	2.161	0.031	Significant
UB	←	PS	1.259	0.059	21.489	***	Significant

direct influence on perceived safety. Although Challenger et al. (2009) confirmed that communicating with crowd is essential in maintaining order and crowd behaviour, it is not surprising that PPI is not significant in this case because pilgrims are spiritually deep in their individual thoughts and ritual deeds that they do not pay any attention to announcements or even signs.

For hypothesis **H3a** (*Perceived Insufficient Space* (*PIS*) *has a significant direct influence on Perceived Safety* (*PS*)), the established path coefficient of PIS to PS is 0.003 ($p < 0.882$). Again, this is not statistically significant and therefore conclude that PIS does not have a significant direct influence on perceived safety. This is a surprising outcome because one would expect that the excessive congestion that clearly exceeds the recommended crowd limits per metre square PIS should be significant. Although these results differ from published studies such as Westover (1981), there are other studies that agreed with the findings, such as Alnabulsi and Drury (2014) that went further to argue that the pilgrims were high in what they term 'social identification' as Muslims. It means that the persons in a crowd act as one because they share a common social identity which increases cohesion within the crowd and in-turn increases socialising and positive feelings.

To test hypothesis **H7a** (*Perceived Risk of Structural Failure* (*PRSF*) *has a significant influence on Perceived Safety* (*PS*)), the results show $\beta = -0.002$ and $p < 0.925$. It means it does not support the hypothesis. Therefore PRSF has no significant direct influence on perceived safety. Although there was an incidence of crane on a construction site collapsing on pilgrims in 2015, this outcome is expected because pilgrims consider the building to be structurally sound especially having all elements fully cladded with concrete-like material and they do not feel any structural movement as they conduct their rituals in the mosque.

However, by again making reference to the values on Table 1, each of the following hypotheses is **supported** and discussed below:

To test the hypothesis **H1a** (*Perceived Force* (*PF*) *has a direct significant influence on Perceived Safety* (*PS*)), the path coefficient between PF and PS is significant at 0.229 ($p < 0.001$). This suggests that for every one-unit increase in the PF, its effect on PS would increase by 0.229 units. It is therefore concluded that PF has a significant direct influence on PS. This is often produced by either hearing, sensing or seeing the force as pilgrims move and perform their rituals in and around the Holy Mosque. Berlonghi (1995) has confirmed that such forces are created when density exceeds a certain level and may lead to a disaster.

Testing hypothesis **H4a** (*Perceived Poor Real-Time Management* (*PPRTM*) *has a significant influence on Perceived Safety* (*PS*)), the results show $\beta = 0.076$ and $p < 0.011$. It means that PPRTM has a significant direct influence on perceived safety. Similarly for hypothesis **H5a** (*Perceived Risk of Stampede (PRS) has a significant influence on Perceived Safety (PS)*), $\beta = 0.035$ and $p < 0.039$. It means PRS has a significant direct influence on perceived safety. Again, for hypothesis **H6a** (*Perceived Risk of Riot* (*PRR*) *has a significant influence on Perceived Safety* (*PS*)), the values of $\beta = 0.19$ and $p < 0.001$ were obtained. It also confirms that PRR has a significant direct influence on perceived safety. These results have confirmed the importance of avoiding occurrence (or near-miss occurrence) of riot and the need to ensure real-time management. Interestingly, both PPRTM and PRR are found to be more important than the risk of stampede. It means that where there is evidence of timely crowd management (crowd stop & start, re-directions & diversions, entry & exit controls) and orderliness of procession, the pilgrims tend to feel safer even if it takes longer.

For hypothesis **H8a** (*Perceived Risk of Terrorist Attack* (*PRTA*) *has a significant influence on Perceived Safety* (*PS*)), $\beta = 0.073$ and p value <0.001. This outcome supports the hypothesis that PRTA has a significant direct influence on perceived safety. The same outcome is for hypothesis **H9a** (*Perceived Risk of Explosion* (*PRE*) *has a significant effect on Perceived Safety* (*PS*)) having $\beta = 0.116$ and $p < 0.001$. Also for hypothesis **H10a** (*Perceived Risk of Natural Disaster* (*PRND*) *has a significant influence on Perceived Safety (PS)*) with $\beta = 0.048$ and value of $p < 0.031$. Although terrorist attack or explosion has never occurred in the Holy Mosque, the pilgrims clearly perceived the threat of terrorism or an explosion. Three key items made the pilgrims to feel unsafe including poor security checks at the entrances, absence of security at the courtyards, and absence of security at the major points of ritual activities. The results are supported by the work of Arana and Leon (2008), which indicated that perceive threat of terrorism directly influence the decision that persons make and the action they take. With the 2016 Hajj occurring during the hot season, it is also expected that the effect of natural disaster on PS should be significant because the factor includes sunstroke, lack of shaded areas, and lack of alternatives to reduce high temperatures. Many experts have already confirmed that high temperatures may increase aggressive behaviour, cramps, exhaustion, dehydration and heat stroke.

For the key hypothesis **H11** (*Perceived Safety* (*PS*) *has a significant direct influence on User Behaviour* (*UB*)), the value of $\beta = 1.259$ and the p value <0.001. This confirms that perceived safety has a very high impact on the behaviour of the pilgrims and the relationship is statistically highly significant. Challenger et al. (2009) agrees with this finding when they said that the sense of safety has an influence on the behaviour of people in a space.

In summary, 7 hypotheses have been supported (H1a, H4a, H5a, H6a, H8a, H9a, H10a and H11). Three have been rejected: H2a is ***rejected*** ($P = 0.207$), which means that the information provided to pilgrims during Hajj is sufficient such that it has no significant effect on the pilgrims to feel unsafe. H3a is also ***rejected*** ($P = 0.882$), which means that the space provided in the Holy Mosque or the resulting high crowd density does not affect the feeling of unsafe. H7a is also ***rejected*** ($P = 0.925$), which means that the possibility of structural and mechanical collapse does not have an effect on their perception of feeling unsafe.

5 Testing Indirect Effect (Mediation)

The study went further to examine the mediation effect (indirect effect) on the relationship between the independent and its dependent variables in the model. According to Gaskin and Lam (2016), mediation means that the effect of one variable on another is transmitted (at least in part) via a third or intervening variable. Computationally, it is the product of at least two paths that can be traced from one variable to another. It implies that to analyse the mediation effect both the direct and indirect effects must be recognised. The direct effect refers to the effect from an independent variable that goes directly to the dependent variable while the indirect effect is the effect that goes indirectly from independent to the dependent variable through the mediator variable which can either be a partial or full mediator.

To assess the existence of mediation effects, the study employed resampling producer "Bootstrapping". Awang (2015) has recognised that this test is required by researchers to confirm the effects of mediation, and it is especially used for testing the indirect effect. The mediation effects were tested using the Maximum Likelihood Bootstrapping resamples procedure in AMOS 22 with bootstrap samples of 2000, and 95% bias-corrected confidence intervals. The results, shown on Table 2 contains the parameter estimate for the regression weight, upper and lower limit of the confidence intervals, P-value, standard errors (SE), standard error estimate for the standard error (SE-SE), mean parameter estimate (Mean), bias for the parameter estimate (Bias), the standard error (SE-Bias), and type of the mediation for Perceived Safety (PS) mediating the relationship between each of the 10 critical risk factors and User Behaviour (UB). The results of all the studied paths showed that the Bootstrap estimate for the mediation effect was not biased.

To interpret the results, if the figure zero (the null) falls outside the lower and upper limit of the confidence intervals, there is significant evidence to reject the null and infer that the indirect effect is significant. If zero (the null) falls within the interval, it fails to reject the null which infer that the effect is not significant. Also, where the direct and indirect effect are both significant, the mediation type is considered to be 'partial mediation'.

From the results in Table 2, the following hypotheses were therefore **supported** because 'zero' falls outside the lower and upper limits of the confidence intervals for the respective parameters, and that there is partial mediation because the direct and indirect effects are both significant (which means PS mediates the relationship between the risk factor and UB):

- **H1b** (*PS mediates the relationship between PF and UB*)—the indirect effect of PF on UB was statistically significant ($\beta = 0.289$, $p = 0.001$) and 'zero' falls outside the lower and upper limit of the confidence intervals (0.204, 0.386).
- **H4b** (*PS mediates the relationship between PPRTM and UB*)—the indirect effect of PPRTM on UB was statistically significant ($\beta = 0.096$, $p = 0.027$) and zero falls outside the lower and upper limit of the confidence intervals (0.012, 0.192).
- **H6b** (*PS mediates the relationship between PRR and UB*)—the indirect effect of PRR on UB was statistically significant ($\beta = 0.239$, $p = 0.001$) and zero falls outside the lower and upper limit of the confidence intervals (0.183, 0.304).
- **H8b** (*PS mediate the relationship between PRTA and UB*)—the indirect effect of PRTA on UB was statistically significant ($\beta = 0.092$, $p = 0.005$), and zero falls outside the lower and upper limit of the confidence intervals (0.030, 0.150).

Table 2 The mediation effect between critical factors and UB

Parameter	β	Maximum likelihood			Bootstrap					Type of mediation
		Lower	Upper	p	SE	SE-SE	Mean	Bias	SE-Bias	
PF → PS → UB	0.289	0.204	0.386	0.001	0.046	0.001	0.289	0.001	0.001	Partial mediation
PPI → PS → UB	−0.033	−0.098	0.028	0.301	0.032	0.000	−0.034	−0.001	0.001	No mediation
PIS → PS → UB	0.004	−0.057	0.061	0.910	0.030	0.000	0.003	−0.001	0.001	No mediation
PPRTM → PS → UB	0.096	0.012	0.192	0.027	0.046	0.001	0.096	0.001	0.001	Partial mediation
PRS → PS → UB	0.044	−0.003	0.091	0.065	0.024	0.000	0.043	0.000	0.001	No mediation
PRR → PS → UB	0.239	0.183	0.304	0.001	0.030	0.000	0.240	0.001	0.001	Partial mediation
PRSF → PS → UB	−0.002	−0.049	0.047	0.947	0.025	0.000	−0.003	−0.001	0.001	No mediation
PRTA → PS → UB	0.092	0.030	0.150	0.005	0.030	0.000	0.092	0.000	0.001	Partial mediation
PRE → PS → UB	0.146	0.094	0.200	0.001	0.027	0.000	0.146	0.000	0.001	Partial mediation
PRND → PS → UB	0.060	0.001	0.124	0.048	0.032	0.000	0.061	0.000	0.001	Partial mediation

- **H9b** (*PS mediate the relationship between PRE and UB*)—the indirect effect of PRE on UB was statistically significant ($\beta = 0.146$, $p = 0.001$) and zero falls outside the lower and upper limit of the confidence intervals (0.094, 0.200).
- **H10b** (*PS mediate the relationship between PRND and UB*)—the indirect effect of PRND on UB was statistically significant ($\beta = 0.060$, $p = 0.048$), and zero falls outside the lower and upper limit of the confidence intervals (0.001, 0.124).

However, the following 4 hypotheses were **rejected** because the indirect effect is statistically not significant and 'zero' falls within the lower and upper limit of the confidence intervals. Evidently, both the direct and indirect effects are not significant which confirms 'no mediation'. It therefore concludes that Perceived Safety (PS) **does not mediate** the relationship between the respective safety factor and User Behaviour (UB):

- **H2b** (*PS mediates the relationship between PPI and UB*)—the results indicate that the indirect effect of PPI on UB was statistically not significant ($\beta = -0.033$, $p = 0.301$), zero falls within the lower and upper limit of the confidence intervals (−0.098, 0.028).
- **H3b** (*PS mediates the relationship between PIS and UB*)—the results indicate that the indirect effect of PIS on UB was statistically not significant ($\beta = -0.004$, $p = 0.910$) and zero falls within the lower and upper limit of the confidence intervals (−0.057, 0.061).
- **H5b** (*PS mediates the relationship between PRS and UB*)—this indicates that the indirect effect of PRS on UB was statistically not significant ($\beta = -0.044$, $p = 0.065$), clearly zero falls within the values of the lower and upper limit of the confidence intervals (−0.003, 0.091).
- **H7b** (*PS mediates the relationship between PRSF and UB*)—the results show that the indirect effect of PRSF on UB was statistically not significant ($\beta = -0.002$, $p = 0.947$), and that zero falls within the lower and upper limit of the confidence intervals (−0.049, 0.047).

To summarise the outcomes, the rejected hypotheses could be interpreted as follows: H2b is rejected which means that the information provided to the pilgrims during Hajj event could be adequate; H3b is also rejected which means that the space provided in the Holy Mosque or the resulting high crowd density does not affect the pilgrims such that they become stressed or anxious; H5b is also rejected which means that although the risk of stampede influence the pilgrims perception of safety, the perception does not mediate its influence on the behaviour of the pilgrim in the Holy Mosque; and H7a is also rejected which means that pilgrims' perception of the possibility of structural and mechanical collapse does not have an effect on their behaviour.

6 Conclusion

The paper discussed the direct and indirect effect among the variables. It tested the proposed Structural Equation Model (SEM) and presented the interrelationships among the variables including twelve constructs (Perceived Force, Perceived Poor Information, Perceived Insufficient Space, Perceived Poor Real Time Management, Perceived risk of Stampede, Perceived risk of Riot, Perceived risk of Structural Failure, Perceived risk of Terrorist Attack, Perceived risk of Explosion and Perceived risk of Natural Disaster, Perceived Safety and User Behaviour). The overall findings have established that there is a direct influence of perceived safety (PS) on the pilgrims' behaviour (UB) in the Holy Mosque. The research provides convincing evidence that perceived safety should never be overlooked when determining the level of safety (safe condition) of a crowded large space building. It has established that seven (7) major factors have a direct influence on perceived safety, namely (in the order of significance): perceived force, perceived risk of riot, perceived risk of explosion, perceived poor real time management, perceived risk of terrorist attack, perceived risk of natural disaster, and perceived risk of stampede. With the exception of the perceived risk of stampede, these factors also have an indirect effect on user behaviour. Raineri (2015) has already established that crowd behaviour is a major factor in crowd disaster, it is therefore plausible to conclude that anything that significantly influences crowd behaviour could result in an unsafe situation that could lead to a disaster.

The analysis of the direct effects revealed that 9 hypotheses were supported, but 3 variables do not have a significant effect on perceived safety, namely: Perceived Poor Information ($p = 0.207$), Perceived Insufficient Space ($p = 0.882$), and Perceived risk of Structural Failure ($p = 0.882$). This paper also discussed the results of the mediation effect (indirect effect) on the relationship between the independent and its dependent variables in the model. The results found that there were significant indirect relationships between 6 safety factors (namely: perceived force, perceived poor real time management, perceived risk of a riot, perceived risk of terrorist attack, perceived risk of explosion, perceived risk of natural disaster) and user behaviour.

The paper suggests that the emphasis on expansion of the Holy Mosque as a mitigating strategy helps in objective safety provision, but it is not sufficient to provide a safe condition. It also suggests that Space (PIS), Information (PPI) and Structural failure (PRSF) are not the most critical subjective safety factors for Facilities Managers to worry about. The important items are: an orderly procession of pilgrims to prevent perceived force (PF) or risk of riots (PRR); provision of better and reliable hard services to mitigate the risk of explosion (PRE); and better security screening to decrease risk of terrorist attack (PRTA).

The following recommendations are made to enhance safety at the Holy Mosque:

- It is recommended that risk assessment should include an additional section to address subjective safety;
- To enhance the confidence of pilgrims as they go into the Holy Mosque, it is recommended to deploy an effective use of modern technology to control the

inflow and outflow of the crowd by counting the actual numbers of people that enter and exit the Holy Mosque to effectively control the capacity and to avoid extreme high density in the Holy Mosque at all times. The information could also be used to effectively plan the rate of arrivals of pilgrims to the Holy Mosque at peak times during Hajj to help avoid large gatherings at the entrances and exits as the pilgrims queue to enter the Mosque;

- Provide effective maintenance of all M&E hard services in the facility to avoid likelihood of failure or explosion;
- Provide a form of security screening system at entrances that can reliably reduce the risk of terrorist attack and improve the confidence of pilgrims;
- Deploy appropriate strategies to mitigate unnecessary occurrence of perceived force e.g. to stop pilgrims from moving in the opposite direction of Tawaf; to stop 'large groups' from performing the Tawaf at the ground floor level.

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Smart Manufacturing, Design and Logistics

Applying Mixed Methods Sequential Explanatory Design to Innovation Management

Warit Wipulanusat, Kriengsak Panuwatwanich, Rodney A. Stewart and Jirapon Sunkpho

Abstract This article discusses a procedure of mixed methods sequential explanatory design used to conduct sequential QUAN → QUAL mixed methods study. The methodological procedures are explained using a mixed methods study of innovation in the Australian Public Service (APS). The sequential explanatory design incorporated quantitative and qualitative approaches in two consecutive phases within one study. The quantitative method (i.e. questionnaire survey) was conducted in the first stage, followed by the qualitative approach using thematic analysis. The questionnaire survey data to be complemented by an archival analysis approach under a two-phase analysis. The archival analysis provided fresh context to understand the innovation process in the APS. The findings from both phases of the study were then examined and combined to draw the conclusions. This study made several contributions to the body of knowledge related to research methodology by not only adopting a quantitative-dominant mixed method approach, but also by employing integrated methods used for a deeper understanding of the impact of socio-psychological constructs on workplace innovation and career satisfaction.

Keywords Innovation · Mixed methods research · Sequential design

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_40

1 Introduction

Research methodology is defined as the overall approach implemented in a research process, from the theoretical background to the data collection and analysis (Remenyi 2002). It is vital to select the methodology at the outset of the research to obtain valid and reliable results. The quantitative and qualitative strands of research both possess their own weaknesses. For example, while the quantitative method can be criticised for not considering specific research contexts, not giving participants a voice, and lacking depth, the qualitative method can be denounced for small sample sizes, possible researcher biases, and lack of generalisability. Therefore, mixed methods research has been widely accepted as a third approach within social science. This approach adopts multiple data collection tools by combining both quantitative and qualitative methodologies to adequately answer a research problem, and also minimise biases inherent in studies which apply a single approach (Creswell 2013). Quantitative and qualitative approaches are used in combination to complement each other to capture the trends and details of a phenomenon (Ivankova et al. 2006).

By using a mixed methods research methodology, the power of numbers and generalisable outcomes can be balanced with the rich context of the lived experiences of people; therefore, gaining a deeper and richer understanding of a research problem than either traditional research approaches offered on their own (Teddlie and Tashakkori 2009). Therefore, both positivist and social constructionism could be applied in one study by combining qualitative and quantitative approaches to provide wider perspectives and a clear understanding of the phenomenon being investigated.

When both quantitative and qualitative research methods are used in one study they must be conducted either sequentially or concurrently. Sequential mixed methods data is analysed in a particular sequence which strives to explain or expand on the findings of one approach with the other approach, whereas concurrent mixed methods collect and analyse both the quantitative and qualitative data at approximately the same time (Creswell 2013). In the sequential explanatory design, priority is normally given to the quantitative phase. Researchers first collect and analyse the quantitative data, then use qualitative methods to gain further explanation and interpretation of the quantitative results obtained in the first phase. The analysis of quantitative data would be the primary method of the study. The logic for this approach was that the quantitative data and subsequent statistical analysis provided a general understanding of the issues under investigation. The statistical results were then refined and further explained in the qualitative phase by exploring participants' views in more depth.

2 Methodology

Advancing knowledge in the discipline of management requires a research design that yields data, evidence, and rational considerations to shape knowledge (Creswell 2013). The research design is the central point of a study because it provides the method for data collection and analysis to answer the research questions. As such, each component of the research design must align with the research questions. Thus, the selection of the research design plays an important role in the range of dimensions for the research process. This study is framed by nine research design components: the purpose of study, the study setting, unit of analysis, sampling design, time horizon, data collection method, and measurement of variables (Cavana et al. 2001; Sekaran and Bougie 2011).

Due to limited time and resources, the study adopted a cross-sectional research design method to obtain a 'snap-shot' of the current context. This research study was conducted within a working environment of public sectors in a non-contrived setting. The statistical modelling investigated causal relationships between the constructs in the theoretical framework and examined the questionnaire survey data using multivariate analyses.

Figure 1 presents the research activities which achieved the research objectives of the paper. Prior to the first research phase, knowledge was compiled via a critical and comprehensive review of relevant national and international literature, including international academic and organisational journals, historical studies and prior experiences, textbooks, and other published material, as well as theses and reports. As shown in Fig. 1, Phase 1 of the research design involved conducting data analysis to test the developed conceptual model. The quantitative phase was designed to answer the posed research questions and determine the acceptance or rejection of the null hypothesis for each research question. Data was obtained from a questionnaire survey of engineering professionals in Australian public sectors. Finally, statistical analysis was conducted to determine the main constructs and factors of the conceptual model and to finalise the model.

According to the philosophical assumptions of this study, the sequential explanatory design allowed the questionnaire survey data to be complemented by an archival analysis approach under a two-phase analysis. The archival analysis provided fresh

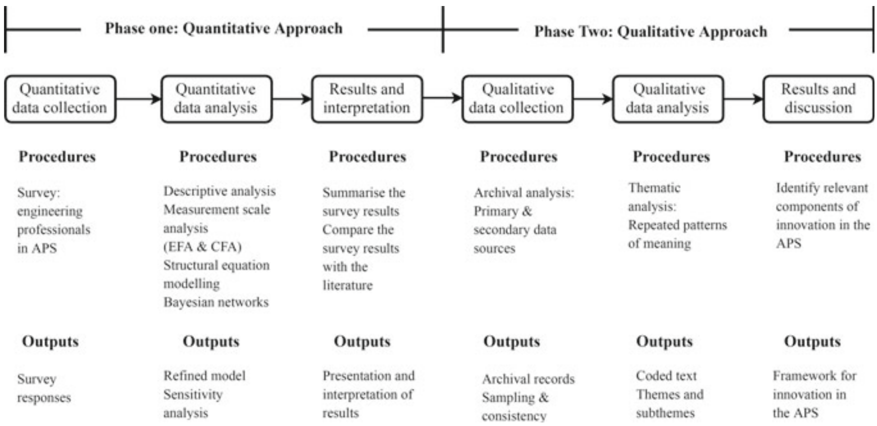

Fig. 1 An overview of the explanatory sequential mixed method design

context to understand the innovation process in the APS. Therefore, the factors impacting innovation in public sectors were investigated by employing qualitative approaches in Phase 2 of the research design. The findings from Phase 1 and 2 the study were then examined and combined to draw the conclusions.

3 Results

3.1 Analysis Phase 1: Quantitative Approach

The primary objective for this phase was quantitative validation of the relationships among the constructs in the conceptual model. This phase also enabled the researcher to capture the perceptions of employees regarding the climate for innovation and workplace innovation, as well as how dominant such views were across public sectors. The primary research questions are: "what is the nature of the relationship among leadership for innovation, ambidextrous culture for innovation, psychological attachment to organisation and how do they combine to impact workplace innovation and career satisfaction".

3.1.1 Quantitative Data Collection Method

The implementation of the quantitative phase commenced with multivariate statistical analyses of the data collected from the data set of the State of the Service Employee Census 2014. These types of analyses were considered appropriate for this study because they allowed patterns in complex data sets to be determined and corresponding explanatory variables to be identified. The analysis was conducted to achieve three main objectives: (1) obtaining an overview of the respondent profiles and current practices of APS through descriptive analysis; (2) testing the quality of the measurement scale by empirically assessing reliability and validity, as well as disclosing the factors underlying the conceptual model constructs; and (3) assessing and refining the model.

The State of the Service Employee Census 2014 targeted full-time, permanent civil servants of Federal Departments with 100 or more employees. Overall, 99,392 employees responded to the employee census, a response rate of 68% (Australian Public Service Commission 2014b). The State of the Service Employee Census 2014 was used as the only data source in this study. Therefore, it was deemed unnecessary to include the descriptions regarding the basis for the development of the original survey instrument. The target population for the study was the engineering profession in federal agencies. This group is classified as the Engineering and Technical Family in the APSC Job Family Model. As this study examined the effect of socio-psychological constructs on workplace innovation and career satisfaction from the perspectives of engineering professionals, only the survey responses from the Engineering and Technical Family were used. After eliminating the responses from other APS professionals, a total of 3570 observations were retained for this study. Although utilising secondary data limits the available sample to a pre-determined selection of respondents, the large sample size of this national survey has been deemed to have yielded a sufficient sample for this study.

The State of the Service Employee Census 2014 was administered to measure employees' anonymous attitudes and opinions regarding important issues, including health and wellbeing, recruitment and retention, performance management, leadership, innovation, social media, working environments, and general impressions of the APS. The employee census questions which used the five-point, ordinal Likert scale measured respondents' perceptions of the level of importance and their satisfaction with or the effectiveness of workplace issues. Respondents were givens options to express one of two extremes of views with 1 representing "strongly agree" and 5 for "strongly disagree", as well as a midpoint that allowed respondents to enter a 'neutral' response (Australian Public Service Commission 2014a). After an extensive review of all the questions in the State of the Service Employee Census 2014, 48 of the survey questions were selected and grouped according to the conceptual model and the model constructs. To align the survey responses to this study, the original Likert scale was re-coded into 1 representing "strongly disagree", 5 for "strongly agree", and 3 for "neutrality".

3.1.2 Quantitative Data Analysis

Before conducting further analysis, it was necessary to ensure the measurement scale used in the APS questionnaire was reliable and captured the meaning of each model construct. Reliability is defined as the extent to which a questionnaire yields consistent results through repeated administrations. To measure scale reliability, the study utilised 'Cronbach's alpha' which provided an indication of how consistent the responses were across items within the scale. These results determined that the measurement scales consisted of a set of homogeneous items to measure the meanings of the constructs. In addition, 'item-total correlations' were conducted to purify the assessment of uncorrelated items before finding the factors that represented the constructs (Kline 2015; Wipulanusat et al. 2017a).

In addition to assessing reliability, the validity of the measurement scale was evaluated using factor analysis, which was conducted using two sequential approaches: (1) exploratory factor analysis (EFA) and (2) confirmatory factor analysis (CFA). EFA was conducted to condense the large number of items into a smaller, more controllable set of dimensions (Hair et al. 2010; Wipulanusat et al. 2017b). EFA was applied to each construct to determine the adequate number of latent factor structures and to disclose the number of conceptual and statistical factors underlying the set of items in each model construct. The results were then affirmed using CFA to provide a foundation for subsequent model assessment and refinement. The CFA results

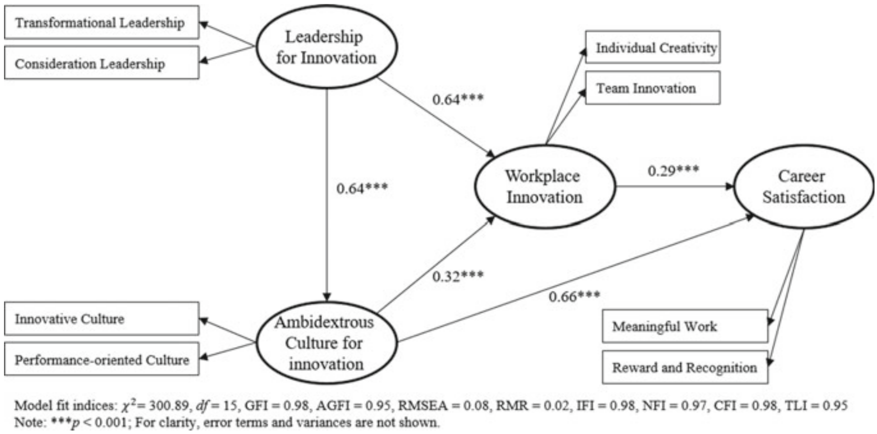

Fig. 2 Structural model (Wipulanusat et al. 2018)

demonstrated whether the measurement model had acceptable levels of goodness of fit, convergent validity, discriminant validity and unidimensionality.

This study combined Bayesian network (BN) with Structural Equation Modelling (SEM) to examine the causal relationships among the model constructs, which was subsequently used as a BN structure to predict workplace innovation and career satisfaction. The final empirical SEM confirmed the causal relationships between the four constructs of the structural model as shown in Fig. 2.

Finally, a theoretically based and empirically validated model from structural equation was used to develop BN at the factor level as presented in Fig. 3. Therefore, this research proposes a causal modelling approach by linking the SEM to the BN which can be utilised as a tool for decision making regarding innovation in the public sector.

Researchers can benefit from integrating the strengths of SEM and BN. SEM provided an empirically validated model based on theoretical considerations, which was appropriate as a basis to develop a causal map. The BN was used to examine causal relationships between the factors identified in the empirical model.

3.2 Analysis Phase 2: Qualitative Approach

In the second phase of the research design, a qualitative approach was employed to provide more detail and rich data for the purpose of understanding of the phenomenon under investigation. This characterises the present study as explanatory research that aims to identify the actual rationale and seek more description about a particular observed phenomenon. The results were used to explain whether the theoretical framework sufficiently represents the real-life organisational phenomenon within the public sector context. A qualitative approach can be conducted with an array of

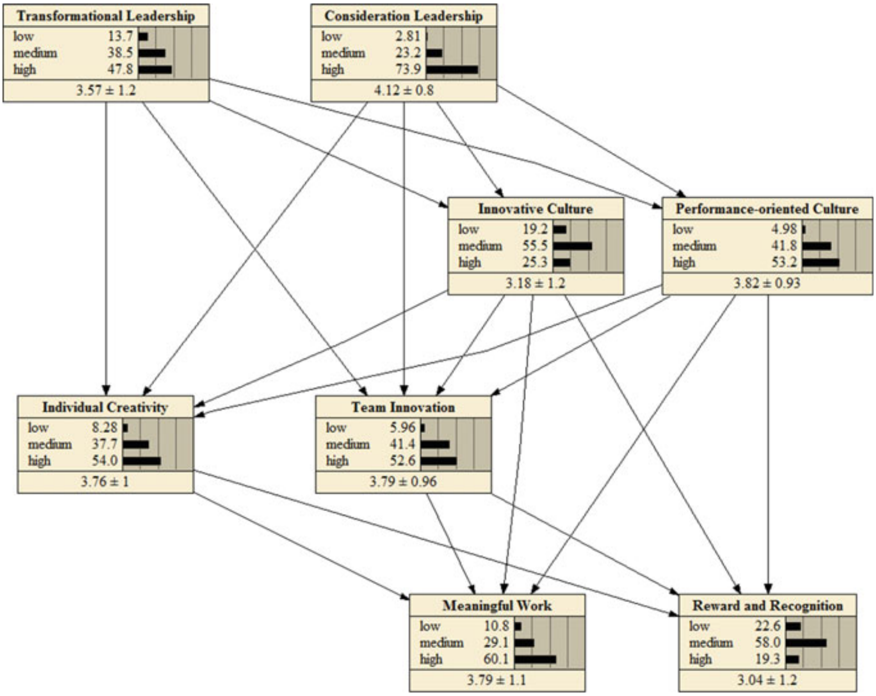

Fig. 3 Bayesian network

methods including documents, archival records, interviews, and observations (Yin 2013). In this study, archival analysis was utilised.

3.2.1 Archival Analysis

Archival analysis is a systematic method to review and evaluate the themes that emerge from archival records. Archival records are appropriate to explain the incidence or prevalence of a phenomenon, to obtain a holistic picture of an on-going phenomenon, and can be used to address research issues over time. Archival research provides multiple levels of evidence: individual, community, organisational, and societal and gives detailed, objective, and subjective explanations of phenomena from multiple perspectives to respond to research questions (Hadfield 2010). This approach is an observational method that is considered unobtrusive because the researcher studies social behaviour without affecting it. Thus, researcher bias is minimised, except in relation to the selection and interpretation of archival records.

Archival analysis was considered appropriate for this study. This is because archival data is normally accurate, can be analysed repeatedly, has broad scope, and can be approached using reliable search methods (Yin 2013). Additionally, comprehension and validity are enhanced as a result of both the historically contextual situatedness of accounts and through comparisons between recorded observations and interpretations (May 2001). The advantage of archival analysis is it provides an in-depth, replicable methodology to access individual or organisational structures such as cultures, messages, values, intention, cognitions, and attitudes, and to gain insights into managerial cognitions which surveys or interviews cannot provide at the same level of detail (Pollach 2012). The archival analysis in this study was conducted to establish timely and sequential historical records that addressed the research questions of this study. This method can be viewed as an extended approach conducted to complement the primary quantitative approach. Therefore, this study applied archival analysis in combination with primary analysis obtained from the questionnaire survey to answer the research questions more thoroughly.

Archival records consisted of recorded talks presentations by senior APS Managers in Innovation Month seminars from 2014 to 2018 and other related official documents. The recorded and transcribed presentations were considered the primary qualitative data. The relevant secondary data, such as official reports and websites, was also reviewed.

3.2.2 Thematic Analysis

In this study, archival records were the main source of qualitative data. Archival records can be obtained from various sources such as letters, memoranda, agenda, announcements, speeches, presentation, minutes of the meetings, administrative documents, organisational reports, newspapers, and other articles appearing in the mass media (Bowen 2009; Yin 2013). This research considered video transcripts of speakers from a government website to be primary qualitative data. In addition to the primary qualitative data, the reviewed secondary qualitative data included inquiries, annual reports, department strategies, and websites. The evidence provided the themes of interest and explained the relationships between these themes. With respect to the adoption of archival records for this study, it is possible to argue that they have a secondary role in the research process. The role of the archival records is to offer a complementary perspective on the development of the arguments and provide fresh context to understand the innovation in public sectors. The qualitative data collection method maximised the amount and scope of information available to the researcher and improved the reliability of the data by providing triangulation between data sources.

The first step focused on viewing the available recorded talk from Innovation month events held by the APS. Available video presentations from the Department of Industry, Innovation and Science YouTube channel were viewed and reviewed to create the transcripts. After that, the transcripts were read without analysis or coding to gain a feel for the content (Bryman and Bell 2015). Following this, the raw data was analysed to highlight important text. The second step of the analysis involved searching for keywords associated with drivers and barriers that relate to innovation in the Australian Public Service. As these words were located during the text searches, preliminary broad themes were assigned and the highlighting tool in NVivo utilised to mark the text (Wipulanusat et al. 2019).

The third step consisted of categorising the organisational and institutional actors into categories and coding accordingly. Interpretative analysis was conducted to understand the meaning, sense, and coherence of each text or text analogue found in the archival records (Myers 1994). The preliminary and secondary codes were reviewed by the researcher to ensure that interpretation bias was minimised. An iterative process was deployed between the video presentations, official reports, and the literature to confirm the second-order codes. This information from the qualitative analysis phase was applied to explain the innovation process in the Australian Public Service.

Archival records were thematically analysed to explore for themes and subthemes. An inductive approach was used to code the text without using an initial a priori coding template. Four themes emerged from the analysis of the archival records: innovation characteristics, innovation typology, drivers of innovation, and barriers to innovation.

4 Methodological Contributions

This study made several contributions to the body of knowledge related to research methodology by not only adopting a quantitative-dominant mixed method approach, but also by employing integrated methods used for a deeper understanding of the impact of socio-psychological constructs on workplace innovation and career satisfaction. The methodological contributions of this study include:

- Opportunities for replicating large data sets that have already been collected by government are starting to emerge. This study proposes the use of secondary large data sets in public management studies which can be replicated to determine if similar patterns of results are obtained in different institutional contexts.
- The study adopts an archival analysis which is an unobtrusive method to explore organisational topics that are difficult to study because of access issues. The archival analysis was utilised to obtain a better understanding and explain the current phenomena of innovation in the APS.

5 Conclusions

In order to achieve the intended objectives, a sequential mixed methods research design was adopted in this study so that the results from the first phase could be used to advise the development of the second phase (Creswell 2013). In particular, a sequential explanatory design was implemented with the quantitative approach as the predominant method conducted first, followed by the qualitative approach to explain the quantitative results.

For the quantitative approach (first phase), survey data released by the Australian Public Service Commission (APSC) from the 2014 APS employee census was used for this study. A quantitative analysis of the survey data was conducted to develop a hybrid SEM–BN approach used for data analysis. The conceptual model was formulated using previous empirical evidence and theory and examined causal relationships among the unobserved constructs. This study investigated the construct validity through both exploratory factor analysis (EFA) and confirmatory factor analysis (CFA). EFA was employed to analyse the inter-relationship between variables and to explore the factor structure of their measure. CFA was conducted to determine the validity and reliability of all the constructs. After the measurement model was validated, the structural model was conducted to test the proposed structural relationships among the latent constructs. This study used a theoretically based and empirically validated model from SEM to develop BN at the factor level. The BN was then applied for scenario-based simulations to provide managerial actions for the APS.

The subsequent qualitative approach (second phase) utilised a thematic analysis to explore senior APS leaders' perspectives on innovation from different standpoints because they work in different areas of the APS. Video transcripts of speakers were considered useful to reflect their viewpoints. Thematic analysis was conducted to reveal themes and subthemes typically associated with innovation in the APS from archival records. These themes and subthemes from the messages given by leaders determined how they regarded an innovation agenda for the APS. The findings revealed leaders' perspectives about key drivers and barriers to innovation. This study is unique in the sense that it integrates novel approaches based on both quantitative and qualitative research methods.

While this paper provides methodological contributions, there is also a potential limitation. Archival records offer a variety of potential uses to construct and reveal indicators of precedents or previous experiences that affect present actions and policies (Parker 2004). Many documents in public sectors are easily accessible and well organised to promote transparency and accountability (Berg 2001). There are some limitations however, regarding public data. For instance, public data are potentially prepared for certain audiences. Further, the results may be distorted, but using supporting records, such as mass media or actuarial records, can help eliminate these potential problems (Breg 1989). As government policy is often written in general statements that lead to many interpretations, this study conducted checks and re-checks regarding government policies and practices.

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A Child Orthosis Design and Simulation Based on Dynamic Considerations

Cristian Copilusi, Nicolae Dumitru, Alexandru Margine, Adrian Rosca and Eugen Rosu

Abstract This paper addresses a knee orthotic system design used on a 4-year-old child with locomotion problems. This knee orthotic system design was made by performing a dynamic analysis of the proposed child locomotion system. The aim of this dynamic analysis was to obtain knee joint connection forces in case of a walking activity. For the proposed dynamic model, input data such as hip, knee and ankle joint motion laws were considered. These were obtained through an experimental analysis with a high-speed video camera equipment on a healthy child. Thus, a database was created, which was used as input data for numerical simulations made in a dynamic mode with MSC Adams. Through these numerical simulations, important results were obtained, and these will further validate the proposed prototype.

Keywords Dynamics · Mechatronic system · Locomotion system · Multibody systems · Knee orthosis

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_41

1 Introduction

In the past, different human rehabilitation systems had evolved, but they address adults and elderly persons. Today, the research in the human rehabilitation locomotion field has extended to children.

Regarding children locomotion rehabilitation, it is a well-known fact, that it is in continual growth and should be resized or redesigned often. Thus, orthotic systems with applications on children's walking recovery were designed based on simple criteria like the ones from Theranova (2016). They are not expensive due to their simple functions, and they also lead to a partial walking recovery for a child with locomotion problems. To overcome these disadvantages, complex orthoses based on mechatronic systems like the ones from Banala (2007), Onose (2016) and Sawicki (2009) were developed. These orthoses were designed from dynamic considerations by analyzing a child's certain activities like walking or running and using important dynamic data as input on orthosis designs.

The design purpose of complex orthotic systems is to obtain a natural motion and to amplify and correct the child motion from a certain joint. For this, the complex orthoses have on their structure a mechanical system, which is especially designed and personalized for the analyzed child. Because of this, at the moment, universal mechatronic systems implemented on children locomotion rehabilitation have not been designed. Thus, the research core focuses on designing a mechatronic system characterized by a modular structure. This can be easily adapted on the lower limbs of children between the ages of four to seven years old. The proposed mechatronic system was designed from dynamic considerations, and it represents the research main objective. An additional objective is to analyze and apply dynamic results on a case study, namely a 4-year-old child with congenital disorders at the right knee joint level.

By considering similar researches like Copilusi (2012a, b), Banala (2007), Onose (2016) and Sawicki (2009), the starting research point can be identified. This was to obtain input data for dynamic analysis of the proposed human subject. In this case, the input data were represented by the experimental knee motion laws of a 4-year-old child, which is presented in the second part of the paper. With the obtained data, a child locomotion system dynamic model was elaborated, and the theoretical results were represented by knee connection forces. The method and the results, which is applicable on a parameterized model, are provided in the third part of this research. Theoretical results are important for virtual simulations of the proposed modular knee orthosis concept. Thus, by using MSC Adams, the proposed knee orthosis functionality was verified and approved by developing numerical simulations on dynamic modes similar to the real ones. These are described in the fourth section of this research, along with the final conclusions.

2 Child Locomotion System Motion Analysis

An experimental analysis was performed by considering two 4-year-old children with similar anthropometric data. The analysis aim was to obtain specific human locomotion system angular variations during walking for a single gait. These results represented the input data for a whole child locomotion system dynamic analysis.

In addition, a comparative analysis was performed for one analyzed child who has congenital disorders at the right knee. This analysis was performed in specific clinical conditions by using high speed camera motion analysis equipment called CONTEMPLAS (Contemplas 2010). The workflow is schematized in Fig. 1.

For the experimental analysis, a set of six reflective markers were attached on each of the children's limbs, as well as the joint centre for the hip, knee and ankle joints. These markers have reflective properties, and the motion analysis system can track them automatically, by generating trajectories and angular variations of the analyzed human subjects. A snapshot during analysis for the healthy child is shown in Fig. 2.

The analyzed children performed several walking steps in the defined workspace, and for each child, only a single gait was extracted from these steps. It is important to

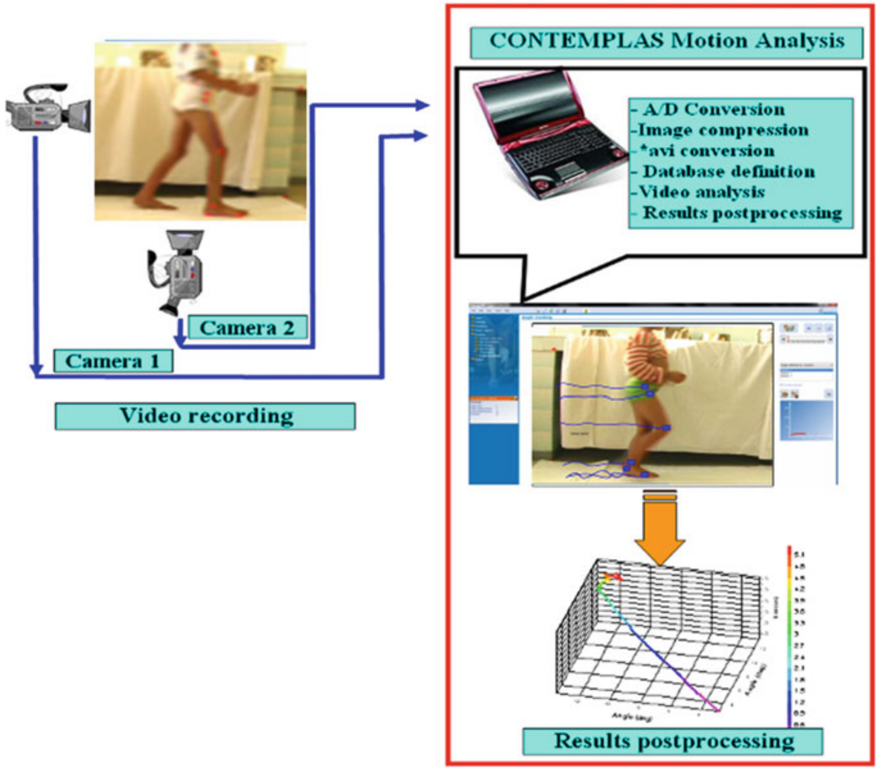


Fig. 1 CONTEMPLAS motion analysis workflow (Copilusi 2012a, b)

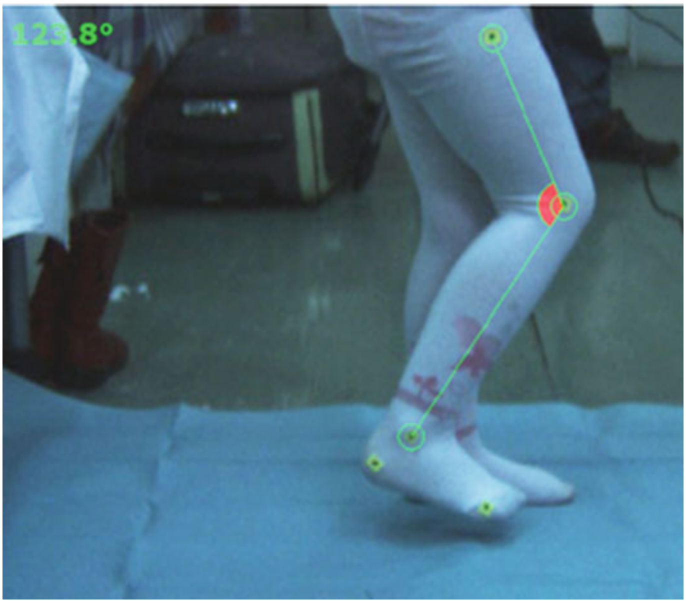
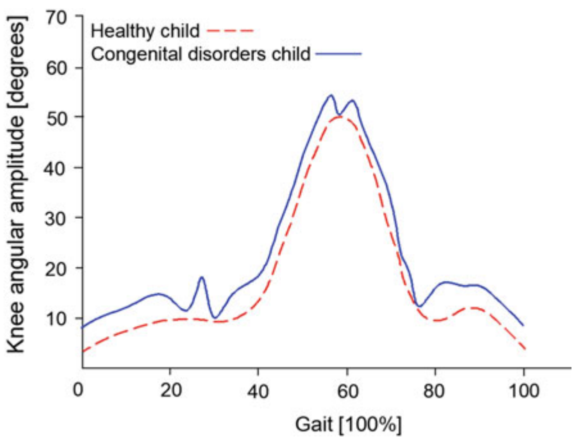


Fig. 2 Markers attached on the healthy child

note that the time period is different between the healthy child and the child with the congenital disorders. In the case of a healthy child, a complete gait was performed in 1.15 s, but in the case of the child with congenital disorders this was done in 1.28 s. These time intervals were important to retain for dynamic computations and also virtual simulations.

The obtained results are shown in the graphs with angular variations in the right knees for both human subjects. A comparative graph is provided in Fig. 3, which

Fig. 3 Knee angular amplitude for a complete gait for the analyzed children



clearly shows the difference between the angular amplitudes of a healthy child and the one with congenital disorders. These results represent a 100% full gait in both cases.

From Fig. 3, it can be observed that the knee amplitude of a child with congenital disorder has some distortion zones on the resultant curve, with a maximum value approximately equal to 53.592° and the minimum value around 9.521°. However, in case of the healthy child the obtained curve is smoother, and the maximum and minimum values are about 48.741° and 4.0023°, respectively. It can also be observed that the curvature paths are similar in both cases.

3 Child Locomotion System Dynamic Analysis

By taking into account other mathematical models especially developed for a dynamic analysis of the whole locomotion system like Anderson (2001), Dumitru (2008) and Sohl (2001), an inverse dynamic analysis was accomplished based on Newton-Euler method completed with Lagrange multipliers. The mathematical model for this analysis was created using the dynamic model from Fig. 4. The input data for this analysis were the geometric elements (L_{OT}, L_1, L_2… $L1_6$) and generalized coordinates variation laws from kinematic joints: q_1, q_2, q_3,…, q_{16} obtained through experimental analysis.

The constraint equations are:

$$\varphi(q, t) = 0 \tag{1}$$

$\mathbf{q_r}$—Generalized coordinates vector considered when the elements are rigid ones; t—time. The motion equation has the following form:

$$\begin{bmatrix} M & J_q^T \\ J_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_a \\ a \end{bmatrix} \tag{2}$$

where: M, represents the mass matrix with: M = diag (mi, Ji); $i = \overline{1, 16}$. We obtain the Lagrange's multipliers are:

$$\lambda = \left[J_q\right]^{-1} [Q_a - M \cdot \ddot{q}] \tag{3}$$

The motion laws $\mathbf{q(t)}$, $\mathbf{\dot{q}(t)}$ and $\mathbf{\ddot{q}(t)}$ were known from the experimental analysis accomplished in dynamic mode. From Eq. (3), we determine λ Lagrange's multiplier, with a programming algorithm from the MAPLE software. Thus, an inverse dynamic analysis was computed from which kinematic joint connection forces would be obtained. These forces were determined by taking into account the Lagrange multiplier as:

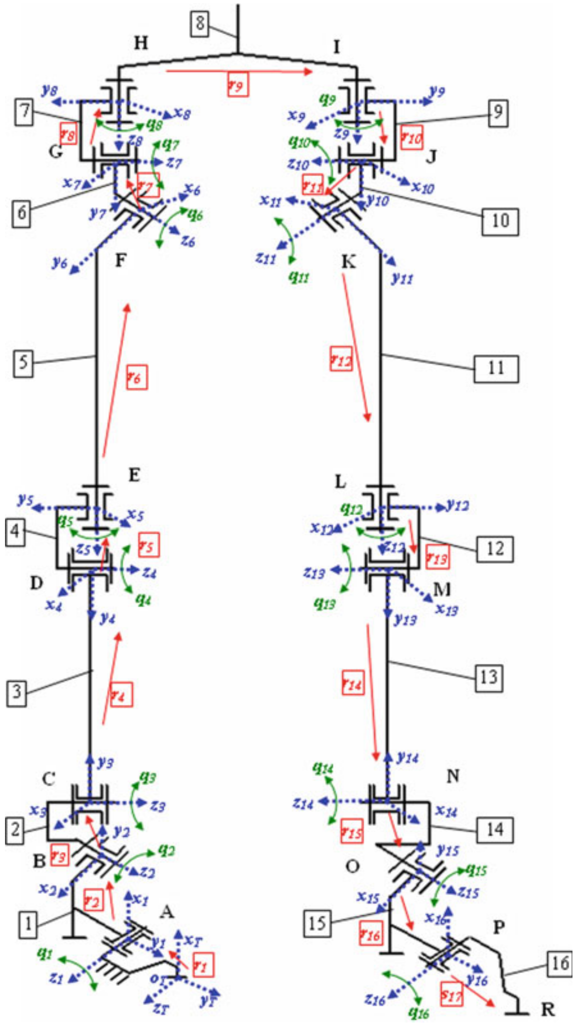


Fig. 4 Human locomotion system dynamic model scheme

$$F_i^{\prime\prime r(i,j)} = [R_{i,i^{\prime\prime}}]^T \cdot [A_{oi}]^T \cdot [\lambda]^{r(i,j)} \quad (4)$$

For numerical processing, the geometrical elements dimensions were in millimeters as follows: $L_{OT} = 50$; $L_1 = 45$; $L_2 = 45$; $L_3 = 180$; $L_4 = 5$; $L_5 = 205$; $L_6 = 5$; $L_7 = 5$; $L_8 = 200$; $L_9 = 5$; $L_{10} = 5$; $L_{11} = 200$; $L_{12} = 5$; $L_{13} = 180$; $L_{14} = 45$; $L_{15} = 45$; $L_{16} = 50$. The aim of this algorithm was to obtain connection forces components, which occur in the walking activity, for a complete gait cycle at each joint level from this mathematical model. This is equivalent to the human locomotion system. The connection forces for each joint were then obtained based on the above-mentioned algorithm. Figure 5 shows the connection forces for only the knee joints for the healthy child input data.

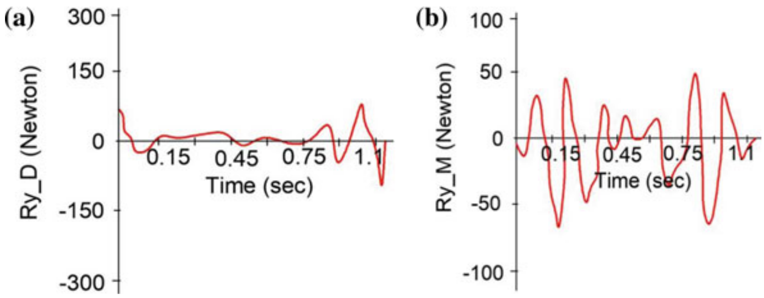


Fig. 5 Computed connection forces for knee joint in case of the healthy child: **a** left lower limb; **b** right lower limb

From Fig. 5, some high values through oscillations due to the ground and foot contact can be observed. The connection force value reaches a maximum of 8.238 Newtons and a minimum of −8.776 N for the right foot while for the left foot, the connection force value has a maximum and a minimum of 4.932 N and −7.389 N, respectively. Thus, an unbalanced force distribution due to the experimental data inputs can be noted; and a friction coefficient with a general value of 0.0015 would also be used in the mathematical model.

These values were later converted in a polynomial function and used as input data on virtual simulations for the proposed mechatronic orthosis. They will actually be considered as load data applied on MSC Adams environment for the analyzed mechatronic orthosis.

4 Virtual Simulations and Numerical Processing

By considering the obtained results from the computed dynamic analysis, a mechanical system will be designed and this will be a part of the orthosis concept.

Thus, the orthosis structure will be made from two fundamental parts, a mechanical system and an electronic command and control unit. For virtual simulations and numerical processing, only the mechanical system will be simulated on dynamic conditions with MSC Adams/Adams View module.

The orthosis mechanical structure has a modular form similar with a metallic bracelet characterized by adding or detaching segments. The concept is schematically presented in Fig. 6; it has one central joint namely A, which is a rotational one. This central joint will be placed in a knee joint centre. The entire structure has 7 links, consisting of 6 translational and rotational joints and one pivoting link (link no. 6). Due to the geometrical form of knee orthosis links, the shank element will not only perform a rotational motion around joint A but also a translational one on an arc circle around joint H. This will be made when Cable no. 1 is pulled and Cable no. 2

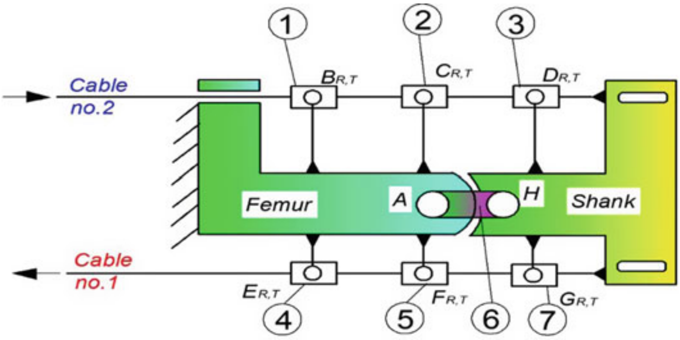


Fig. 6 Knee modular orthosis kinematic scheme

is released. Other joints presented in Fig. 6 like B_{RT}, C_{RT}, D_{RT}, E_{RT}, F_{RT}, G_{RT}, are used for cable guiding and these are composed of rotational and translational joints.

This structure will have at the end of each extremity two brackets in order to attach on the desired limb. This will be a universal one and it could be attached on children aged between 4 and 7 years. The mechanical system actuation has two cables with pulleys for assuring the joint flexion. Due to the particularity of the human joint motion which does not perform a pure rotation around an axis, the proposed mechanical system on this configuration will develop a trajectory on an arc circle combined with a small rotation on a centre axis.

The aim of this numerical processing is to determine the dynamic answer, namely the von Mises stress at the level of each cable and also the cable forces during motion in order to choose an orthosis proper actuator. Based on the structural scheme presented in Fig. 6, a 3D model, as shown in Fig. 7, was designed, as shown in Fig. 7. According to Fig. 7, the actuation system will be made through cable no. 1 for flexion and cable no. 2 for inverse motion. One end of the cables was fixed on the

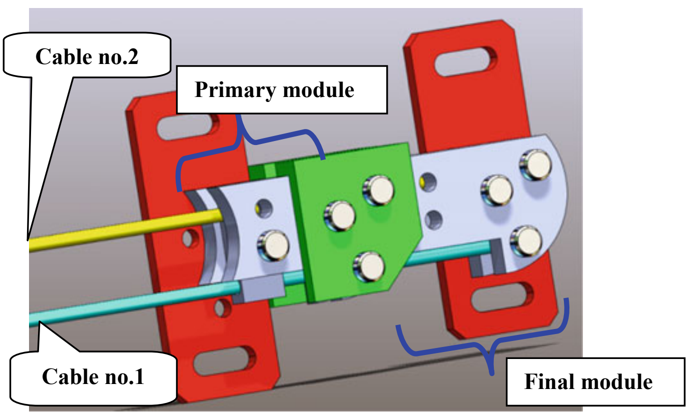


Fig. 7 Knee modular orthosis virtual model with components identification for a 4-year-old child

final module segment, and the other end will be linked to a servomotor in case of the real prototype. The presented 3D model from Fig. 7 was imported through a special interface on MSC Adams environment. Initial conditions were applied, including proper rotational joints and the element from the primary module was considered fixed in space. Joint friction forces were considered with a proper coefficient like the one from the dynamic analysis according to Giesbers (2012). For virtual simulations, these cables were attached to some virtual springs, and the aim of these simulations was to obtain the force cables developed during simulations, as well as the von Mises stress when these were considered flexible ones. From the entire structure, only the cable elements were considered flexible and the other orthosis parts were rigid bodies. The contact between bodies was setup at a depth penetration of 0.000061 mm. The orthosis mechanical structure was considered as made of aluminum alloys which confer a small weight and can be easy to wear for by the analyzed child.

At the end of the final module bracket, the connection force polynomial form was introduced as a function depending on time, as seen in Fig. 8. In this case, the time interval was setup at a value of 1.15 s for virtual simulation in dynamic conditions. The obtained results are shown in Figs. 9, 10 and 11.

Figure 9 shows the obtained force variation over time for cable no. 1; a maximum force value of 67.652 N, as well as, a small deviation at a time sequence of 0.6 s can be observed. However, this behavior of the flexible cable can be interpreted as the elastic behavior of the cable when this reaches the maximum value and the orthosis mechanical system reaches the maximum angular amplitude during knee flexion. Some snapshots during virtual simulations are presented in Fig. 10. There is reportedly only a half sequence when it reaches the maximum angular amplitude, and at maximum force value of the cable no. 1, the von Mises stress maximum value was observed to be around only 20.165 MPa for both cables. A von Mises stress variation during time sequence is shown in Fig. 11, where there are two curves, one

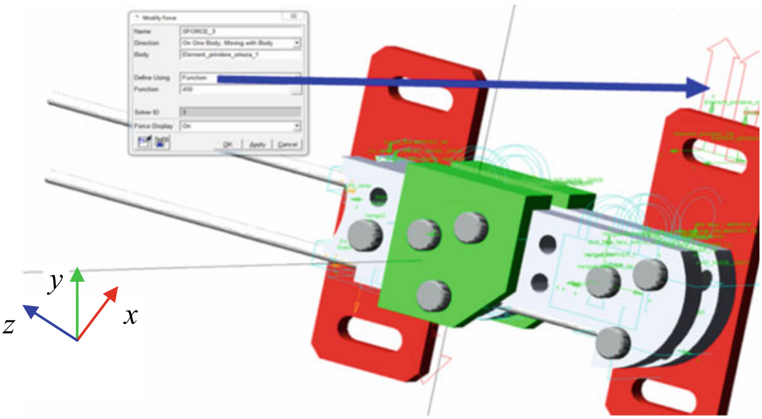


Fig. 8 Aspects regarding the connection force application for the proposed orthosis mechanical system

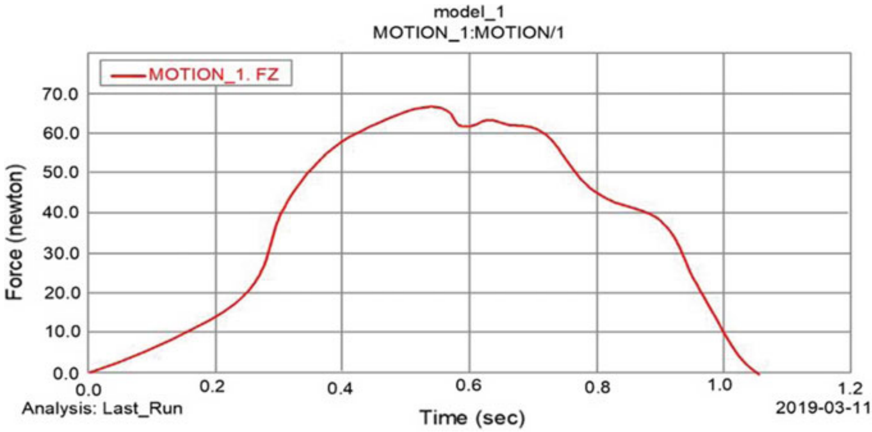


Fig. 9 Force variation diagram for cable no. 1 of the knee modular orthosis

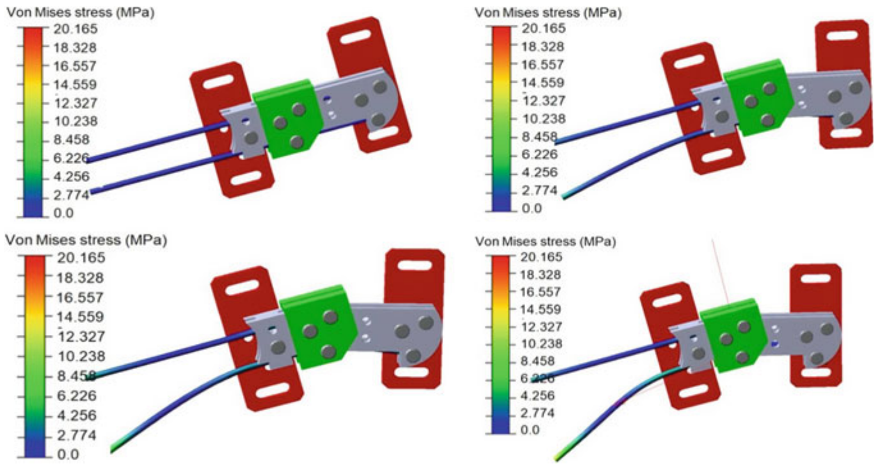


Fig. 10 Snapshots during virtual simulations under MSC Adams environments in dynamic conditions for the proposed orthosis mechanical structure

for cable no. 1 and the other for cable no. 2. Small deviations of around 0.5–0.6 s for both cables can also be seen on this graph.

By considering the obtained results, the modular knee orthosis concept was validated and the problem was solved by knowing the force maximum value reported in Fig. 9. This would lead to the selection of cables with proper diameters and a servomotor with a proper torque.

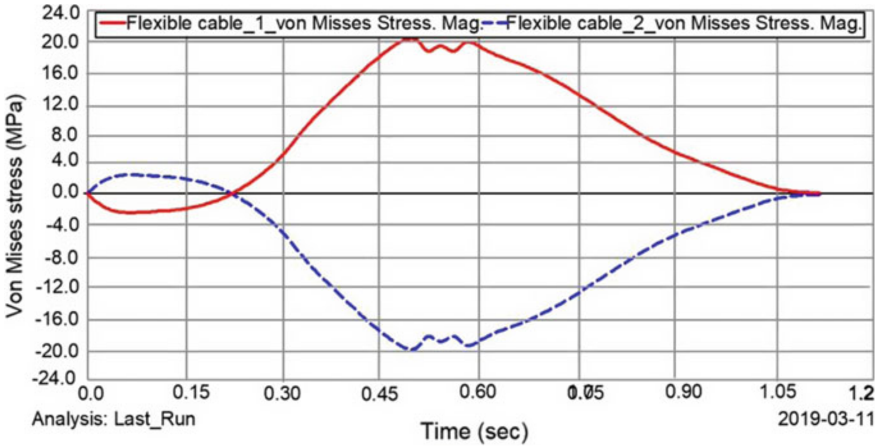


Fig. 11 Computed von Mises stress for flexible cables during simulation versus time

5 Modular Knee Orthosis Prototype

By considering the design principles applied on the elaborated concept, a prototype was manufactured, as shown in Fig. 12. This has a length of 100 mm, a width of 70 mm and a thickness of 10 mm. In addition to being able to bend at almost 80°, this prototype will allow the user to add another module due to his modular configuration.

This prototype is controlled by an Arduino UNO electronic hardware and a servomotor with a torque of 8 Nm at a voltage of 5 Vcc. The entire mechatronic system has two pressure sensors attached on the child's foot for the command and control unit in order to give electric signals for pulling one cable and releasing the other during the child's gait. The entire command and control unit, together with the battery and servomotor, will be placed in a special pocket attached with a belt on the child's pelvic zone. Figure 13 shows the orthosis mechatronic system. Some preliminary tests in clinical conditions were done on the proposed patient, and the results are presented in Fig. 14. These experimental tests were performed in similar conditions with the ones reported in the case of a healthy child.

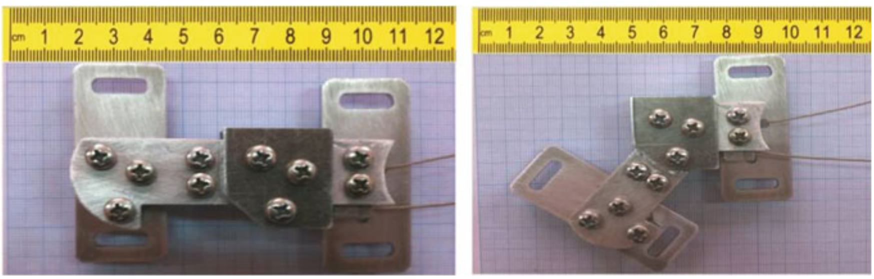


Fig. 12 Modular knee orthosis mechanical system real prototype

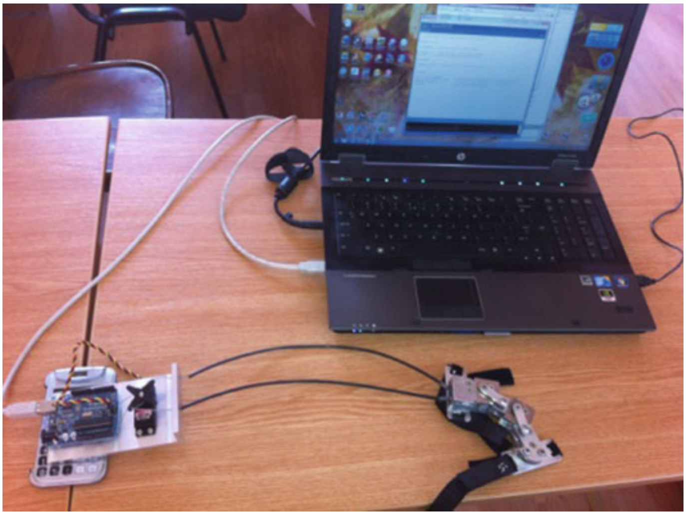


Fig. 13 Modular knee orthosis prototype

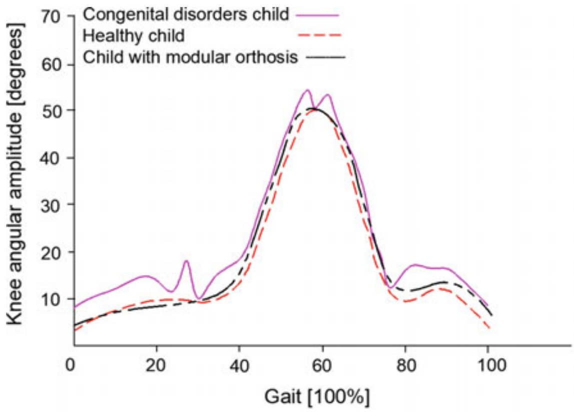


Fig. 14 A comparative analysis after preliminary tests of the knee orthosis prototype versus time

As seen in Fig. 14, the dotted curve corresponds with the experimental tests on the child with the attached modular orthosis prototype. It looks like this is very appropriate as not only the pattern but also the values align with those of the healthy child during tests. Moreover, at around 60% of a complete gait, it can be seen that the obtained path is smooth. The maximum value in case of knee angular amplitude during walking is around 49.021°, and this curve was obtained in case of a complete gait in 1.18 s.

6 Conclusions

A prototype of a knee modular orthosis was designed and elaborated. This would be used on a 4-year-old child's locomotion rehabilitation. The resultant parameterized dynamic model can be adapted to children of any age. Although simulation results and numerical processing had outlined a good performance for suitable user-oriented walking specific operation, its design may require additional components in future developments. The concept was fairly simple, wearable and lightweight, and it was run with only one actuator. This was controlled through a command and control acquisition board with a simple programming algorithm that can be adapted to any knee motion law pattern especially developed by a healthy child with almost identical anthropomorphic data as the one placed on walking therapeutic and recovery programs. The obtained prototype can be extended in case of children with different ages, and several models can be designed in order to identify a universal functionality principle. Future development of the prototype can lead to its successful implementation as an orthotic device for children's walking recovery.

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Kinematics and Design of a Leg Exoskeleton for Human Motion Assistance

Ionut Geonea, Nicolae Dumitru, Cristian Copilusi, Alexandru Margine and Laurentiu Racila

Abstract This paper presents studies concerning the design of exoskeletons for human lower limb motion assistance. A study concerning the structural and mechanical design in Solid Works is presented on the first part of the paper. In the second part, a human gait motion analysis with goniometer sensors is performed. Also, a kinematic characterization for the new proposed leg exoskeleton is performed. The exoskeleton achieved design is based on a seven-link mechanism, designed to accomplish requirements of human locomotion. The kinematic computational model and the obtained results with plots in ADAMS software are presented. The obtained simulation results are compared with experimental human gait, and they are useful to characterize the exoskeleton motion and to demonstrate suitable performance for human rehabilitation purposes.

Keywords Design · Kinematics · Dynamics · Exoskeleton · Rehabilitation

1 Introduction

The main reason for rehabilitation of human walking is to help a patient recover from injuries and neuronal diseases or to recover certain locomotor skills, to promote as much independence in day-to-day activities and to assist the patient to compensate for deficiencies that cannot be treated medically (Dollar and Herr 2008).

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_42

Therefore, worldwide efforts are being made to automate locomotion rehabilitation (Chen et al. 2016). Robotic devices have the potential to make therapy more accessible and thus available to many patients. In the field of medical recovery, locomotor recovery is required for patients who have had strokes or spinal cord injuries in order to be able to re-practice their walk capabilities. The purpose of rehabilitation exercises is to perform certain movements through repetitive activities that cause motor plasticity for the patient and thus improve the locomotor activity and minimize functional impairments (Anam and Al-Jumaily 2012). The rehabilitation of the movement is dependent on the affected leg, so the affected leg has to undergo physical exercise. One-third of stroke survivors do not regain their walking and out-walking ability; they walk in a typical asymmetric manner. Rehabilitation therapies are essential for recovery, and therefore, many researches are ongoing in the field. The rehabilitation process for regaining significant mobility can be divided into three stages (Díaz et al. 2011): (1) the patient in bed is mobilized in the seat as soon as possible, (2) restoring walking, and (3) improving walking (i.e., free walking if possible). Robotics for rehabilitation treatment is an emerging field that is expected to grow as a solution for automation of rehabilitation. Robotic rehabilitation is able to: replace a therapist's physical training effort, allow for more intense repetitive movements and therapy at a reasonable cost, and quantify the level of motor recovery by measuring strength and trajectories.

In recent literature, many papers deal with robotic rehabilitation of lower limbs. The purpose of these researches is to review the existing interfaces as well as the ongoing work, to show researchers the current state of the art and the progress in the field. From the category of robotic systems that track patient movement on the ground, KineAssist, WalkTrainer and Rewalk are marketed (Yan et al. 2015). Other systems available on the market are Lokomat, LokoHelp and ReoAmbulator. These allow patients to move under their own control instead of executing movements with predetermined trajectories. Review studies concerning the current state of exoskeleton systems for lower limbs are presented by many authors (Dollar and Herr 2008; Huo et al. 2014). They show the development of exoskeleton systems in the last 60 years from the point of view of science and fiction at first to the products currently marketed. The first research in the area of exoskeleton systems dates back to 1960, and the initiative returns to two separate groups of researchers, one from the US and one from the former Yugoslavia. The first group aimed at developing a technology to improve the abilities of the human carrier body, often for military purposes, while the second group attempted to develop a technology for assisting people with disabilities.

In this sense, rehabilitation systems have been developed and are subject to numerous patents. For example, a method and system for training body weight support during movement on a conveyor belt is presented in U.S. Patent US6666831 B1 from 23 December 2003. The system uses a programmable stepper device that acts as an exoskeleton type motor system from a fixed base (Edgerton et al. 2003). From the category of active rehabilitation systems, the exoskeleton systems are of particular interest. Problems concerning the dynamic modeling of exoskeletons are discussed in some literature (Nabipour and Moosavian 2018). The aspects of exoskeleton power control are also studied (Choi et al. 2019).

2 Exoskeleton Design

In this paper, an assistant exoskeleton system for persons with locomotor disabilities is designed. Other exoskeleton systems, with one motor for actuation, are developed and presented in other studies (Geonea et al. 2015). The proposed system for assisting human locomotion is composed of two leg mechanisms and a top frame that attaches to the human subject. The leg mechanisms have in the structure 7 kinematic links connected by 10 rotation joints, as is depicted from the kinematic scheme shown in Fig. 1. Numerical digits from 1 to 7 are used for the mechanism links and letters for kinematic joints.

The design solution is shown in Figs. 2 and 3. The system includes a frame (9) attached to the patient's pelvis with straps. The proposed system for assisting human locomotion differs from existing solutions because it uses a new leg mechanism with a single motor to transmit motion to the drive link. These types of solution do not require the use of command and control systems to achieve the motion laws of lower limb. Instead, the vast majority of existing solutions use open kinematic chains with motors placed to joints (hip, knee and ankle).

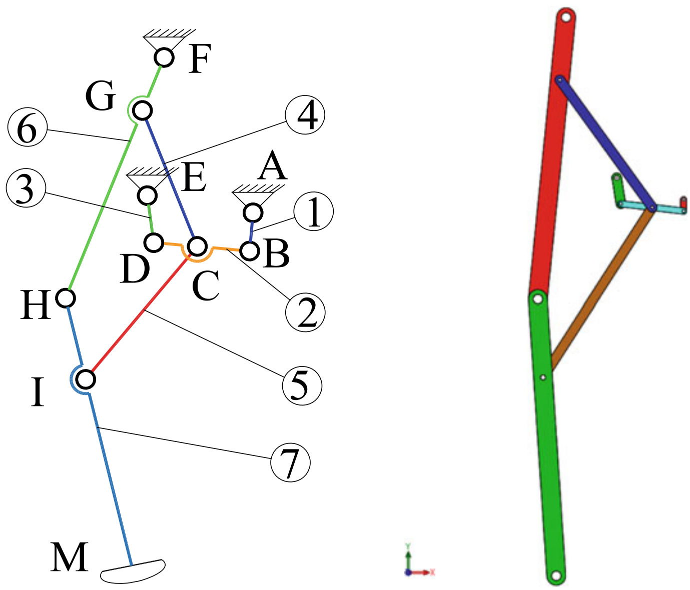


Fig. 1 Leg of the exoskeleton kinematic scheme and design of one leg

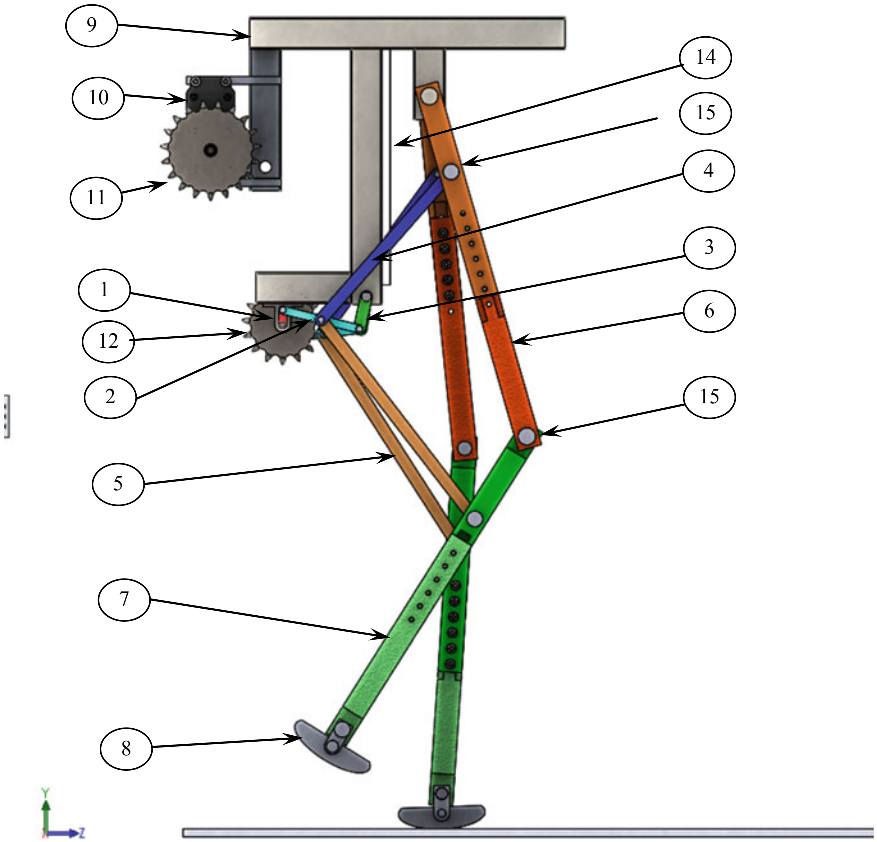


Fig. 2 The 3D designed model of the exoskeleton (right view)

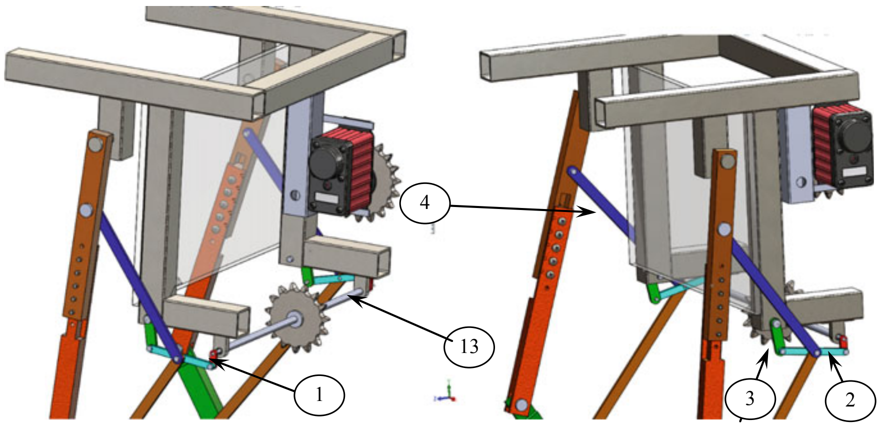


Fig. 3 Exoskeleton prototype (left view)—details of the upper part

The exoskeleton consists of two mechanisms for the left and right leg. The electric motor with gearbox reducer (10), which is mounted on the upper frame (9), is used to drive the two mechanisms. By means of a chain wheel drive, the motion is transmitted to the shaft (13) which is mounted on the upper frame (9) by means of radial bearings with needles or sliding bearings.

Another novelty of the solution consists of the design of a mechanism with an anthropomorphic structure, which is implemented as a leg of an exoskeleton, used to assist the movement of persons with locomotor disabilities. The designed mechanism has a structure and movement similar to the human leg (it achieves similar motion of the joints as human gait) and has the human leg segmentations in its structure. The link (6) has the structural role of the femur and the link (7) through the segment (HM) fulfills the functional role of the tibia. The computed trajectory described by the ankle is ovoid, similar to that performed by human subjects at normal walking. From the kinematics of the systems, the computed angles in the H and F joints corresponding to the hip and knee joint show similar variations to human subjects. Since the parameters of human walking show variability from one individual to another, or even from one step to another, of the same subject, within certain limits, for the design of the mechanism, it was considered an average cycle for the laws of variation of the angles in the joints.

The driving link of the mechanism is the crank (1) for each leg. The fixed joint M (between foot and tibia) corresponds to the ankle joint. The link (6) of the mechanism structurally shapes the femur and the link (7) structurally shapes the tibia. Also, the rotation joint F represents the hip joint, and the joint H is the knee joint. The mechanism achieves in the joints the corresponding flexion-extension motions of the human leg.

The driving links (1) of the two leg mechanisms are connected to the shaft (13) with opposite angular positions at 180°. On the upper frame with joints F and E (materialized by spindle or bolt), the kinematic links (6) and (3) are connected. In order to allow the exoskeleton to be adapted to human subjects with different leg dimensions, the links (6) and (7) consist of two parts sliding in a parallelepipedal channel (Fig. 3). The two parts, which make up the adjustable element, allow the length of the element to change, after which the two sides are screwed to prevent relative movement.

The exoskeleton has a human foot-like structure (Fig. 4): the rotation joint (F) represents the hip joint and the rotation joint (H) represents the knee joint. The segments (FH) and (HM) structurally shape the human femur and the tibia. The exoskeleton assembly worn by a human mannequin is presented in Fig. 4.

3 Human and Exoskeleton Leg Kinematic Characterization

Experimental data acquired for normal walking during 30 s from a 35-year-old healthy subject are reported as angle variation in time, for the ankle, knee and hip joints, only in sagittal plane, for the right leg (Fig. 5) and for the left leg (Fig. 6).

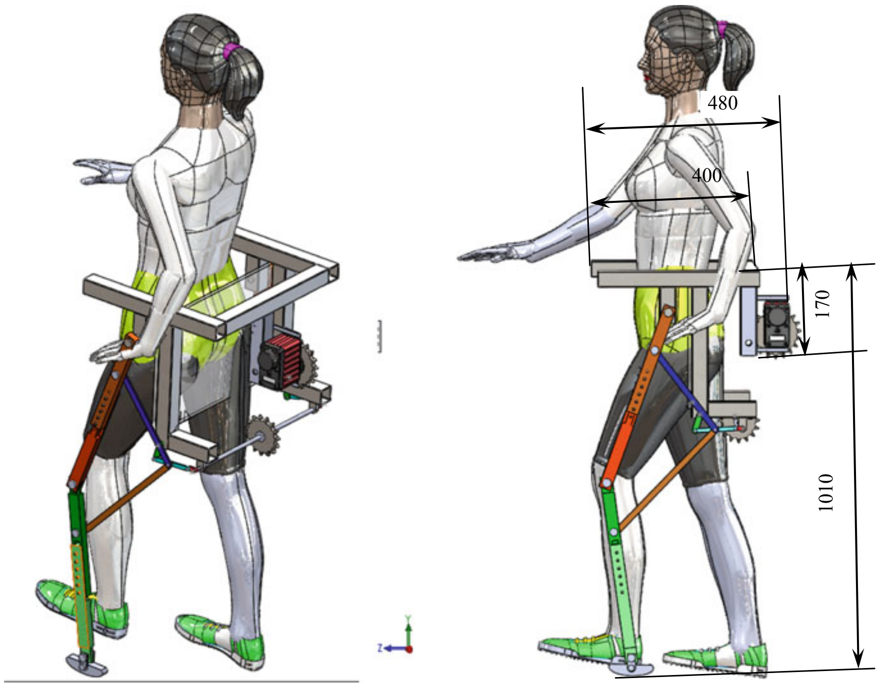
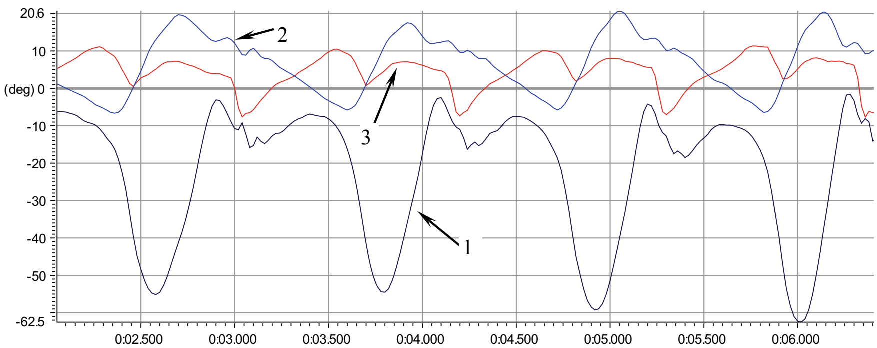


Fig. 4 Dimensions of the human exoskeleton assembly, in (mm)



1-knee flexion/extension; 2- hip flexion/extension; 3 – ankle flexion/extension;

Fig. 5 Healthy human measured joints angle, in sagittal plane, for right leg

The anthropometric data of the human subject are: body weight = 78 kg, height = 1.68 m, hip-knee length = 0.44 m, knee-ankle length = 0.40 m, ankle-little toe = 0.19 m. The subject used to test was a healthy one and had no evidence or known history of motor and skeletal disease or record of surgery to the lower limbs. The study is approved by the Human Ethics Research Committee of Faculty.

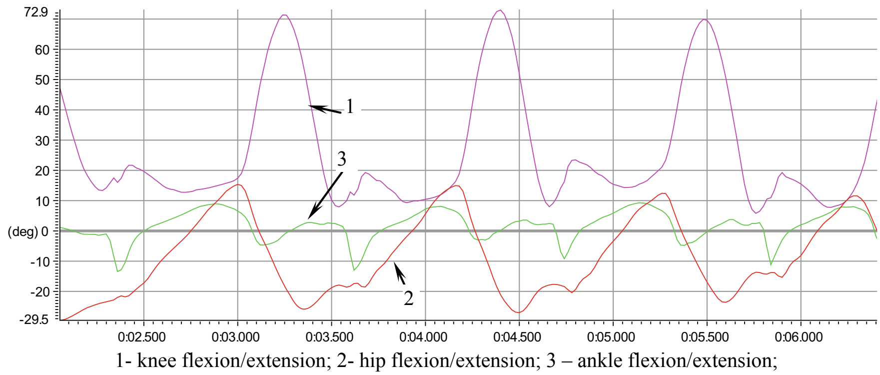


Fig. 6 Healthy human measured joints angle, in sagittal plane, for left leg

A theoretical analysis of the leg exoskeleton kinematics was performed in order to evaluate and simulate performances and operation. The point M position, reported to the XY reference system, Fig. 7, is evaluated as a function of input angle φ_1 and dimensional parameters of the linkage. Geometrical parameters are:

- fixed joints coordinates: A, E, F. So, $x_F = y_F = 0$; $x_E = 80$ mm; $y_E = -255$ mm; $x_A = 186$ mm, $y_A = -290$ mm.
- links length: $l_{\mathrm{AB}} = 12{,}5$ mm; $l_{\mathrm{BD}} = 10$ mm; $l_{\mathrm{BC}} = 50$ mm; $l_{\mathrm{ED}} = 42$ mm; $l_{\mathrm{FG}} = 100$ mm; $l_{\mathrm{GH}} = 250$ mm; $l_{\mathrm{HI}} = 124$ mm; $l_{\mathrm{HM}} = 440$ mm.

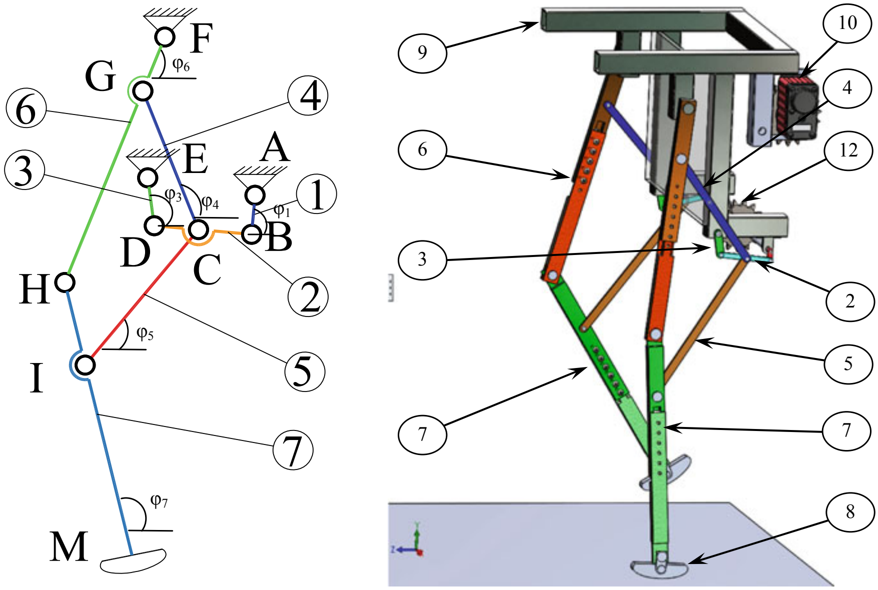


Fig. 7 Kinematics scheme and design for the leg of the exoskeleton

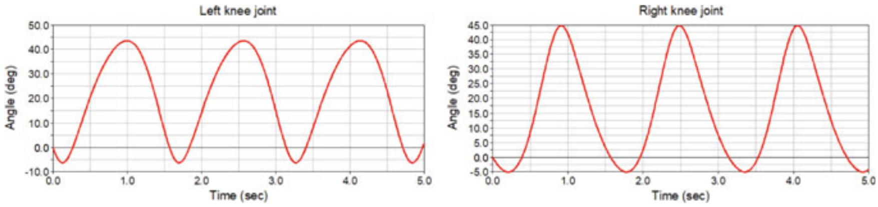


Fig. 8 Exoskeleton knee joint angular variation

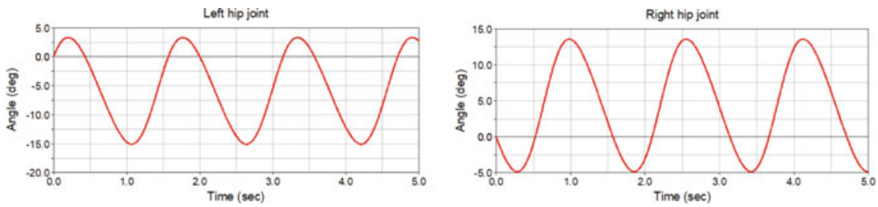


Fig. 9 Exoskeleton hip joint angular motion

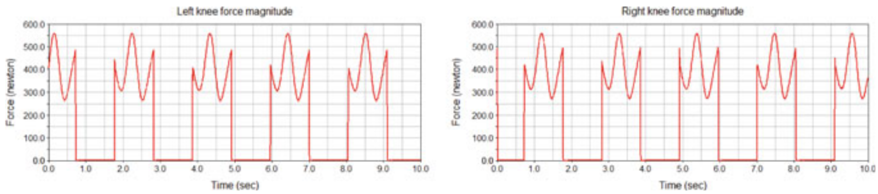


Fig. 10 Exoskeleton knee joint force magnitude representation

The geometrical dimensions are: $l_{\mathrm{AB}} = 12.5$ mm; $x_{\mathrm{A}} = 182.27$ mm; $y_{\mathrm{A}} = -247.36$ mm. It is considered an angular velocity of link (1) equal to 2 rad/s. The coordinates of the joint B are computed with Eq. (1).

$$\frac{d\varphi_1}{dt} = \omega \Rightarrow \varphi_1 = \omega \cdot t;\;\; \omega_1 = 2\,\mathrm{rad/s}.$$
$$\begin{cases} x_B = x_A + l_{AB} \cdot \cos\varphi_1 \\ y_B = y_A + l_{AB} \cdot \sin\varphi_1 \end{cases} \tag{1}$$

The joint coordinates are: $x_B,\ y_B$; x_E= 80 mm, y_E= −255 mm.
Equation (2) is used to compute the joint D coordinates:

$$\begin{cases} x_D = x_B + l_{BD} \cdot \cos\varphi_2 = x_E + l_{DE} \cdot \cos\varphi_3 \\ y_D = y_B + l_{BD} \cdot \sin\varphi_2 = y_E + l_{DE} \cdot \sin\varphi_3 \end{cases} \tag{2}$$

In order to compute the angle φ_2, the terms that contain the other unknown φ_3 are grouped.

$$\begin{cases} l_{DE} \cdot \cos\varphi_3 = (x_B - x_E) + l_{BD} \cdot \cos\varphi_2 \\ l_{DE} \cdot \sin\varphi_3 = (y_B - y_E) + l_{BD} \cdot \sin\varphi_2 \end{cases} \tag{3}$$

We use the notations: $(x_B - x_E) = a_1$; $(y_B - y_E) = a_2$.
After squaring and summing Eq. (3), Eq. (4) is obtained.

$$a_1^2 + a_2^2 + l_{BD}^2 - l_{DE}^2 + 2a_1 l_{BD} \cos\varphi_2 + 2a_2 l_{BD} \sin\varphi_2 = 0 \tag{4}$$

Equation (4) is a trigonometric equation with variable coefficients, of the form:

$$A_2 \sin\varphi_2 + B_2 \cos\varphi_2 + C_2 = 0 \tag{5}$$

The angle φ_2 is computed with Eq. (6).

$$\varphi_2 = 2arctg \frac{A_2 \pm \sqrt{A_2^2 + B_2^2 - C_2^2}}{B_2 - C_2} \tag{6}$$

where: $A_2 = 2a_2 l_{BD};\ B_2 = 2a_1 l_{BD};\ C_2 = a_1^2 + a_2^2 + l_{BD}^2 - l_{DE}^2$

In order to compute the angle φ_3 the terms that contain the other unknown are grouped. It results in the trigonometric equation with variable coefficients:

$$a_1^2 + a_2^2 - l_{BD}^2 + l_{DE}^2 - 2a_1 l_{DE} \cos\varphi_3 - 2a_2 l_{DE} \sin\varphi_3 = 0$$

The angle φ_3 is computed with Eq. (7).

$$\varphi_3 = 2arctg \frac{A_3 \pm \sqrt{A_3^2 + B_3^2 - C_3^2}}{B_3 - C_3} \tag{7}$$

where: $A_3 = -2a_2 l_{DE};\ B_3 = -2a_1 l_{DE};\ C_3 = a_1^2 + a_2^2 + l_{DE}^2 - l_{BD}^2$.

3.1 Kinematic Computation of the Assur Structural Group FGC

Equation (8) is then written to compute the joint G coordinates.

$$\begin{cases} x_G = x_F + l_{FG} \cdot \cos\varphi_6 = x_C + l_{CG} \cdot \cos\varphi_4 \\ y_G = y_F + l_{FG} \cdot \sin\varphi_6 = y_C + l_{CG} \cdot \sin\varphi_4 \end{cases} \tag{8}$$

We use the notations: $(x_F - x_C) = a_3$; $(y_F - y_C) = a_4$.

In order to compute the angle φ_6, the terms that contain the other unknown φ_4 are grouped. After squaring and summing Eq. (8), Eq. (9) is obtained.

$$a_3^2 + a_4^2 + l_{FG}^2 - l_{CG}^2 + 2a_3 l_{FG} \cos\varphi_6 + 2a_4 l_{FG} \sin\varphi_6 = 0 \tag{9}$$

Equation (9) is a trigonometric equation with variable coefficients, of the form (5).

The angle φ_6 is computed with Eq. (10).

$$\varphi_6 = 2arctg\frac{A_6 \pm \sqrt{A_6^2 + B_6^2 - C_6^2}}{B_6 - C_6} \tag{10}$$

where: $A_6 = 2a_4 l_{FG};\ B_6 = 2a_3 l_{FG};\ C_6 = a_3^2 + a_4^2 + l_{FG}^2 - l_{CG}^2.$

In order to compute the angle φ_4 the terms that contain the other unknown are grouped. It results in the trigonometric equation with variable coefficients:

$$a_3^2 + a_4^2 + l_{CG}^2 - l_{FG}^2 - 2a_3 l_{CG} \cos\varphi_4 - 2a_4 l_{CG} \sin\varphi_4 = 0$$

The angle φ_4 is computed with Eq. (11).

$$\varphi_4 = 2arctg\frac{A_4 \pm \sqrt{A_4^2 + B_4^2 - C_4^2}}{B_4 - C_4} \tag{11}$$

where: $A_4 = -2a_4 l_{CG};\ B_4 = -2a_3 l_{CG};\ C_4 = a_3^2 + a_4^2 + l_{CG}^2 - l_{FG}^2$

3.2 Kinematic Computation of the Assur Structural Group CIH

Equation (12) is written to compute the joint I coordinates.

$$\begin{cases} x_I = x_H + l_{IH} \cdot \cos\varphi_7 = x_C + l_{IC} \cdot \cos\varphi_5 \\ y_I = y_H + l_{IH} \cdot \sin\varphi_7 = y_C + l_{IC} \cdot \sin\varphi_5 \end{cases} \tag{12}$$

We use the notations: $(x_H - x_C) = a_5$; $(y_H - y_C) = a_6$.

In order to compute the angle φ_7, the terms that contain the other unknown φ_5 are grouped. After squaring and summing Eq. (12), Eq. (13) is obtained.

$$a_5^2 + a_6^2 + l_{IH}^2 - l_{IC}^2 + 2a_5 l_{IH} \cos\varphi_7 + 2a_6 l_{IH} \sin\varphi_7 = 0 \tag{13}$$

Equation (13) is a trigonometric equation with variable coefficients, of the form (5).

The angle φ_7 is computed with Eq. (14).

$$\varphi_7 = 2arctg\frac{A_7 \pm \sqrt{A_7^2 + B_7^2 - C_7^2}}{B_7 - C_7} \tag{14}$$

where: $A_7 = 2a_6 l_{IH};\ B_7 = 2a_5 l_{IH};\ C_7 = a_5^2 + a_6^2 + l_{IH}^2 - l_{IC}^2.$

For computation of the angle φ_5 the terms that contain the other unknown are grouped. It results the trigonometric equation with variable coefficients:

$$a_5^2 + a_6^2 + l_{IC}^2 - l_{IH}^2 - 2a_5 l_{IC}\cos\varphi_5 - 2a_6 l_{IC}\sin\varphi_5 = 0$$

The angle φ_5 is computed with Eq. (15).

$$\varphi_5 = 2arctg\frac{A_5 \pm \sqrt{A_5^2 + B_5^2 - C_5^2}}{B_5 - C_5} \tag{15}$$

where: $A_5 = -2a_6 l_{IC};\ B_5 = -2a_5 l_{IC};\ C_5 = a_5^2 + a_6^2 - l_{IH}^2 + l_{IC}^2.$

4 Numerical Results of Exoskeleton Motion

A mechanical design and simulation of a proposed exoskeleton worn by a human is represented in Fig. 4. The structure has to be designed in order to allow adjustments of mechanism links in accordance with different human body constitution. A dynamic simulation has been developed by using a proper model for operation tests in ADAMS environment. Contact, stiffness, damping coefficients, and friction force coefficients have been defined accordingly. Dynamic model with proper joints and foot-ground contact is based on virtual 3D model. Computed exoskeleton walking sequences are represented in Fig. 11, and main kinematic results are shown in Figs. 8, 9, 10. From Figs. 8, 9, and 10 it can be remarked that appropriate values are obtained as compared with those from experimental tests and numerical kinematic analysis.

5 Conclusions

A new prototype of a motion assistance and rehabilitation exoskeleton for human is developed with low cost and easy-operation features. The exoskeleton purpose is to fully help or partially assist human walking and assure proper gait rehabilitation. The kinematics of the exoskeleton leg is similar with the human normal gait, although its

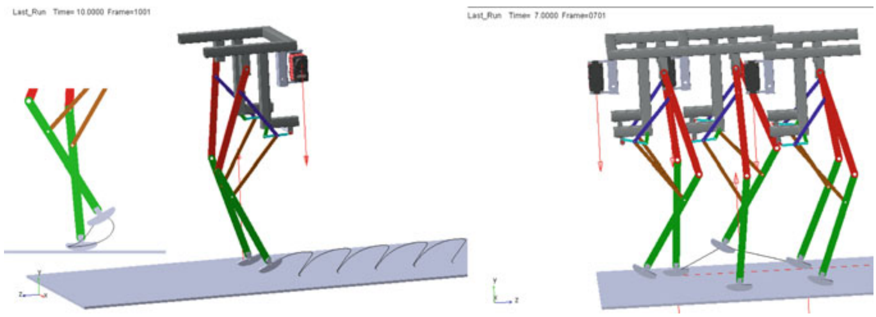


Fig. 11 Exoskeleton computed motion and walking frames

design may require additional improvements in future developments, such the foot shape optimization and ankle motion. The future development of the proposed solution should be successfully implementation as a motion assistance and rehabilitation exoskeleton.

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Influence of Hot-Dip Galvanizing on Mechanical Properties of Pressure-Locked Gratings

Paweł Krupicz

Abstract Pressure-locked gratings are made by pressing cross bars into tapered slotted bearing bars under high pressure. The end result is a grate with rectangular meshes. Grating design process is based on the assumption that the load is carried by the bearing bars. Grating as a final product is protected against corrosion, usually using hot-dip galvanization. Comparative observation of non-galvanized and hot-dip galvanized gratings shows that zinc not only forms a thin coating on the whole surface of bearing and cross bars, but also fills the voids located in the joints of the bearing and cross bars. Steel changes its properties due to high temperature in the hot-dip galvanization process. Additionally, during the technological process the material of a bearing bar is subject to plastic deformations. Therefore it can be assumed that the above mentioned changes affect the mechanical properties of the grating, especially its stiffness and strength. However, grating design process includes only strength characteristics of non-galvanized bearing bars, determined by steel grade. The aim of the paper is to investigate effect of hot-dip galvanizing on the mechanical properties of gratings and make the recommendations for their production. The paper compares the results of tensile tests of samples of non-galvanized bearing bars without heat treatment, non-galvanized bearing bars subjected to hot-dip galvanizing temperature and hot-dip galvanized bearing bars. The assembled samples of hot-dip galvanized steel gratings and non-galvanized steel gratings were subjected to a bending test. There was a significant increase in the stiffness of the hot-dip galvanized grating. Calculation coefficient was proposed to be included in the design stage of production process to incorporate increase of stiffness of galvanized grating caused by hot-dip galvanization. Guidelines are presented how include results of the work in the production management of galvanized steel products manufacturing.

Keywords Hot-dip galvanizing · Mechanical properties · Pressure-locked steel grating · Steel · Production management

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_43

1 Introduction

The paper describes results of testing of pressure-locked steel grating made of S235JR steel and recommendations for production management of this product. Pressure-locked grating is produced by pressing cross bars into tapered slotted bearing bars (Fig. 1). The end result is a grate with rectangular meshes.

Pressure-locked grating design process is based on the assumption that the load is carried by the bearing bars. The permissible stress and maximum deflection in bearing bar cannot be exceeded in any cross-section of the grating according EN1990 (2002), EN1993 (2005) or RAL-GZ 538: Gitterroste (2008). The construction design process involves the construction geometry, bearing bar characteristics, i.e. yield strength R_e and Young modulus E, as well as the construction safety coefficient (Sondej 2012). The value of yield strength for S235JR steel, included in the calculations, is specified in the EN 10027–1 (2016) standard and equals $R_e = 235$ MPa. The actual R_e value of a particular batch is defined by the steel manufacturer and specified in the mill certificate, which the procurer receives along with delivery. Its value is actually always higher than the one specified in the standard mentioned above. In the production process the bearing bar material is subject to repeated plastic strains during unreeling, re-reeling and straightening. As a result it undergoes a strain hardening. As a result, the yield strength rises (Maksymiuk et al. 2017).

The final stage of a technological process is applying an anti-corrosion protection by hot-dip galvanization. Due to the zinc's melting point (416 °C), the galvanization process is carried out at a temperature ca. 450 °C. Such high temperature changes the steel parameters (Skowroński et al. 2014; Chen and Young 2006). Hot-dip galvanizing process also changes the structure of the steel and changes parameters of the steel (Safaeirad et al. 2008; Kuang et al. 2017). The observation of hot-dip galvanized gratings shows that zinc not only forms a thin coating on the whole surface of bearing bars and cross bars, but also fills the voids located in the joints of the bearing and cross bars, changing the geometry of a bearing bar as a result. Therefore it can be assumed that the mechanical properties of the grating also change, especially its stiffness and maximum load (bearing capacity) in the range of elastic strains. It is

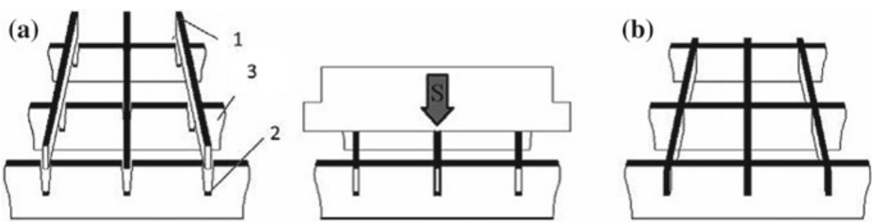


Fig. 1 Stages of pressure-locked grating assembly: **a** cross bars (1) before being pressed into slots (2) in bearing bars (3), **b** assembled grating (Krupicz et al. 2018)

reasonable to question whether there is a change in the R_e and E values in the technological process and how that change, along with the zinc's interaction with bars connection, affects the grating bearing capacity.

During mass production of the gratings the bearing and cross bars used in the process are not identified with a particular batch of the material. Therefore it is possible that bearing bars in a grating may have different characteristics of materials coming from various batches and different thickness in relation to catalogue values, albeit still within the acceptable tolerance of a steel sheet production.

The first aim of the work is to evaluate the yield strength of bearing bars randomly selected at the production hall. They were divided into 3 groups: black steel bars unmodified by the production process, bars heated at a temperature of 450 °C, and hot-dip galvanized bars. Additionally, a stiffness assessment of experimental grating, before and after hot-dip galvanization, was carried out.

The second aim of the work is to define recommendations for production management on the basis of the study results. It should be checked if the current management of materials used for the production and production process is effective in terms of production of pressure-locked gratings. They should have properties requested by costumer. There are many models for material selection and processes improvements (Jahan et al. 2010) for example economical models for raw material selection (Chen et al. 1993). However selection of the most suitable production procedure should depend not only on material properties but also on the product design procedures, which should consider also production method. In this case used design method do not take into the account production method. This can cause that product has better properties comparing to customer requirements.

2 Testing Methodology and Samples

Samples for tensile tests were prepared from the materials used during production of bearing bars. Testing samples weren't identified with a particular batch of the material. They were chosen randomly among various bars prepared for production. Yield strength of every sample was determined based on a static metal tensile tests in accordance with EN ISO 6892-1 (2016). Tensile test samples had a shape shown on Fig. 2.

Three types of samples were tested: (S)—raw samples, i.e. black steel samples unmodified by the production process, (T)—raw samples heated at a temperature of 450 °C for 15 min, (Z)—hot-dip galvanized samples. Nominal dimensions of a cross-section of the (S) and (T) samples at the measurement length were: A_0= 1.80 mm, B_0 = 15 mm. There were 3 pcs of (S) samples and 3 pcs of (T) samples tested.

The acceptable grating load can be modified in the design process by changing the height of the bearing bar while leaving the bar thickness unchanged. In order to determine whether the hot-dip galvanization has an impact on bearing bars differing in height, samples (Z) were tested with dimension A_0 = 1.80 mm and 3 different

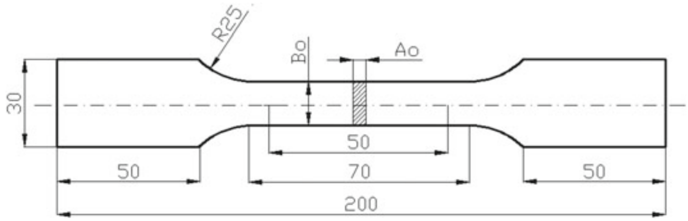


Fig. 2 Shape and dimensions of samples subject to tensile tests

values of B_0 dimension: 10, 15 and 20 mm. There were 9 pcs of (Z) samples tested: 3 samples for each values of B_0 dimension.

Tensile tests were carried out on durability testing machine MTS 322 with a sample deformation speed increment of $\varepsilon = 2 \times 10^{-3}$ 1/s. Change of length of the sample was measured using Epsilon Technology Corp extensometer 3542 with a measuring base of 50 mm. Based on the tensile tests data the following values were determined: yield strength R_e, tensile strength R_m and Young modulus E. The comparison of these values allows an analysis of differences of the material in batches and analysis of influence of the hot-dip galvanization process on material.

Bend tests were performed on experimental gratings as well. During the tests the stiffness of "raw" non-galvanized grating made of black steel (S) and hot-dip galvanized grating (Z) was compared. For that purpose 6 pcs of gratings with 33 × 33 mm mesh were assembled. They were made of 3 bearing bars with a nominal cross-section dimensions 1.9 × 35.0 mm (real dimensions 1.86 × 34.14 mm) and 6 cross bars with a nominal dimensions 1.9 × 8.0 mm (real dimensions 1.89 × 7.97 mm). Bearing bars had 10.0 mm deep slots for installation of cross bars. Three experimental gratings were hot-dip galvanized after the assembly.

The grating was treated as a bar made of three bearing bars, simply supported on a length of 210 mm and loaded with a point load at half of its length. Both types of gratings were subjected to bending tests with simultaneous recording of the force and the deflection of the cross-section at the point of application of the force. Three (S) gratings and two (Z) gratings were subjected to bending tests (the third (Z) grating did not pass the quality control - after the assembly and hot-dip galvanizing it was found out that the bearing bars were not parallel to each other). Bending tests were carried out on durability testing machine MTS 322 with a displacement speed of 0.02 mm/s. The value of the applied force and deflection of the grating were recorded .

3 Test Results and Analysis

3.1 Bearing Bar Samples Tensile Tests

The results of (S) bar samples tensile tests are shown on Fig. 3. The results of (T) bar samples tensile tests are shown on Fig. 4. The results of (Z) bar samples tensile tests are shown on Fig. 5.

The samples (S), (T) and Z1, Z2, Z3 had a dimension $B_{0\ nom} = 15$ mm, samples Z4, Z5, Z6: $B_{0\ nom} = 20$ mm, samples Z7, Z8, Z9: $B_{0\ nom} = 10$ mm.

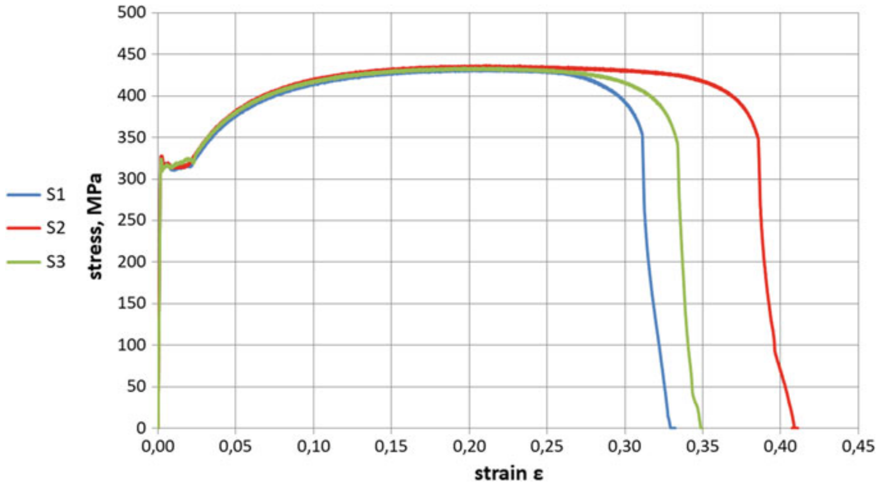


Fig. 3 Samples (S) tensile test graph ($B_{0\ nom} = 15$ mm)

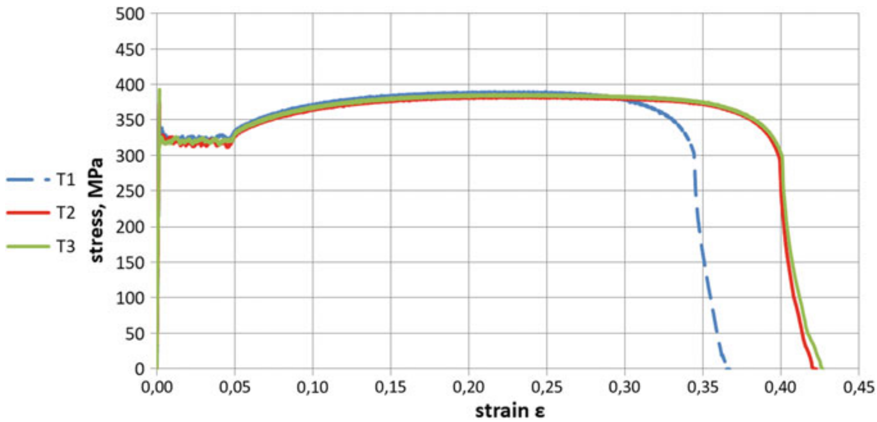


Fig. 4 Samples (T) tensile test graph ($B_{0\ nom} = 15$ mm)

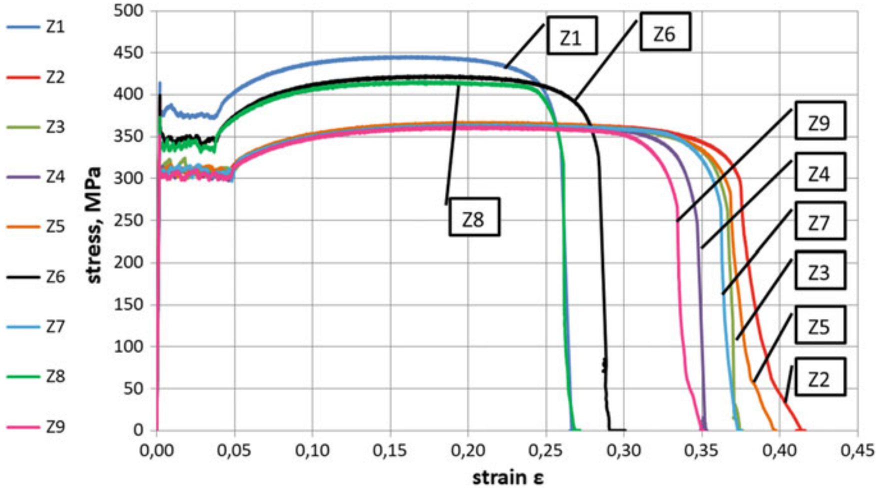
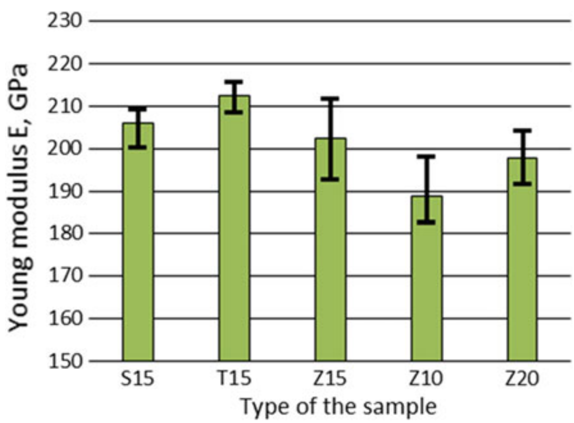


Fig. 5 Samples (Z) tensile test graph (samples Z1, Z2, Z3 $B_{0\ nom} = 15$ mm; samples Z4, Z5, Z6 $B_{0\ nom} = 20$ mm; samples Z7, Z8, Z9 $B_{0\ nom} = 10$ mm)

The analysis of tensile test graphs shows that for samples (S) (Fig. 3) and (T) (Fig. 4) tensile test graphs look the same for each of those groups. For samples (Z) three groups of results can be distinguished (Fig. 5). A clear indication of the influence of hot-dip galvanizing on samples depending on the height of the sample is not possible. It may be a result of overlapping of three factors: (1) the material of these samples could have had a different characteristics before galvanizing, (2) galvanizing temperatures, (3) different thickness of a zinc layer on the samples.

Figures 6, 7, and 8 show the values of Young modulus E, yield strength R_e and tensile strength R_m depending on type of material used as a sample. The drawings show average values of these quantities and their minimum and maximum values.

Fig. 6 Young modulus *E* depending on the sample type



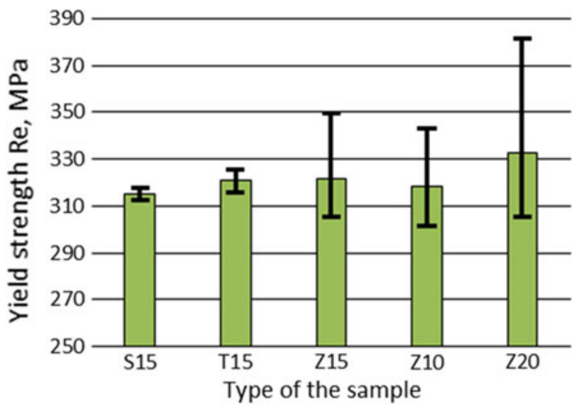


Fig. 7 Yield strength R_e depending on the sample type

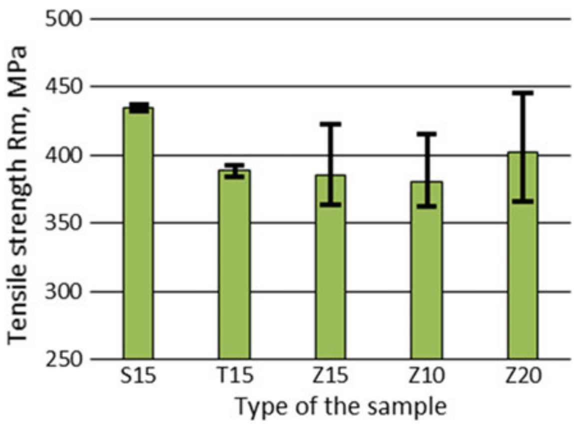


Fig. 8 Tensile strength R_m depending on sample type

The influence of galvanizing temperature and galvanizing process was evaluated by comparing test results of samples (Z) and (T) with test results of samples (S). Samples for all the tests were chosen randomly, therefore it is possible they come from different material batches.

The data shown on Fig. 6 indicate that the Young modulus of heated samples (T) is higher than Young modulus of raw samples (S). The heating process is brief (15 min), but conditions for recrystallization were created.

All the Young modulus values for galvanized samples (Z), taking into account the dispersion of the values, are similar to the *E* values of raw samples (S). It may be a result of overlapping of two opposite processes. The galvanizing temperature may increase the *E* value. The applied zinc layer may decrease the *E* value, because zinc, in comparison to steel, has lower values of Young modulus *E*. The influence of sample width is inconclusive.

Average values of yield strength *Re* (Fig. 7) have shown a slight increase in particular groups in comparison to raw samples (S). A rise of average yield strength

R_e along with increase of sample width was also observed. This may be connected with the bigger mass fraction of steel in the sample, which has a higher yield strength R_e in comparison with zinc. However, taking into account high discrepancies between the maximum and minimum R_e value in the galvanized samples, results of the tests indicate that the production process should not include a rise of yield strength in bearing bar material during the hot-dip galvanizing process. A similar conclusion is applicable to the tensile strength value R_m (Fig. 8). However, considering average values R_m it should be noted that the galvanizing process decreases said values in comparison to the raw material (S). The smallest decrease of R_m was observed in the widest samples, because steel has a higher value of tensile strength R_m in comparison to zinc.

3.2 Experimental Gratings Bend Tests

The results of bending tests are shown on Fig. 9. Relation between force and displacement during the bending of gratings (S) and gratings (Z) is presented. Bending tests show that tested (S) grating have very similar mechanical properties comparing to each other as well as (Z) gratings. This same force causes considerable bigger deflection of (S) grating comparing with hot-dip galvanized (Z) grating.

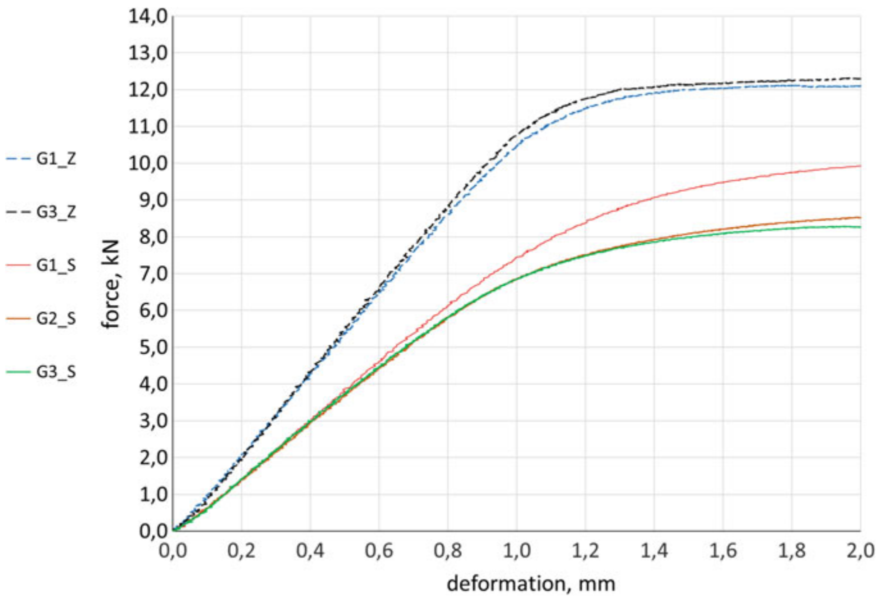


Fig. 9 Force-displacement relationship during bending of gratings (S) and gratings (Z)

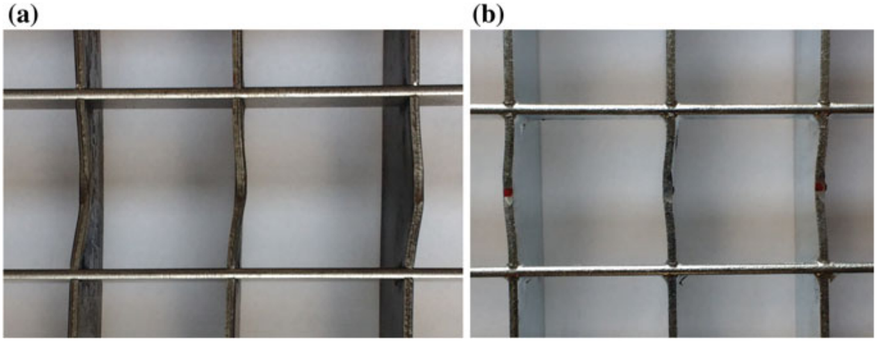


Fig. 10 A view of the buckled bearing bars: **a** grating (S), **b** grating (Z)

The destruction of the gratings occurred by buckling of the loaded bars at the length equal to the distance between cross bars. A fragment of the grating with buckled bars is shown on Fig. 10.

The analysis of the grating bending graphs shows that, in a certain extent of its deformations, the relation between a forced deflection of the grating and the force necessary to deflect it is linear. This also means that the stiffness of grating is defined as

$$k = \frac{P}{f} = tg\alpha = const. \tag{1}$$

The limit of the linear increase of the force in relation to the displacements determines the force which is maximum bearing capacity of the grating. The stiffness of the non-galvanized grating (S) and its bearing capacity is lower than the stiffness of the galvanized grating (Z). Maximum bearing capacity of tested grating is following: $k_{(S)} = 7.7$ kN/mm for (S) grating and $k_{(Z)} = 11.2$ kN/mm for (Z) grating. Stiffness of tested hot-dip galvanized grating (Z) is 45% higher than the stiffness of not galvanized grating (S).

Bend deflection of the beam in the direction of the force P at the mid-span of the distance between support points l, can be calculated using the equation:

$$f_t = \frac{1}{48} \cdot \frac{Pl^3}{EJ} \tag{2}$$

where J is moment of inertia and $J = bh^3/12$. Because there are 3 bearing bars in the grating, the bend deflection of the experimental grating equals

$$f_t = \frac{1}{12} \cdot \frac{Pl^3}{Ebh^3} \tag{3}$$

where: b—thickness of bearing bar, h—approximate bar height.

However, the question arises what height h should be taken to the calculation of the moment of inertia calculation J, due to the tapered slots in bearing bars, which are not fully filled with a cross bar. Therefore bar height h of tested gratings was determined, using the Eq. (3). It is possible, when the stiffness of the grating is known. Then

$$h = \sqrt[3]{\frac{P}{f}\frac{l^3}{12Eb}} = \sqrt[3]{k\frac{l^3}{12Eb}} \tag{4}$$

According Formula (4) bearing bar calculation height h was calculated for (S) grating $h_{(S)}$= 25.0 mm. This value is equal to height of the bearing bar (35 mm) reduced by depth of the slot for installation of cross bar (10 mm). In case of (Z) grating calculation height equals $h_{(Z)} = 28.4$ mm.

Bar calculation height h for the purpose of grating production process can be calculated using real bearing bar height H and reduction coefficient factor z. Formula is following

$$h = zH, \tag{5}$$

Calculated average values of z coefficient determining the height of a bearing bar is $z_{(S)} = 0.73$ for non-galvanized grating and $z_{(Z)} = 0.83$ for hot-dip galvanized grating.

3.3 Guidelines for Production Management of Galvanized Steel Products

The current production process of pressure-locked gratings does not identify the batch of raw material from which the material for the manufacturing of products is taken. In accordance with the current procedure of grating design, this is not important. Each batch of raw materials meets the minimum requirements for steel used in production (for S235JR steel $R_e = 235$ MPa). The conducted research indicates that the used materials have much better properties, i.e. the actual yield strength is much higher than stated in the standard. The yield strength of tested materials ranged from about 300 to 370 MPa (Fig. 7) depending on the batch of material and its processing. This is a value from about 30 to 60% higher than the value currently taken into account in the design. Therefore it possible to design products that meet the customer's requirements with less materials used.

The same effect, i.e. reduction of the amount of material used in the production of gratings can be achieved by using the information from Fig. 8. Strengthening the structure as a result of hot dip galvanizing enables the use of bearing flats with a lower height.

The following changes in the production process of pressure-locked gratings should therefore be considered on the basis of the results of the research presented in this article:

1. Investigation of the actual parameters of the raw material (metal sheet from a roll delivered from a steelworks) used in production/optionally values given in the metallurgical certificate of the batch of raw material can be used.
2. Maintaining a record of available raw materials and semi-products with information on their parameters specified in point 1.
3. Defining the design of a pressure-locked grating as a step in the production process of pressure-locked grating. The design should take into account the actual parameters of the available raw material, the possibility to design on the basis of the amount of available material and whether the grating will be hot-dip galvanized or there is any other process during production that may change its mechanical properties.
4. Introduce a labelling of semi-products for the production of gratings (i.e. steel strips) that identify them with the raw material (to determine the properties of the material).
5. Introduction of control over the use of appropriate materials in the production of gratings (semi-products indicated in the project/materials which meets the requirements set out in the project).
6. Random control tests of manufactured products confirming that the gratings meet the customer's requirements.

Introduction of the above mentioned changes in the production process will be possible under the condition that:

- test results will be replicated in subsequent experiments;
- preservation of higher parameters of products during their use will be confirmed;
- formal procedure for placing on the market products designed in accordance with the above procedure will be specified;
- it will be verified whether the above-mentioned procedure reduces the costs of grating production (comparison of savings related to reduced raw material consumption with additional costs of production organization and product formal approval should be done).

4 Conclusions

The conclusions from the performed tests are as follows:

- the Young modulus E of the samples heated at the galvanizing temperature (T) is higher than the modulus of the raw samples (S); the heating process is brief (15 min), but conditions for the structure recrystallization were created;

- the Young modulus E values for galvanized samples (Z), taking into account their maximum and minimum values, are similar to the values of black steel samples (S);
- the average value of yield strength R_e (Fig. 6) is bigger in the (T) and (Z) samples comparing with (S) samples; a rise of R_e average values along with increase of sample width was also observed;
- the increase of yield strength R_e of bearing flat bars material, which occurs during the hot dip galvanizing process, should not be included in the design for the grating production process, as long as the mill certificates are not taken for the design and production processes; a similar conclusion is applicable to the tensile strength value R_m;
- the measured values of R_e in case of all samples are much higher (>20%) than the minimum R_e value specified in standard PN-EN 10027-1 (2016) (235 MPa);
- analysis of average R_m values shows that the hot-dip galvanizing process lowers the R_m values in (Z) material in comparison to (S) material; the smallest decrease of R_m was observed in the widest samples, because steel has a higher value of tensile strength R_m in comparison to zinc;
- stiffness of tested hot-dip galvanized grating (Z) is 45% higher than the stiffness of not galvanized grating (S);
- reduction coefficient factor z is proposed to be used for the calculations of gratings, calculated average values of z coefficient determining the height of a bearing bar for the calculations are: $z_{(S)} = 0.73$ for tested non-galvanized gratings and $z_{(Z)} = 0.83$ for tested hot-dip galvanized gratings;
- the results of the research indicate that it is possible to obtain products with the parameters required by the customer using less raw materials; for this purpose, however, it is necessary to add additional steps in the production process of pressure-locked gratings and to identify in detail the batches of raw material at each stage of production; the introduction of these changes requires both further material testing and analysis of the cost-effectiveness of the above mentioned changes in production.

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Lean Industry 4.0—Wastes Versus Technology Framework

Krzysztof Ejsmont and Bartłomiej Gładysz

Abstract Both lean management and Industry 4.0 are obviously important in practices of modern manufacturing companies. Lean management a is well-known and deeply researched approach while Industry 4.0 is also well recognized, but still relatively new with a big part of the theory and practice to be developed, validated, verified and applied. However, Industry 4.0 gains more and more interest of both researchers and practitioners and is very important for manufacturing and other industries. The main goal of this paper is to analyze synergies, or deficits, of lean management and Industry 4.0. For this purpose, a lean framework for waste typology was combined with the Industry 4.0 potential to decrease those wastes. It was also analyzed if some properties of Industry 4.0 may lead to increase in some types of waste. Each type of waste was analyzed to consider its possible decrease and increase through the application of Industry 4.0 grounding of field practice and literature analysis.

Keywords Industry 4.0 · Lean management · Lean manufacturing · Waste

1 Introduction

Industry 4.0 refers to a series of changes in the way that products and services are manufactured. Grounding on the systematic use of the Internet of Things, Augmented Reality and other technologies, revolutionary change is observed in production relations between the employer and the employee. This is a significant challenge for managers.

Industry 4.0 enables fast collection, analysis, and communications of big sets of data between machines. This forms an enabler for faster and more flexible response to existing problems, as well as for more efficient processes to produce high quality products at a decreased cost. All these elements will consistently lead to the increase

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_44

in production efficiency and then changes in the labor force profile and required skills.

The basis of lean management (LM) is the elimination of wastes, while taking into account the role of the employee in creating the value of products and services provided.

A global survey conducted by The Boston Consulting Group (Küpper et al. 2016) has shown that leading industrial companies recognize the importance of both lean management and digitization in their long-term planning. In a survey conducted among more than 750 production managers, 97% of respondents in the automotive industry stated that lean management would be of great importance in 2030, compared with 70% who said that it is important today. Of these respondents, 70% said that digitization of the factory would be very important in 2030, compared with 13% who claimed that it is important today.

Although the need to implement both Lean Management and Industry 4.0 is clear to many managers, they are not sure how to combine these two elements to achieve their convergence and avoid contradictions. BCG experts indicate that companies must think about Lean Industry 4.0 in terms of individual cases of practical use—the optimal combination of lean tools and digital technologies. Then, they must carefully choose from case to case, which individual practices should be applied for addressing key problems.

By using integrated Lean Industry 4.0 solutions to eliminate production problems, factories can achieve a number of benefits. The research problem formulated in this article is to examine the possibilities of Lean Management and Industry 4.0 integration in the context of elimination of wastes. The efforts were aimed at finding evidence from literature and systemizing knowledge on how Industry 4.0 technologies can support lean initiatives in the context of the set of wastes and selected lean methods, concepts, techniques. The proposed framework consists of Industry 4.0 support for the: (1) elimination of specific wastes and (2) application of selected lean tools.

2 Literature Review

The systematic literature review strategy proposed by Levy and Ellis (2006) i.e., choose, know, understand, apply, examine, combine and evaluate, was adopted. In this paper, studies related to lean management and lean manufacturing combined with Industry 4.0, as shown in Fig. 1, were reviewed.

The IEEE/IEE Electronic Library, Scopus, Web of Science Core Collection databases were chosen for the review. The initial searching query was 'Lean Industry 4.0'.

In the databases, after entering the indicated query, the following number of publications appears: IEEE/IEE—13, Scopus—144, WoS—93. Authors included documents that discussed relations between LM and Industry 4.0. Particular attention has been paid to publications regarding the issue of LM wastes and the possibilities

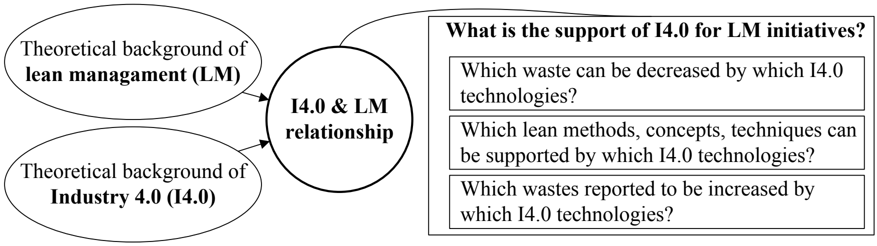

Fig. 1 Framework of the study

of their reduction using Industry 4.0 tools. LM techniques have also been identified in specified articles, which can be helpful in supporting Industry 4.0 applications. Authors excluded documents that were not in English, papers in abstracts which did not appear at the same time words 'Lean' and 'Industry 4.0' or authors have not identified any binding relation between them. Papers dated 2011–2019 were investigated. Authors also reviewed reference lists of found articles for important references missed in the database search. 74 relevant works (journals or proceedings) were selected after screening abstracts of found papers. Then, 9 articles were removed which did not have the full version in the searched databases (only abstracts). A full list of identified publications is available from the authors.

From the selected publications, 31 articles discuss LM wastes related to Industry 4.0. The majority of publications were dominated by a qualitative approach, which only described the potential possibilities of using Industry 4.0 to reduce the 8 main wastes of LM. Only in a few publications, quantitative LM wastes reduction values were identified because of the Industry 4.0 solutions. It is worth emphasizing that none of the publications describe a situation in which the Industry 4.0 application causes an increase in any of the 8 LM wastes.

In addition, 17 publications describe how selected LM techniques can support the application of Industry 4.0 tools. Usually it is a general qualitative description explaining how a given technique can contribute to a more effective functioning of the Industry 4.0. A few publications have been case studies which very precisely presented how the selected LM technique can support Industry 4.0.

2.1 8W-I4.0 (8 Wastes—Industry 4.0) Framework

2.1.1 8 Wastes and Industry 4.0 Technologies

In this section the set of lean wastes was confronted with the potential of I4.0 to decrease in specific waste. Papers found in the query were analyzed and the evidence of I4.0 support for LM in the literature was discussed.

In many publications, it was possible to reduce transport losses because of the Industry 4.0 concept. This kind of losses was considered mainly in terms of internal logistics. Examples of the reduction of losses related to transport using Industry 4.0 are autonomous transport robot including automated small parts storage and order picking and use of internal ICT in conjunction with AGV (Automatic Guided Vehicle) to transport spare parts in stock for production lines and transport objects within the material flow automatically. Despite many publications regarding transport losses related to Industry 4.0, only in one of them can be found a quantitative value concerning the reduction of this factor (Satoglu et al. 2018a, b). The use of tablets made it possible to interact with employees within the transport system. This allowed for more efficient delivery of materials and shortening of the paths (by about 25%), with the same level of supplier reliability.

In many publications, the issue of losses related to inventory in the context of the use of Industry 4.0 was described. Most often mentioned are the following solutions that can reduce inventory: CPS, 3D printing, IoT, Data Analytics, RFID, ICT, simulation, optical order system, iBin (advanced Kanban), autonomous robotic carrier, new data acquisition technology and Big Data analysis, Kanban 4.0, AGVs, Drones and 3D Printing Levers, Digital Warehouse Operations Lever, various sensors and smart bins/boxes, smart sensors. In one publication (Lugert et al. 2018), which was a comprehensive review of the literature on wastes in LM related to Industry 4.0, it was stated that inventory could be improved by 70.2% thanks to the use of appropriate Industry 4.0 tools.

Losses related to unnecessary motion were considered only in terms of the shop floor. The publications indicate how Industry 4.0 can help reduce this type of loss. The main activities in this area are: application of the Indoorway InSites 4.0 platform for multidimensional motion analysis (Wielki and Kozioł 2019), new HMIs & Wearable Computing Levers (Romero et al. 2018), Adaptive Robotics, Augmented Reality, Cloud Computing, IoT. Two publications provided quantitative values for reducing losses caused by unnecessary motion. The first publication (Powell et al. 2018) deals with the issue of "Smart Tool Management", and the authors are of the opinion that this concept will reduce the tool-inventory by at least 30% and will have a positive impact on the cost of tooling. In the second publication (Axelsson et al. 2018), it was found that with the use of Industry 4.0 tools it will be possible to reduce fuel consumption by 30% due to the elimination of unnecessary movements of the machine.

Losses caused by too long waiting times in the context of the use of Industry 4.0 were discussed in several publications. The main area of research was production, although in 2 publications medicine was considered (Camgoz-Akdağ et al. 2018; Ilangakoon et al. 2018). It was stated in them that the use of Industry 4.0 technologies would improve the performance of the healthcare system and decreased waiting times. In production area, there are also ways to reduce losses due to waiting: simulation and virtualization, adaptive robotics, Data Analytics, Cyber-Physical Systems Lever. Only in one publication (Wang et al. 2016) is the numerical value of the reduction of waiting time. Thanks to the use of VSM, it has become possible to reduce the manufacturing lead time from 108.14 to 9.94 days.

Several authors reported convergence of I4.0 technologies and eliminating overproduction. This was discussed showing that transparency of the processes is improved through data analytics enhancing forecasts quality and real time identification/location of objects enabled by I4.0 technologies such as e.g. RFID.

Data analytics along with simulation and virtualization were seen as enabler for decrease of overprocessing. However, overprocessing was directly addressed only in two papers. This seems to be awkward, as overprocessing might be treated as the waste leading to all the other types of wastes.

The possible decrease in the number of defects effecting from implementation of I4.0 technologies was widely discussed by several authors. However, there were no detailed case studies presented, nor concrete numbers reported, nor simulation models presented. It was reported that I4.0 technologies should lead to decrease in defects by better transparency, process and quality control.

Skills were mainly discussed in the context of the change and requirements to enable I4.0 implementation. However, six papers addressed directly elimination of incorrectly used skills of workers. It was assumed that using I4.0 technologies would lead to the better use of trained staff by moving them from sit-to-site problem to troubleshooting. It was indicated that automation of simple tasks enabled with I4.0 concept implies a decrease in skills waste.

Table 1 presents the 8 main wastes of LM along with publications that describe how the Industry 4.0 application can reduce them. Most publications present the possibility of reducing losses related to inventory (16) and transportation (15). The least number of publications concerned losses related to overprocessing (2), overproduction (5) and waiting (5). In the exemplary reference, mostly we can find publications which give only a very general description of how Industry 4.0 may be useful in the reduction of types of wastes. The articles are dominated by qualitative descriptions, that are mostly based on the belief in the opportunities and benefits of Industry 4.0 and not verified by empirical research or case studies.

2.1.2 Lean Tools (Methods, Concepts, Techniques) and Industry 4.0 Technologies

Table 2 presents LM techniques, methods and concepts that were identified in the analyzed publications. Papers that formed a basis for Table 2 are only those which were discussing lean wastes (see Table 1). They were combined with Industry 4.0 solutions, which may be support in their application. The greatest possibilities of using Industry 4.0 technologies (18) give them application in Kanban, pull signals, Just in Time and Just in Sequence techniques. However, there are LM techniques that can use only a few Industry 4.0 tools, e.g. 5S (1), Cellular Manufacturing (2), Continuous flow (2), Andon (3). It seems that the possibilities of using Industry 4.0 solutions in the support of LM techniques depend on the degree of their complexity and the possibility of using them in enterprises. The more areas of a company a particular LM technique covers, the more Industry 4.0 tools can support them. The most frequently mentioned solutions of Industry 4.0 that could support LM techniques were: Sensors and Actuators (7), Data Analytics (6) and Automated identification/location (5). However, many Industry 4.0 solutions were assigned to support only one LM

Table 1 Lean waste decrease supported by Industry 4.0 solutions

Waste	References	No. of papers
Transportation	Blöchl and Schneider (2016), Doh et al. (2016), Dombrowski et al. (2017), Duarte and Cruz-Machado (2018), Edirisuriya et al. (2018), Jayaram (2016), Kolberg and Zühlke (2015), Lugert et al. (2018), Mayr et al. (2018), Romero et al. (2018), Ruiz Zúñiga et al. (2017), Ruppert et al. (2018), Sanders et al. (2016), Satoglu et al. (2018a, b), Wielki and Kozioł (2019)	15
Inventory	Blöchl and Schneider (2016), Blöchl et al. (2017), Buer et al. (2018), Doh et al. (2016), Edirisuriya et al. (2018), Kolberg and Zühlke (2015), Kolberg et al. (2017), Lugert et al. (2018), Mayr et al. (2018), Romero et al. (2018), Ruiz Zúñiga et al. (2017), Ruppert et al. (2018), Sanders et al. (2016), Satoglu et al. (2018a, b), Wang et al. (2016), Yin et al. (2018)	16
Motion	Ahmad et al. (2018), Axelsson et al. (2018), Powell et al. (2018), Romero et al. (2018), Satoglu et al. (2018a, b), Wielki and Kozioł (2019)	6
Waiting	Camgoz-Akdağ et al. (2018), Ilangakoon et al. (2018), Romero et al. (2018), Sanders et al. (2016), Satoglu et al. (2018a, b)	5
Overproduction	Ilangakoon et al. (2018), Mayr et al. (2018), Powell et al. (2018), Romero et al. (2018), Satoglu et al. (2018a, b)	5
Overprocessing	Ilangakoon et al. (2018), Satoglu et al. (2018a, b)	2
Defects	Brusa (2018), Buer et al. (2018), Ma et al. (2017), Mayr et al. (2018), Powell et al. (2018), Romero et al. (2018), Sanders et al. (2016), (Satoglu et al. (2018a, b), Slim et al. (2018)	9
Skills	Buer et al. (2018), Edirisuriya et al. (2018), Ilangakoon et al. (2018), Mora et al. (2017), Powell et al. (2018), Romero et al. (2018)	6

technique. The total number of identified Industry 4.0 solutions that may support LM techniques, methods and concepts was 38.

3 Discussion and Conclusion

After analyzing the available literature on the issue of Lean Industry 4.0, we can see that there is an increasing interest of scientists in this subject. In recent years, the number of publications in this area has been systematically increasing. Despite the growing interest of scientists in the subject considered in the article, there is a research gap regarding the use of Industry 4.0 solutions in the context of the support for wastes elimination. The article structures issues related to this area and indicates

Table 2 Industry 4.0 potential support for LM

Techniques, methods, concepts	Industry 4.0 potential support	References
5S	Virtual and Augmented Reality (V&AR)	Wagner et al. (2017)
Kanban/pull signals/Just in Time/Just in Sequence	Sensors/Actuators (S&A), Automated identification/locating/inventory of WIP/goods/assets etc. (RFID, RTLS, etc.), Smart reallocation of order, Material replenishment monitoring, 3D Printing, Real-time data, Digitalization, Product controls environment, Cloud Computing, Big Data, Data Analytics, M2M Communication, V&AR, SOA, Subcontracting, Decentralized decision making	Ahmad et al. (2018), Davies et al. (2017), Enke et al. (2018), Kolberg et al. (2017), Lugert et al. (2018), Mayr et al. (2018), Mrugalska and Wyrwicka (2017), Romero et al. (2018), Sanders et al. (2016), Satoglu et al. (2018a, b), Wagner et al. (2017), Wang et al. (2016)
TPM	S&A, Data Analytics, V&AR, Machine-worker communication, Condition-based maintenance, Self-maintenance assessment, Predictive maintenance, Digitalization	Davies et al. (2017), Enke et al. (2018), Sanders et al. (2016), Satoglu et al. (2018a, b)
Andon	S&A, CPS, Wearables	Mayr et al. (2018), Mrugalska and Wyrwicka (2017)
VSM	IoT, Digitalization, V&AR, 3D Printing, Automated identification/location, Semantic Technologies, Pint-sized automation equipment, S&A	Ahmad et al. (2018), Camgoz-Akdağ et al. (2018), Davies et al. (2017), Enke et al. (2018), Lugert et al. (2018), Mayr et al. (2018), Mrugalska and Wyrwicka (2017), Wang et al. (2016)
Jidoka	IoT, S&A, CPS, Cloud Computing, SOA, Agent, Semantic Technologies, Big Data, Data Analytics, M2M Communication	Buer et al. (2018), Lugert et al. (2018), Ma et al. (2017), Satoglu et al. (2018a, b), Slim et al. (2018), Wagner et al. (2017)

(continued)

Table 2 (continued)

Techniques, methods, concepts	Industry 4.0 potential support	References
Supplier Feedback/Development	IoT, Data Analytics, Collaborative manufacturing, Better communication mechanisms, Synchronization of data, Standardized interfaces, Virtual organizations—synergetic cooperation	Sanders et al. (2016), Satoglu et al. (2018a, b)
Quality Control and Process Control	S&A, Data Analytics, Pattern Recognition, Workpiece-machine communication, Improved man–machine interface, Automated identification/location, Integration & management, Digitalization, Digital business models, Product controls environment	Enke et al. (2018), Mayr et al. (2018), Sanders et al. (2016), Satoglu et al. (2018a, b)
Setup Reduction	S&A, Automated identification/location, Self-optimization and machine learning, Workpiece-machine communication	Sanders et al. (2016), Satoglu et al. (2018a, b)
Cellular Manufacturing	Adaptive robotics, Data Analytics	Satoglu et al. (2018a, b)
Continuous flow	Automated identification/location, M2M communication	Mayr et al. (2018), Powell et al. (2018), Sanders et al. (2016)

which I4.0 solutions can be useful to the support LM tools. The article can also serve as a kind of a signpost for researchers and practitioners dealing with the reduction of LM wastes using I4.0 solutions. Thanks to the publication, it will be very easy to get to the papers related to particular types of LM wastes and support to select the LM techniques in the context of using I4.0. It should be emphasized that in the literature there is no comprehensive study regarding the subject of wastes reduction and LM support by Industry 4.0. Most publications in this area are proceedings, not journals.

There are also some limitations in the available articles. Most papers address only initial considerations regarding the possibility of reducing LM wastes with the help of Industry 4.0 or LM techniques that are supported by Industry 4.0 solutions. The descriptive approach dominates, and the presented possibilities of LM and Industry 4.0 integration in the areas of wastes reduction or support for their cooperation are at a very general level. There is a lack of empirical researches and case studies, confirming the statements presented in analyzed papers. There were not found simulation models, which might be of a great value for practitioners planning and implementing the concept of Industry 4.0. There was only one paper that approaches the set of wastes systematically (Satoglu et al. 2018a, b). However, it is limited and is based on a descriptive approach with no details. It also lacks the eight waste, which is skills. This is a strong limitation, because skills are very important for Industry 4.0 and human factor was included in the set of lean wastes long ago. The article also indicates which wastes have not been described in detail and verified by the I4.0 solutions. The publication also allows us to see which LM techniques can be supported by I4.0 solutions and which techniques the use of I4.0 has not yet been widely considered.

Further research should aim at practical verification of the possibilities of LM and Industry 4.0 integration in order to reduce wastes. It will be very important to present the research results in a quantitative (measurable) form, so that their interpretation is objective and it can be unambiguously determined whether LM and Industry 4.0 are complementary or not.

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Application of Reliability Engineering in a Chemical Plant to Improve Productivity

Vuyo Terrence Hashe and Makgomo Thelma Mamatlepa

Abstract This paper is based on reliability case study conducted in a chemical company (Company X) based in Germiston South Africa. The work conducted focused on the causes of production loss due to poor equipment reliability that lead to downtimes. In the chemical, the production team generates works orders through an autonomous maintenance exercise which is aimed at identifying potential equipment defaults before they cause a breakdown. The works orders are categorized under corrective maintenance schedule. There are also time based preventative maintenance works orders that are created on System Application Program (SAP) for critical equipment and their components. More often, the response time from the maintenance team is slower and leads to subsequent breakdowns and production stoppages. The financial documents of the chemical plant showed that on average the plant spends $31,000 per month on maintenance cost. Projections indicate that this could easily amount to more than $376,000 per annum provided that there is no mid-term to long-term intervention to address equipment failures. The main objective of this study is to investigate the causes of reoccurring system failures using the reliability concepts and provide a solution specific to Company X which could be expanded to other companies and industries. This study followed both a qualitative and descriptive case study research approach. Data collection was carried out by attending to equipment breakdowns, observations during the normal daily operations, during production times, studying the historical available maintenance and technical relevant data, staff interviews, company internal information regarding the financial spending for the year of study. Finding indicated that the plant maintenance programmes were inadequate and needed to be revitalised by the introduction and implementation of reliability centred maintenance (RCM) process. The RCM process was suggested to address the issue of identifying key priority equipment responsible for major downtimes and analysing the failure modes so to suggest corrective actions before failure occurs.

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_45

Keywords Downtime · Maintainability · Reliability

1 Background

As early as the 1940s, atmospheric pollution became a problem in most cities in the United States. This was as a result of mass production of cars powered by the internal combustion of engines, which were generating large quantities of man-made urban pollution. This forced the US government in the 1970s to revise the Clean Air Amendment Act which required emissions from car exhausts to be reduced by 90%. The amendment of this act prompted the need for specified technologies to eliminate pollution from cars.

In the early 1970s, Company X successfully developed and demonstrated the positive benefits of platinum containing catalysts to clean up car exhaust emissions. Today, Company X is a leading global supplier of catalytic converters, with manufacturing plants in several regions across the globe as depicted on the geographical illustration in Fig. 1.

In order for Company X to adapt to new and changing markets, the plant has setup stringent key performance indicators (KPIs). Amongst these KPIs, the most important one is to achieve a lead-time target of 6 days in the chemical salts section

Fig. 1 Global presence of Company X

of the plant. This target forces the production team to increase performance for increased significant value for the business. Although KPIs have been revised, the plant's performance in comparison to the revised KPI is still far off from the target. This mainly due to consistent equipment failures and breakdowns in the plant.

2 Methodology and Data Collection

A case study approach is used where the researcher is interested in acquiring insight and understanding of why a certain instance happened the way it did (Noor 2008). Biggam (2008) highlighted that case studies observe characteristics of an individual unit of interest. For this research, this method helped to understand the contributing factors to downtime in the chemical plant, how equipment failure affects plant performance and also availability of critical equipment in the plant.

Tomo (2010) asserts that critical components such as valves, gauges, agitators etc. in a production plant can affect individual operations and the entire process negatively if not reliable. The downtimes associated with such failures can results in losses of production value and escalate the maintenance costs if not addressed timely. Figure 2 presents the average batch lead times per month that were achieved. This data shows an inconsistent performance failing to meet the lead-time target of six days.

Based on the historical performance, equipment and machinery breakdowns play a significant role on failure of the plant to achieve budgeted lead-time target due to uncontrolled failures during the process. Production plant maintenance can be costly if low reliable equipment is in operation (Tomo 2010; Barringer 2004). Unexpected failures occur without a warning and production is constantly interrupted. Production

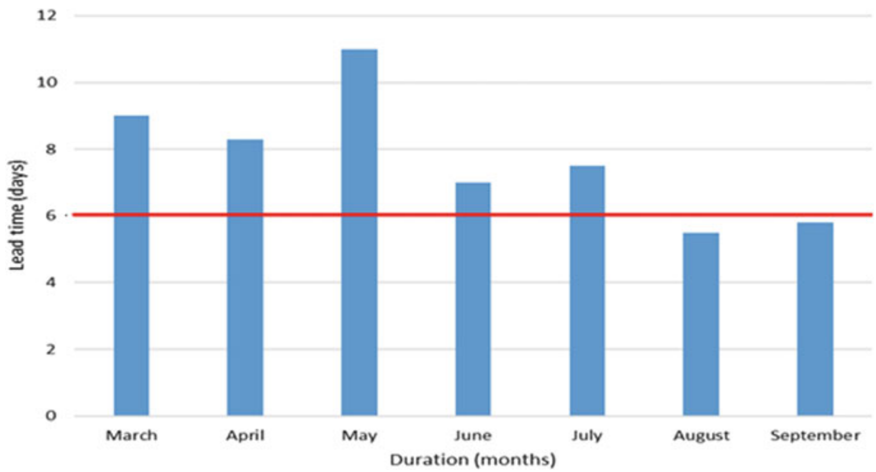

Fig. 2 Average lead-time for platinum batches

interruptions lead to longer processing times, this comes with financial ramifications due to the contractual obligations. Moreover, equipment used in the chemical plant is specialized and external contractors (Original equipment manufacturers, OEMs) service some components. The repair or replacement process during breakdowns comes at a costly price. The financial documents of the chemical plant show that on average the plant spends $34,000 per month on maintenance cost and projections show that this could easily amount to more than $408,000 per annum provided that there is no mid-term to long-term intervention to address equipment failures.

The chemical plant has various processes and in one of the processes called the Salts Process, the production team generates works orders through an autonomous maintenance exercise which is aimed at identifying potential equipment defaults before they cause a breakdown. The works orders are categorized under corrective maintenance schedule. There are also time based preventative maintenance works orders that are created on SAP (System Application Program) for critical equipment and their components. More often, the response time from the maintenance team is slower and leads to subsequent breakdowns and production stoppages. The number of work orders varied over month end due to shortage of spares, staff shortage and more urgent equipment breakdowns amongst other factors. Figure 3 shows sluggish completion of works order from the first 3 month with an improvement during the last four months. However, in August and September an increase is noted. Ultimately, this has a negative effect on equipment availability because these preventative and corrective maintenance work orders are intended to proactively maintain equipment before they fail and improve availability of critical equipment.

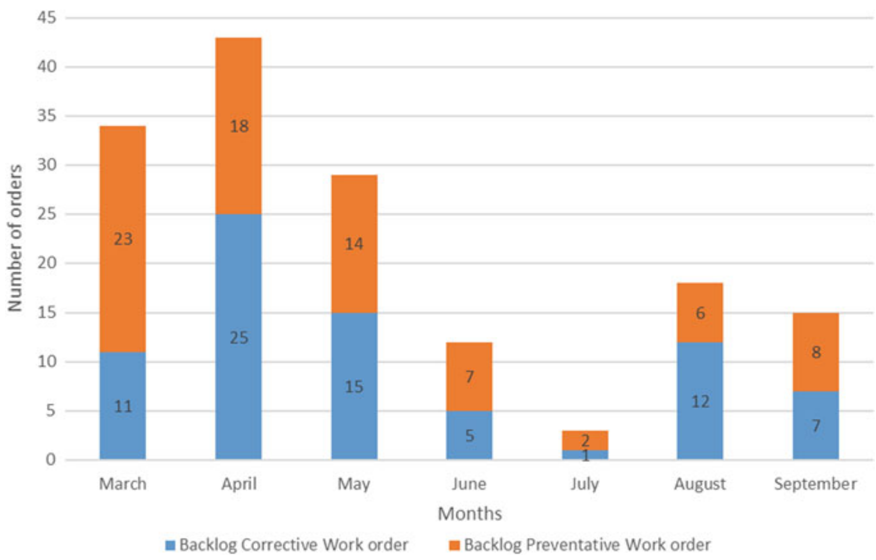

Fig. 3 Preventative and corrective maintenance orders backlog

Cowing et al. (2004) concluded that product reliability is no longer regarded a luxury product attribute but has become a selling point that is crucial for business to acquire new customers and keep existing customers. Tomo (2010) highlighted the importance of doing more with less by pointing out that the practice of cutting down on maintenance may results in catastrophic failures that come at high repair costs. In his explanation, to better define or identify these failures, one has to look at the repair cost and the consequent loss in production.

Data was collected from daily plant activities whereby every process delay was recorded with total duration of the delay or downtime. Production personnel are responsible to record this information as required by the process works instructions. The platinum process is the longest in the chemical plant that makes it more prone to delays due to the numbers of complex stages and equipment that the product passes through.

The collected data was consolidated to determine the factors causing the plant downtimes. The collected data was recorded in a spreadsheet which indicated the each process standard time built-in, therefore every excessive time was quantified and cause of delay was recorded. A reliability engineering analysis method, Pareto was used to graphically present the data and identify problematic areas affecting downtime in the chemical plant. Pareto is known as the 80/20 rule, whereby the focus according to the distribution will be on key elements that offer the largest financial gain. In essence, 10–20% of items on the Pareto distribution will account for 70–80% of the finical impact (Barringer and Monroe 1996).

2.1 Chemical Plant Layout

The chemical plant is presented in Fig. 4 where the process starts with 3 reactors in connected in parallel. R1 (V1001), R2 (V1002) and R3 (V2002) are all process initiating reactors, arranged as a parallel system and availability of each of the reactors is independent of the other. Failure in one of the reactors does not affect the whole system but flexibility of the plant. R4 (V2005), R5 (PTMF), R6 (V2010) and R7 (V2013) are intermediate processing reactors in series, whereby each one of them

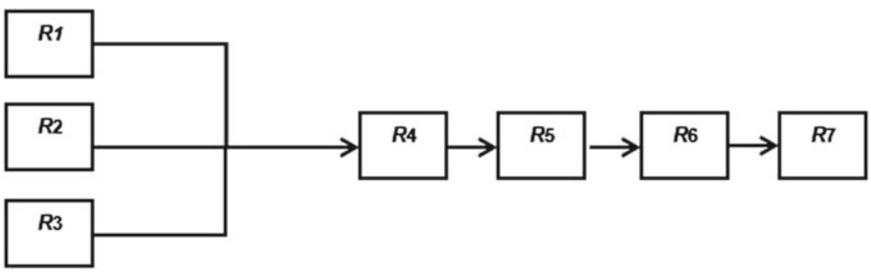

Fig. 4 Plant layout—critical section

performs a different function. From the reliability point of view, the process may be considered as serial system from R4 (V2005) up to R7 (V2013), meaning that failure of any machine or sub-system causes the entire system to halt.

According to Blanchard and Fabrycky (1998) reliability and availability of a system presented in Fig. 4 is given by Eqs. 1 and 2 respectively.

$$Reliability = R1 + R2 + R3 - (R1)(R2)(R3) \tag{1}$$

$$\text{Availability} = \text{Mean time before failure}/(\text{Mean time before failure} + \text{Mean time to repair}) \tag{2}$$

Mean time before failure (MTBF) and mean time to repair (MTTR) are given by Eqs. 3 and 4 respectively.

$$MTBF = \frac{1}{\lambda} \quad where\, \lambda\, is\, the\, rate\, of\, failure \tag{3}$$

$$\text{MTTR} = \text{Total maintenance time}/\text{number of repairs} \tag{4}$$

$$Downtimw = minutes\ per\ year * (1 - availability)\, minutes/year \tag{5}$$

2.2 Plant Downtime

Figure 5 presents the breakdown of downtimes from March to September, where every month equipment downtime is consistently higher followed by process downtime. The month of May was an exception, with most of the downtime attributed to production planning. It can be observed from Fig. 5 that equipment downtime is consistently higher followed by process downtime. A similar study by Tomo (2010)

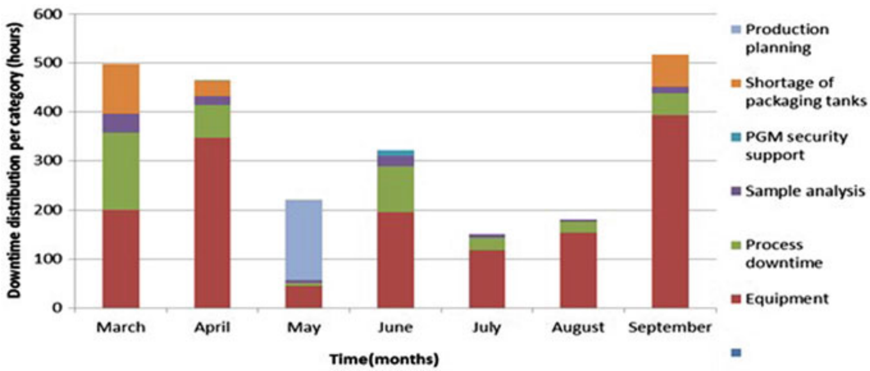

Fig. 5 Overall Downtime per Month

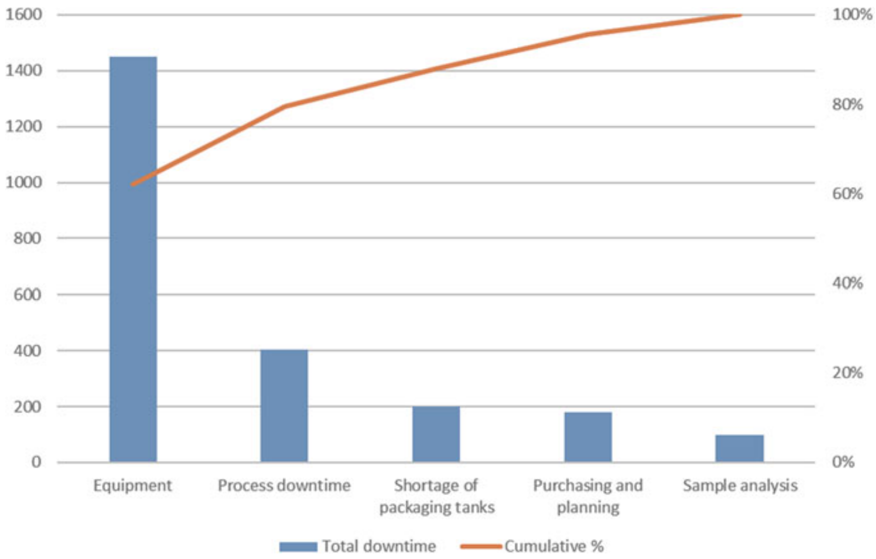

Fig. 6 Pareto Analysis of Downtime Categories

at Sasol Chemical plant concluded that not only equipment failures caused the major downtimes but factors such as raw material shortage, utility outage, planned shut-down, process control and product quality also contributed to production downtime or loss.

According to Bauer et al. (2009) downtime as a reliability index that is mainly associated with unavailability of a system and is given by Eq. 5. Equation 1 was used after identifying the key components in the chemical plant and the results are presented by Pareto Analysis chart in Fig. 6. From the Pareto analysis, it is evident that majority of the downtime that requires immediate attention is caused by equipment breakdowns and process downtime. The application of Pareto analysis is an effective tool to use to identify factors cause failure and downtime in a plant environment (Okorie and Osarenmwinda 2013).

3 Data Analysis

The total equipment downtime was further broken down into individual unit to identify sections of the plant that are problematic. Figure 7 presents the critical equipment that contributed to downtime in the plant during the period of March to September. Two reactors, V2005 (R4) and V2002 (R3) connected series as presented in Fig. 3, Pt membrane filter leads the chart followed by mechanical seals and utilities, in order of severity.

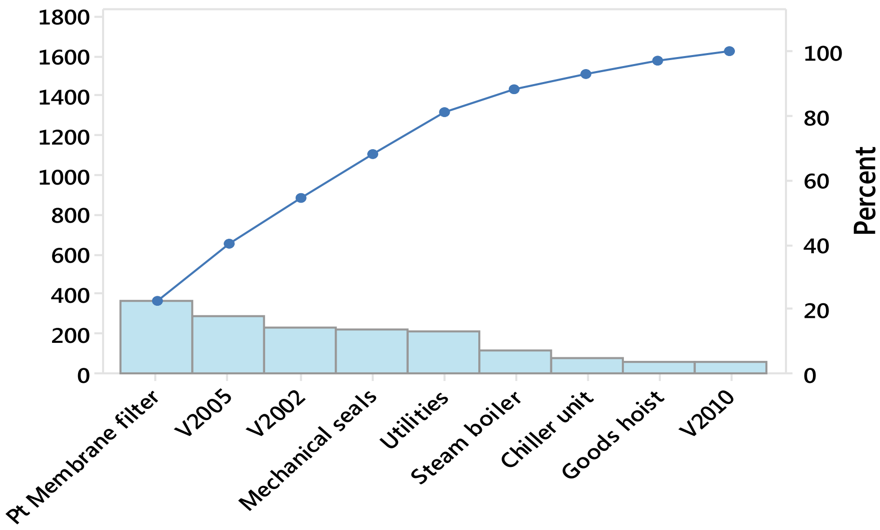

Fig. 7 Total downtime per equipment

Mushtaev et al. (2004) cautioned that most industrial plants are complex and more often the provision of reliability for such plants is based traditional methods from reliability theory that were initially designed for routine plants. This leads to inaccuracy of results from the industrial plant and this renders the results unreliable because one cannot make a well-informed decision from that data. Figure 8 shows the frequency of failures experienced at the critical equipment. The reactors R3 and R4 experienced the most downtimes. Barringer and colleagues (Barringer 2000, 2004, 2006) suggests that mean time before failure (MTBF) need to be determined once the critical equipment have been identified. MTBF is defined is a measure of reliability of repairable items and therefore helps in planning maintenance activities, should breakdowns occur.

Figure 7 shows that 78 equipment failures happened during the period of study with MTBF calculated at 0.027 failures per hour and mean time before failure (MTBF) at 37.04 h calculated from Eqs. 3 and 4. This could be interpreted to say it takes at least one and half day (37.04 h) for a critical equipment to fail in the chemical plant of study. Critical equipment availability was calculated and found to average at about 94.63%. Interviews conducted at the plant indicate that the company does not have set standards regarding the target critical equipment availability.

From the literature, the study showed that choosing the right maintenance method is critical. By comparison, preventative maintenance focuses on preventing failures or incidents by promptly replacing or repairing equipment during routine shutdown or scheduled inspections before they fail and create unnecessary stoppages. This study has revealed that the Chemical plant was using a more reactive approach (corrective maintenance) to maintain equipment in the plant. Due to this approach, the maintenance team struggled to complete all corrective maintenance tasks and

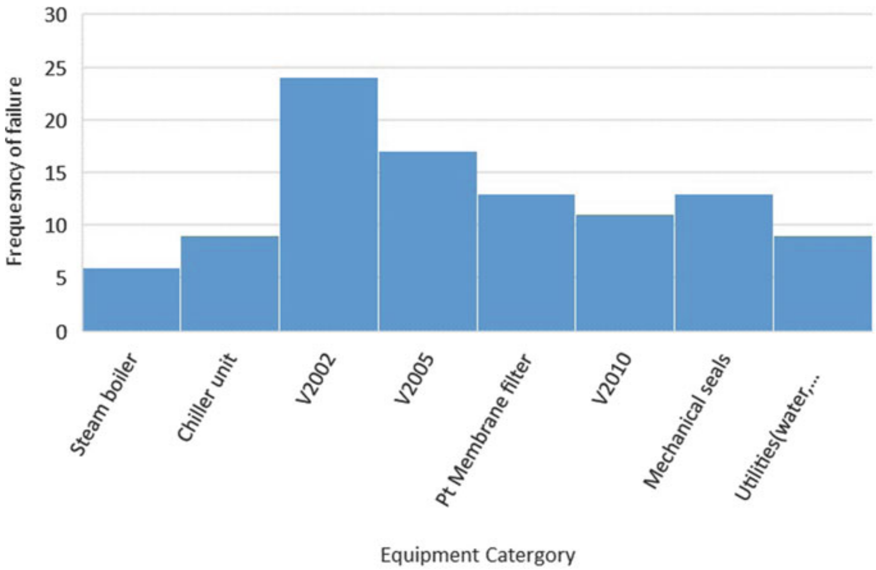

Fig. 8 Frequency of failure per critical equipment

this puts the plant at risk due to sudden failures experienced. Reliability centered maintenance should be adopted in the Chemical plant. Researchers like (Nabhan 2010; Vatn 2007) view reliability centered maintenance as the logical way used to determine what equipment need to be maintained on preventative maintenance basis as opposed to run-to-failure basis. It allows for the performance data of critical equipment to BE collected and analysed to identify specific failure modes. The information is crucial for use in the formulation of preventative maintenance.

Currently the organization does not analyze data for equipment availability in the Chemical plant; this was corroborated by the plant maintenance foreman. This simply means that there is no defined target for availability of equipment in the plant. Figure 9 shows the critical equipment availability for the duration of this study. It can be noted that availability fluctuates between 92.67 and 96.59%. The plant experienced its lowest availability for critical equipment in July, with the rest of the months being above 93%.

The results further reveal that reliability data for the plant is never analyzed to come up with better maintenance philosophies that can be used to improve reliability of the plant and reduce frequent failures in the plant. Although data analyzed shows 10% availability of critical equipment, Mashtaev et al. (2004) argued that certain facets of reliability theory should be revised for application in industrial plants; such as failure.

It can be noted from Fig. 10 that equipment is a major contributor to plant downtime, contributing 62% of plant unavailability. Process related downtime category constitutes 18%, shortage of packaging tanks is third at 8%, and inefficiency of the production plan contributes 7% and sample analysis coming fifth at 5%.

Fig. 9 Critical equipment availability

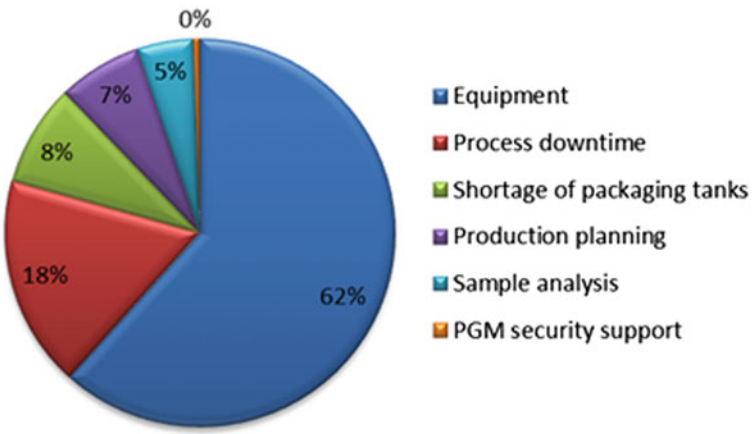

Fig. 10 Total equipment loss

4 Conclusions

The study revealed that major contributing factor to production downtime is equipment failures. Throughout the duration of this study, it was noted that the plant was not available to its maximum capacity. The study showed that critical equipment failure contributed to 10% of the plant unavailability. It further identified equipment that needed the most urgent attention to improve availability and reliability of the plant. These results show the need to focus to focus on reliability of equipment in the Chemical plant, followed by process downtime. According to the Pareto rule, focusing on two will boost the plant performance as they are the main contributors to downtime.

Critical equipment data was collected for the duration of this study and analyzed. From the empirical data, it was noted that availability of critical equipment fluctuated between 92.67 and 96.59%. There was a point where the plant experienced lowest availability of 93%. This shows inefficiency of maintenance practices in the plant. From the data analysis, it was clear that vessel V2002, V2005 and Pt membrane filter were the ones experiencing more failures, implying that they have a shorter mean time to failure (MTTF).

The results show a serious need for RCM to monitor and improve equipment availability in the plant. According to Maoto (2012) in order to have a systematic manner of controlling reliability of a system, the theory of RCM needs to be applied. When RCM is applied, failures that can lead to higher life cycle cost will be managed by proper equipment maintenance strategies. These strategies must be natured by continuously monitoring execution and reviewing their effectiveness every now and again.

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Additive Manufacturing for Cost Efficient Hybrid Welding Jigs

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Abstract The use of the Additive Manufacturing (AM) process Fused Filament Fabrication (FFF) for the manufacturing of pre-series welding jigs for car body assemblies shows potential in terms of cost reduction and design flexibility. A conventional welding jig consists of standard parts and machined parts which can cause high costs in manufacturing. Although many simpler 2D parts which can be cut very economically are used as well, some of those parts have to be machined again in order to integrate all functional features. Additional manufacturing steps cause additional costs and prolong the supply process of those parts. A hybrid jig system that consists of part specific FFF components and standard elements has been developed for the welding of car body assemblies in the pre-series vehicle production. In order to analyse cost and time advantages, an economic assessment is used. It is aimed to determine whether the use of a hybrid jig system for welding operations of car body prototypes generates lower financial and time expenditures compared to conventional welding jigs. The assessment includes a detailed comparison between the manufacturing of a hybrid welding jig and a conventional welding jig for car body assemblies. Additive Manufacturing (AM) of the complex and specific parts with FFF offers time and cost advantages because material and process costs are lower than with milling, and process chains can be simplified. This paper presents the results of the assessment on the hybrid welding jig system and shows the overall potential in the pre-series vehicle production.

Keywords Additive manufacturing · Body shop · Fused filament fabrication · Welding jig

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_46

1 Introduction

In automotive body shops, welding jigs are used which are usually completely manufactured out of steel. This is a well proven way to ensure the stiffness and strength required to meet the prevailing quality requirements of the welded body assemblies. Since the jigs and fixtures have to meet accuracy requirements in the tenth of a millimetre range, the specific components of the jigs and fixtures are correspondingly expensive and time-consuming to manufacture (Fritzsche et al. 2012). These stiff but at the same time rigid and inflexible jigs are also used in pre-series production. However, the pre-series phase is often characterised by component changes and other adaptation measures, which means that the provision of this type of jigs is associated with high manufacturing costs. In general, the usual quantities in pre-production are also significantly lower than in series production. In a pre-series phase, no more than several hundred vehicles are built, in some cases even less than 100 units (Schuh et al. 2008). In this case, the steel jigs used are usually over-dimensioned and exceed the quantity requirements many times. Due to factors such as an increasing number of variants, shorter ramp-up phases and life cycles, as well as the rise of electromobility, there is an enormous cost pressure on the prototype and pre-series phase of automotive production, which to a large extent affects the body shops, including its complex jig technology (Bichler et al. 2018; Hansen et al. 2018; Zhang et al. 2009).

In conventional manufacturing, subtractive manufacturing technologies, such as CNC machining, are used. These remove material from a basic block until the final functional geometry is established. In additive manufacturing, parts are produced from 3D model data by joining materials in layers. With this layer-by-layer fabrication, AM differs from subtractive and forming manufacturing processes. The use of polymer-based AM for jig manufacturing in pre-series body shop offers potential to save costs and reduce provisioning expenses by shortening and thus accelerating the process chain from the first jig design to the operational welding jig. Existing approaches show the general suitability of polymer-based additive fabrication for the manufacturing of welding jigs for pre-series body shops but lack in a comprehensive economic evaluation and a detailed comparison with the costs of current jig production (Guo and Leu 2013; Markforged Inc. 2019; Stratasys Inc. 2019; Thompson et al. 2016).

2 Conventional Pre-series Welding Jigs

Pre-series welding jigs consist of standard parts and specific elements, which are adapted to the components to be welded. Typical standard elements are the base plate, manual clamps, location pins, stands and clamping spindles. In the following, only the manufacturing costs of the component specific elements are considered, since the standard parts are well available and do not offer much cost saving potential. The elements of a jig and fixture system are shown in Fig. 1 (Hesse et al. 2012).

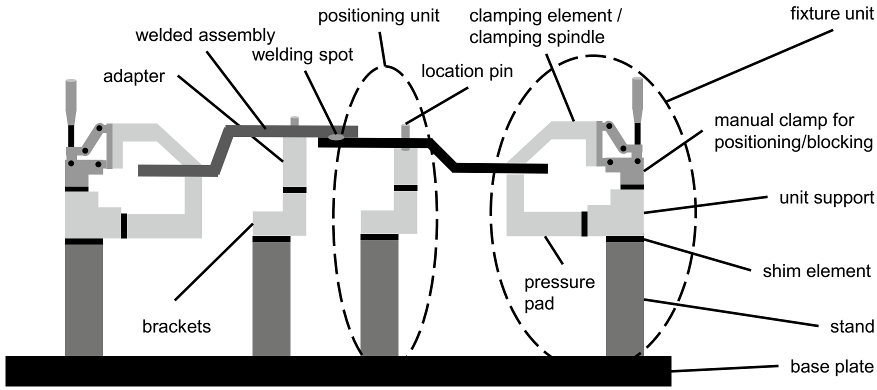

Fig. 1 Functional elements of a pre-series welding jig

2.1 Manufacturing of Conventional Pre-series Welding Jigs

In conventional pre-series welding jig manufacturing, the elements unit support, bracket, clamping arm, pressure pad and adapter are usually made of tool steel such as S235JR+AR using various manufacturing processes. In order to ensure that the respective elements fulfil their functions, it is often necessary to use manufacturing process chains with different manual steps. Cost-effective two-dimensional (2D) cutting processes such as water jetting and laser cutting are used to produce a large number of elements that can be functionally fulfilled with a 2D geometry. In many cases, pure 2D cutting is not sufficient to integrate all functional features, in which case cut-out holes have to be machined afterwards. Holes that are not in the cutting plane must be drilled in an additional step after the cutting process. To meet the accuracy requirements, some of the cut holes must be reamed in order to comply with the tolerances. Threading can also only take place in a post-machining step after the 2D cutting. In pre-series jig and fixture manufacturing, manual drilling and tapping is usually used. In the case of close-contour clamping and pressure pieces, the 2D elements are often post-machined by milling. With machining the 2D pieces, 2.5D or 3D contours can be created, which are required for the functional fulfilment of some of the jig elements. In case of adapter pieces that are needed to direct the force direction by a certain angle, without the availability of suitable standard angles, 2D components are welded together accordingly. This requires an additional manual manufacturing step (Hoffman 2004; Trummer and Wiebach 1994).

2.2 Manufacturing Costs of Pre-series Welding Jigs

The cost of manufacturing includes three terms. The material costs, the machine costs for water jetting and the costs for milling. Both process steps contain the personnel costs for both the CAM process and operation at the machine. Only the costs that can be assigned directly to the component to be manufactured are considered.

$$Total\,cost\,per\,part\,P[EUR] = MP + 1\text{st}\,P + 2\text{nd}\,P$$

with

$MP = Material\ cost\ per\ part\ [EUR]$
$1\text{st}\ P = Costs\ for\ the\ first\ process\ step\ per\ part\ [EUR]$
$2\text{nd}\ P = Costs\ for\ the\ second\ process\ step\ per\ part\ [EUR]$

In this paper, the manufacturing costs of two different welding jigs are analysed. The first jig is a welding jig for a smaller body assembly consisting of a lower sheet and a hat-shaped upper part. The jig is mounted with feet on a welding table and consists of a larger jig body structure that is connected to the feet. The jig body structure contains the location pins for positioning the parts as well as the connection features for the toggle clamp. The clamping arm is extended by means of a clamping element into which two clamping spindles are screwed. The jig positions and fastens the two parts and allows the targeted access of the welding gun for the welding of the parts with a total of four welding spots. The part specific components of the jig clamping element and jig body structure are designed once for fabrication with FFF and once for production with milling processes. This jig is called “small example welding jig”.

The second jig is a pre-series welding jig for a larger welded assembly. The function of the jig is the positioning and fixing of two smaller components, a holder for the brake hose and a second holder for the ABS system, on a longitudinal member. The holder for the brake hose is joined with resistance spot welding and the ABS holder is joined with a gas metal arc welding (GMAW) process. This jig is called “larger welding jig”. Figure 2 shows the two welding jigs.

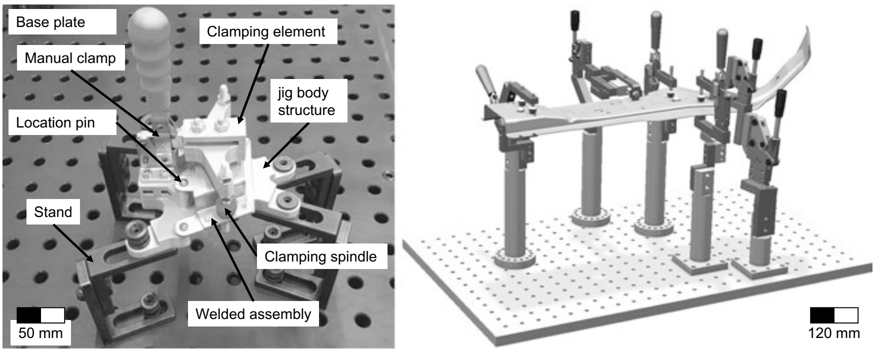

Fig. 2 Small example welding jig (left) and larger welding jig (right)

3 Hybrid Welding Jigs with Additive Manufactured Elements

The idea behind hybrid welding jigs with AM elements is to keep standard elements and some of the simple 2D elements by only using water jetting and add polymer AM elements to reduce the manufacturing costs of the jigs. In order to get a better understanding of why metal based AM is not yet economical, the costs of metal AM of the specific jig elements are estimated as well.

3.1 Polymer Additive Manufacturing

Common AM processes are Stereolithography (SLA), Fused Filament Fabrication (FFF), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Selective Laser melting (SLM), Polygraphy (Polyjet), Direct Light Processing Printing (DLP) and Laser Metal Deposition (LMD). In addition, there are other and related processes for which reference is made to the available literature (Gebhardt et al. 2016). Since the FFF process has significant low manufacturing and material cost among the polymer-based AM processes, the available materials are examined in more detail below. The focus on the FFF process is substantiated by the good results with FFF welding jigs elements that have already been achieved. In Fig. 3, the filament costs of different FFF materials are plotted double-logarithmically above the material stiffness.

The diagram shows that of the wide range of FFF materials, PLA and ABS are among the cheaper ones. At the same time, they have good stiffness properties. PLA continues to work well with common support materials, and its suitability as a

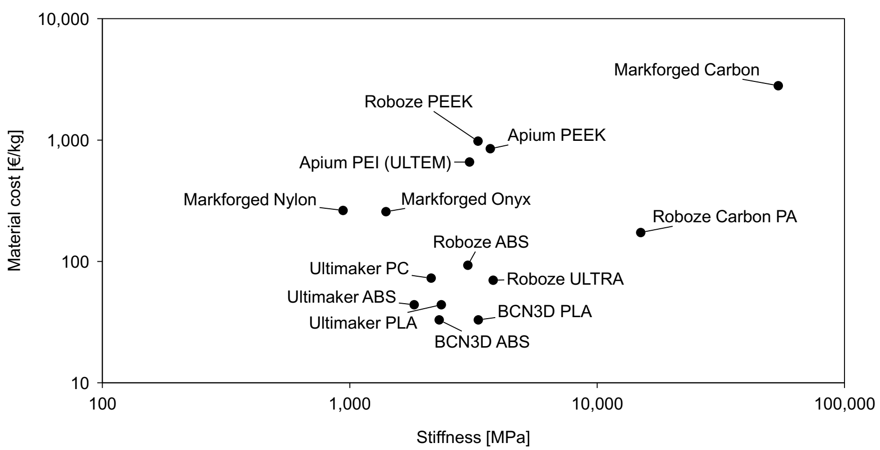

Fig. 3 Filament costs and Young's modulus of selected FFF materials

Table 1 Calculation of hourly rate of a FFF printer

Hourly rate of a FFF printer		
Cost type	Value	Unit
Acquisition cost	5075	€
Runtime	3	a
Operating hours	4768	h
Residual value	400	€
Interest rate	1	%
Maintenance cost	300	€
Electricity cost	0.02	€/h
Space requirement	0.5	m^2
Space cost	30	€/(m^2a)
Annual depreciation	1573.92	€/a
Annual depreciation per hour	0.33	€/h
Space cost per hour	0.00315	€/h
Maintenance cost per hour	0.02098	€/h
Total hourly rate	0.3542191	€/h

feedstock for the jig manufacturing has been demonstrated in a previous study. High performance polymers such as PEEK and fibre-reinforced nylon have a significantly higher stiffness but are much more expensive. Not only the filament costs of those materials are much higher than PLA and ABS, also the investment costs for the printers are higher.

The operating costs of a typical FFF printer are exemplified in Table 1. An AM printer can be used almost around the clock, since during production no personnel deployment is needed. The investment is much smaller than with conventional production machines. This results in an hourly rate of well below one euro per hour of operation.

The typical process chain of part manufacturing with the FFF process begins with the import of the STL file into the software environment of the FFF printer. After adjusting the process parameters, the paths of the print head are calculated and the machine code is generated by the postprocessor. Since the printing process runs smoothly in general, continuous monitoring of the printing process by the operator is not necessary. The finished printed part must then be manually removed from the building platform. Depending on whether support material was used, this must be removed in a post-processing step. Supporting material is always used when the geometry of the part to be printed has overhangs that exceed an angle of 60°.

There are different types of support material. Water-soluble support material has the advantage that the part has a very low risk of damage caused by the removal of the support material. The part surrounded by support material is placed in a water bath in which the support material dissolves. The disadvantage here is that this process takes some time and in case of part faults water can get into the inside of the part. The dissolution of the supporting structure in water is associated with time expenditure, but the costs are low. A simple container, which is filled with water and into which the part is placed, is sufficient. Many support materials are biodegradable; thus, the disposal into the drain is not critical. Supporting material for manual "break away" has the advantage that it is much faster than with the water-soluble process, but it is a manual work. In addition, especially with filigree structures, there is a risk that the part will be damaged. Problems can also often arise because the support material cannot be completely removed. Another option is to print support structures from the same material as the part. This option is usually used when the melting temperature of support and base material differ too much or only single extruders are available. The same disadvantages of "break-away" support occur in this case in a stronger form. An AM-equitable construction can counteract this.

The manufacturing costs of an FFF part consist of the costs for the preparation of the print job, the material costs, the process costs with the machine cost per hour as well as the costs for the post-processing, essentially the removal of the support material.

3.2 Metal-Based Additive Manufacturing

In metal-based AM, Selective Laser Melting (SLM) is the most widely used process alongside Metal Binder Jetting and Laser Material Deposition (LMD). In the SLM process, metal powder is located in a moveable powder bed. An optical system consisting of objectives and mirrors deflects a laser beam to the corresponding points in the powder bed. At this point, the powder is completely melted. This allows the forming of a solid material layer after solidification. The building platform is then lowered by the height of the layer and a new layer of powder is applied. The powder bed is smoothed with a roller to obtain a homogeneous layer. The process steps are repeated until the finished part is fabricated. The part is removed from the building platform and from the supporting structure, which in this case consists of the same material. The support structure is shaped in thin chains which support the overhangs of the part (Atzeni and Salmi 2012).

3.3 Manufacturing Costs of AM Parts

The manufacturing costs of AM parts are given as follows (Schmidt 2015).

$$Total\ cost\ per\ part\ P[EUR] = MP + AP + CP + BP$$

with

$MP = Material\ cost\ per\ part\ [EUR]$

AP = Pre-processing cost per part [EUR]
CP = Processing cost per part [EUR]
BP = Post processing cost per part [EUR]

The pre-processing cost consists of the time the system operator spends preparing the print and the corresponding hourly rate. The post-processing cost of SLM consists of the costs for the subsequent heat treatment of the printed part and the time for the rework multiplied by the hourly rate of the operator. The post-processing cost of FFF consists of time for support removal multiplied by the hourly rate of the worker.

4 Cost Analysis and Comparison

To compare the cost of the pre-series jigs, the smaller example jig and the larger jig are used. The effort invested in development and designing is assumed to be the same for every production process and is excluded in the calculation.

4.1 Manufacturing of Conventional Pre-series Welding Jigs

The material costs for the specific elements of the conventional pre-series welding jigs include only the cost of the actual component, not the cost of material to be removed. These are 2.38 € for the small example welding jig. In the first process step, a 2D shape is created with the use of the water jetting process. The expenses in the first process step consist of approximately one third of machine costs for a total cutting length of 1100 mm (3.76 €) and two thirds of personnel costs (8.80 €). To calculate the machine part, the costs are taken from Table 2 (Kühn et al. 2018). The staff costs of a worker in the German automotive industry are estimated at 60 € per hour.

This results in an amount of 14.86 € in the first processing step. In the second step, the milling process follows to produce the functional geometry with one 2.5D milling process (8 h) and four drilling and threading operations. This consists of 376 € for the milling machine costs and 96 € of personnel costs. Overall, the small example welding jig costs 487 €. This shows that for small jig for the second processing step 97% of the cost must be incurred. The total manufacturing costs of the component

Table 2 Process characteristics of water jetting

Sheet thickness	Traverse speed (mm/min)	Costs (€/m)
5 mm steel	800	0.625
10 mm steel	500	1
15 mm steel	325	1.54
20 mm steel	150	3.33

specific elements of the larger jig are 1420.48 €. For the larger jig, the cost of the second step is about 91% for a summarised milling and drilling process time of 22.9 h, while the proportion of water jetting is 7% with a summarised cutting length of 9040.75 mm.

4.2 Manufacturing of Hybrid Welding Jigs with FFF

The manufacturing costs of the small example hybrid with jig and the large one are analysed with FFF and the polymer PLA. The costs for water jetting remain the same as described above. The costs for AM are composed of material, machine and personnel costs. However, the proportion of personnel costs is higher, since in AM the post processing happens mostly manually. In total, the costs of FFF are significantly lower than those of the milling process. A standard FFF printer prints at approximately 0.028 cm^3/min. This value is to be understood as a guideline because the printing time depends on many parameters. These include the print settings, as well as geometric properties such as protrusions, overhangs or special shapes. The exact consumption values and real machine duration are used for the analysis.

The total FFF-printing costs for the small example jig are 48.91 €. This price consists of 8.20 € material and 10.80 € machine costs. In addition to this, there are the personnel costs for the CAM process, the loading of the printer and the post-processing. These amount to 30 €. The total FFF-printing costs for the larger jig are 649.68 €.

4.3 Manufacturing of Hybrid Welding Jigs with SLM

Another possibility to fabricate the specific jig elements of the small jig is using SLM with steel powder. Due to the more expensive process, the total cost increases to 379.30 €. The material costs are 101.86 € and the machine costs amount 227 €. The personnel costs for preparation and post processing are 60 €. SLM is a process close to end geometry. However, some functional surfaces have to be reworked in a second process step (e.g. threads).

4.4 Comparison

The different costs of the small example jig are illustrated in Fig. 4.

It turns out that using small hybrid welding jigs directly brings a cost savings potential. The greatest potential is shown by the machine costs. This can be explained by the fact that the second processing step in the conventional process requires 97% of the total machine costs. This step will be eliminated through AM. However, as

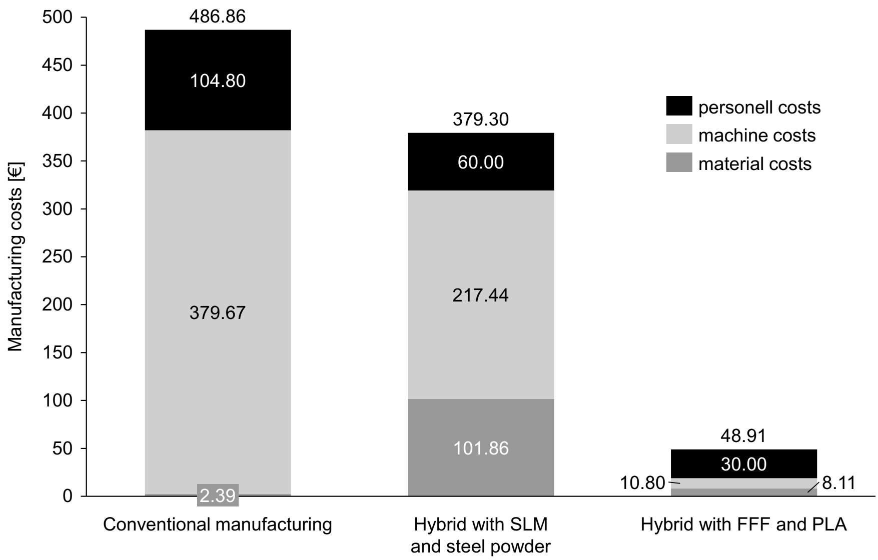

Fig. 4 Manufacturing costs of small example welding jig

described above, the machine cost of commercial SLM is higher compared to FFF printers. The figure also shows that machine costs account for the largest share of costs in the two metal processes. In polymer additive manufacturing, on the other hand, personnel costs account for the largest share of total costs. According to the current state of the art, post-processing in FFF processes is a manual process and thus personnel cost-intensive. Overall, it can be said that with small components, all the cost advantages of the FFF process come fully to grips with the highest potential. Since it is a small jig made up of few parts, differences in production time and assembly time play no role in this comparison.

That changes when considering the larger jig. The mere machine utilization time for conventional production is just under an hour for water jetting and 22 h of subtractive manufacturing. The printing time for an equivalent hybrid jig with FFF is over 370 h. This increases production time by 1600%, while the staff costs stay the same at about 5.5 h. The significant increase can be explained by the fact that a single printer does not have the same productivity as a comparable conventional machine. This increase in provisioning time can be reduced by the parallel use of several printers or by outsourcing the FFF production to external additive manufacturers. The manufacturing costs and time of the larger jig with the different manufacturing processes are shown in Fig. 5. Figure 6 portrays the hybrid jig with FFF elements for welding the longitudinal member assembly.

The largest savings can be found in the machine costs. There, the costs drop to almost 10%. This is due to the significantly lower investment and operating costs of the machines. The higher material price at AM can be explained by the larger volume, which is needed for the same strength, but also by the use of expensive support

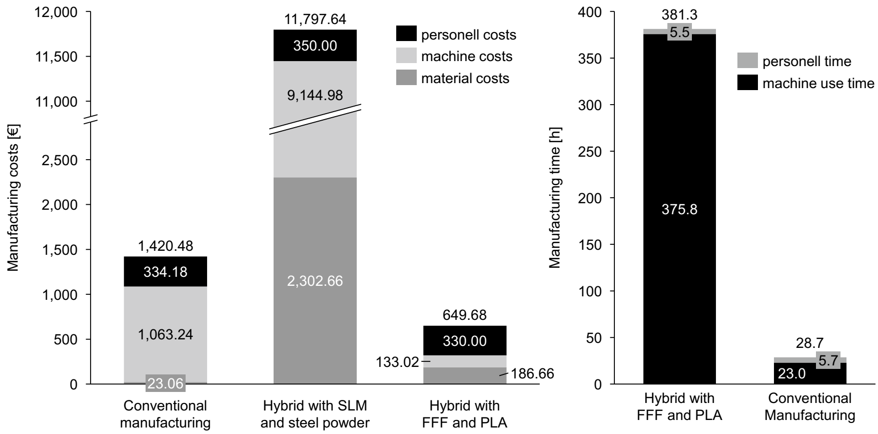

Fig. 5 Manufacturing costs and time of the larger welding jig

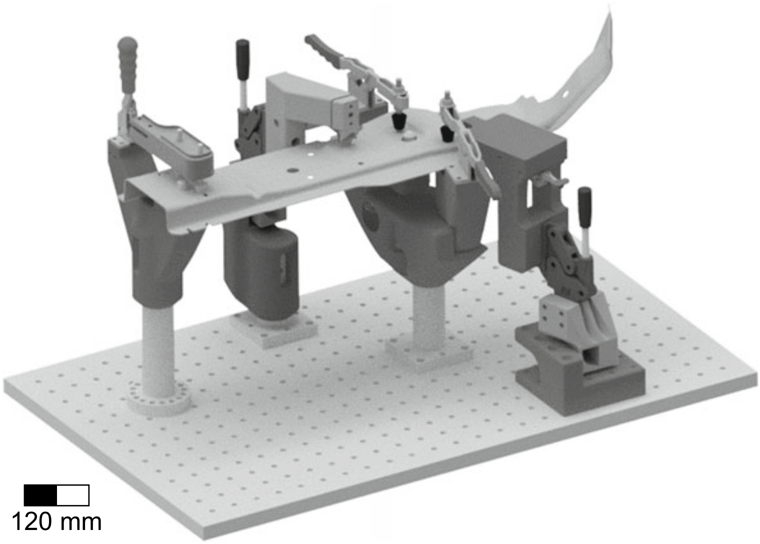

Fig. 6 Larger welding jig as hybrid version with FFF elements

material. The use of SLM to manufacture the jig is by far the most expensive. The total cost with 11,797.64 € is eight times as expensive as conventional production. The cost advantages of the FFF process are not to be borne by SLM, since the machine investment is very high. Another disadvantage are the material costs. These are, at the same volume, already factor 100 above, as in the conventional production process. Especially with SLM the costs of AM are sensitive to the part volume since large parts cause long building times and a high material consumption. This is the reason why the costs of SLM for the large jig are much higher than for the small jig and the proportion to the costs of the conventional manufacturing is inverse in the case of manufacturing the large jig. With conventional manufacturing, the complexity of the parts and the resulting manufacturing steps increases the costs. The influence of size of the parts on the total costs is low.

5 Conclusion

The cost comparison shows that using hybrid welding jigs with FFF elements is a way to reduce the manufacturing costs for pre-series welding jigs by almost the half for larger welding jigs. The cost saving potential gets bigger by using the hybrid welding jigs for all jigs in a pre-series body shop. For welding a complete car body, around 70 different jigs are used. Therefore, using hybrid welding jigs for the prototype und pre-series production allows to reduce costs of the industrialization of new car models and opens possibilities to meet the current challenges within the automotive industry. The cost analysis show that using metal AM is still too expensive, especially for large jigs, but the powder material costs as well as the machine operating costs are decreasing. Using it for the production of series welding jig might be possible soon. The next steps include a comprehensive testing of the hybrid jig system with focusing on the lifetime and the reproducibility of the welded parts.

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An Investigative Study on Production of a Composite Novel Plant Fibre: Mechanical Properties Comparison

Kaelo Olehile and Vuyo Terrence Hashe

Abstract This paper introduces a production process of identifying and producing a novel natural fibre from an indigenous source tree with the intention of reducing the dependency on imported high-quality natural fibres from outside Africa. Commercialized plant fibres from plants like Sisal generate income for their host countries in Central American and European regions. This plant is used in polymer matrix composites as a load-bearing member. This paper identified three plants—Sparmania Africana, Ficus lutea and Ficus sur, of which only the Ficus trees were investigated. The properties investigated were the uniaxial tensile strength and Young's Modulus as these properties enabled the researchers to characterise the material strength. The Ficus lutea out-performed the Ficus sur in terms of the true strength and the engineering strength. The two are almost the same for both materials at 97% when compared. On average, maximum strength is about 22.6 and 17.5 MPa at breaking, with Ficus lutea greater than Ficus sur. Research is statistically valid with a P-value of less than 0.05, this paper achieved a P-value of 0.001162. In addition, the two Ficus plants did not perform well when compared to Sisal plant.

Keywords Natural fibre · Plants · Properties

1 Introduction

Composite materials have been in use for a long time, having evolved through time and risen to such importance that it would be out of the question to live without them. This gave rise to new industries of fibre reinforcements, which later led to the focus on natural fibre as an eco-friendly substitute. Some fibres that are commercially available can be requested in other formats as per the requirements of the customer: they can be woven reinforcements, laminates and nanoparticles, for example. The

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_47

need for this kind of research is substantial in the context of the development of Africa, as Africa clearly has a role to play in the composite story (Taj et al. 2007).

This paper focuses on thermosetting polymer matrix composites that use plant fibres for reinforcement. These reinforcements are in the order of a "randomly placed whiskers" format. The fibres are chopped to about 30 mm in length and are approximately 2.5 mm in diameter (Ray and Sain 2017). Polymer matrix composites contain a discontinuous phase in the form of reinforcement as a principle load bearing member and a continuous phase as a matrix. The matrix provides an intermediate phase for binding and holding the reinforcements together, forming a solid member. The matrix also protects the reinforcements from environmental degradation as well as providing finish, colour, texture, durability and other primary functions like load distribution (Bay 2017).

1.1 Engineering Plant and the Different Fibre Extraction Methods

The method of fibre extraction is particular to the source of the fibre on the plant. Banana fibres, for example, can be mechanically extracted using machines, and Napier grass by using water retting. Fibres are made of cellulose, hemicellulose, lignin and other substances. In chemical extraction of plant fibre, a strong base like NaOH is used to break down and separate the fibre from the rest of the plant (Kumar and Kumar 2011). Tamarind Fruit Fibre is extracted from the shells of the ripened fruit. The shells are broken to extract the fibres and then the fibres are washed and cleaned thoroughly, and pulp removed (Maheswari et al. 2012). Snake grass fibre is extracted by the water retting process. The grass is plucked and cleaned. The external stamp of the grass is removed, and the fibre immersed in water for about four days to allow it to decompose and break down (Sathishkumar et al. 2012). The Ficus Religiosa fibres are removed from dead leaves collected from the ground. The leaves were soaked in water for three weeks and the top layers of the leaves scrapped off gently (Iqbal et al. 2001).

2 Experimental

2.1 Novel Plant Investigation

Africa has internationally recognized biodiversity hotspots areas such as the Cape Floristic Region, the Succulent Karoo shared with Namibia, and the Maputaland-Pondoland-Albany hotspot, shared with Mozambique and Swaziland—that make this kind of research prospective look good. This establishes the fact that Africa most certainly has plants (Bay 2017; Pressey et al. 2003).

Table 1 Local plants comparison and selection

Criteria question	Plants		
	Ficus sur	Sparmania Africana	Ficus lutea
The plant must be local to Africa	Eastern Cape, KZN, Limpopo, Mpumalanga and the Western Cape	Western Cape, Europe	Eastern Cape, KZN, Limpopo, Mpumalanga and the Western Cape
Availability or in abundance	The plant is widely available	Not available	The plant is widely available
Echolocation of the plant	From coastal and riversides forests	Houseplant	From coastal and riversides forests and nature reserves
Mechanical properties, tensile and compressive strength	Strong fibre	Fair fibre	Strong fibre
How is it planted or is it natural	Natural and planted	Planted and natural	Natural and planted
Type of climate the plant grows in	In tropical and sunny	Sunny	In tropical and sunny regions
Fibre lengths	Over 300 mm	Over 30 cm	Over 300 mm
Source of fibre	Buck	Stem	Buck
Growth rate properties (annual or perennial)	Annual evergreen	Perennial	Annual evergreen
How to commercially produce the plant	Can be farmed	Difficult	Can be farmed
Final choice	Ficus sur	Unavailable	Ficus lutea

Within South Africa, Nelson Mandela Bay is one of the biggest biodiversity hotspots. According to the Department of Agriculture and Forestry, it is a juncture where several hotspots meet: these are Nama-Karoo, Fynbos, thicket, and grassland and forest biome. The Department of Agriculture and Forestry further states that there are plant species found only in this area and nowhere else; they are endemic species (Bay 2017; Pressey et al. 2003). Table 1 presents the criteria used in identifying and selection of the best available natural plant.

2.2 *Fibre Extraction and Preparation*

Figure 1 present the process of extracting the plant fibre. The process after the plant has been identified starts by extracting the bark from the plant. The bark is the outermost layer of the stem. This process is displayed in Fig. 2.

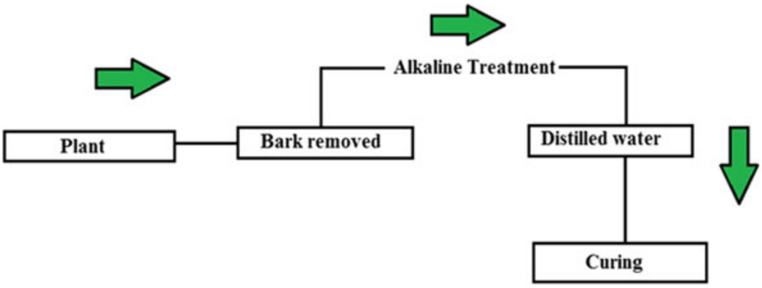

Fig. 1 Process of fibre extraction (Bilba et al. 2013; Grace et al. 1989)

Fig. 2 Manual bark removal

After plant fibre extraction has been completed, a base solution was prepared. This solution was to breaks down soluble cellulose, hemicellulose, pectin, and lignin from the fibre. This solution was prepared by dissolving caustic soda in warm water and this yielded a solution pH of 12.6. Thereafter, the collected bark was soaked in the solution for a week.

The bark was then removed from the solution of 10% sodium hydroxide with the top layer manually scrapped off; the fibre is exposed, dried and then further treated with 100% pure water, and a solution of acetylene to neutralize its basic nature; subsequently, it is treated again with cold water.

2.3 Manufacturing of the Composite Samples

A mould of 170 × 170 × 10 cm was designed and manufactured. Resin was prepared by mixing 100 g of epoxy with 27 g of hardener. The process as presented in Fig. 3 unfolded. The mould was prepared by ensuring it is clean and a release agent applied to facilitate ease of demoulding. Fibre was laid and epoxy-hardener

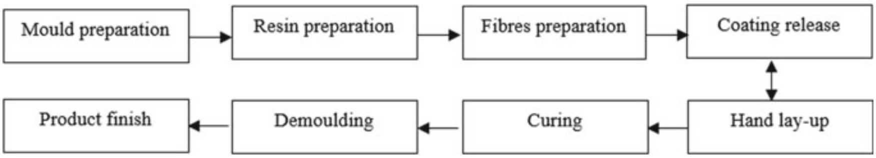

Fig. 3 Manufacturing in accordance with ISO 527-1:2012 (Wittman and Shook 1982) (modified)

mixture applied carefully over the fibre. Another layer followed maintaining layers of 5–6 mm. Samples were left overnight at room temperature (24 h) to cure. The composite samples were removed from the mould, cure in an oven at 160 °C for 3 h and allowed to thermoset. The composite samples were then left for 12 h before trimming and once trimming was complete, samples were heated to a further 30 min to ensure the release of any residual thermal stresses (Lee and Springer 1987). Water jet technology was used to cut the test specimen to ISO 527-2, ASTM D638:1993. Water jet was chosen due its advantages which include accuracy, no heat affected zones, no mechanical stresses, no extra machining necessary for the samples. The specimen were tested to investigate properties like the uniaxial tensile strength and Young's Modulus of the composite material.

3 Results and Discussion

ANOVA calculations enable the comparison of two sample means, and where the two samples have the same variables and undergo the same process, this enables us to study the performance of the sample and give the indication of how likely or unlikely the results would happen by chance numerically (Heiberger and Neuwirth 2009).

Table 2 shows ANOVA single factor calculations comparing Ficus sur and Ficus lutea. The table also gives a *P*-value of less than 0.05, which is 0.001162. The 0.05,

Table 2 Anova—single factor results

Summary				
Groups	Count	Sum	Average	Variance
Ficus lutea	22	468.5209	21.2964	32.86506
Ficus Sur	22	365.7483	16.62492	6.640948

ANOVA						
Source of variation	SS	df	MS	F	*P*-value	F-criteria
Between groups	240.0504	1	240.0504	12.1526	0.001162	4.072654
Within groups	829.6261	42	19.753			
Total	1069.676	43				

called the ‘alpha’ or the probability of a type 1 error if the value is greater than 0.05 than the research, has yielded unusable results because the results happened by chance. However, if the P-value is less than 0.05, the results are over 95% true in the sense that they did not happen by chance (Mahapoonyanont et al. 2010).

3.1 Stress versus Strain

Tensile tests will follow Hooke’s law which describes the initial part of the test of the load and strain being directly proportional: for every increase of the load, the strain will increase. For the brittle material, the slope of the linear part of the curve anywhere below the elastic limit or breaking point is equivalent to Young’s Modulus of elasticity (Rychlewski 1984). The stress obtained from the Ficus lutea is marginally larger than the stress in the Ficus sur composite as presented in Fig. 4.

The instantaneous area, giving the most accurate stress concentration, is the true stress. If the stress is calculated using the original area measured before the start of the test, the stress obtained is the ‘engineering stress’. The area between the engineering stress and the true stress is the energy absorbed before ‘necking’ of the sample (Ling 1996).

Figure 5 shows the engineering stress/strain and true stress/strain. The graphs indicate a 3% difference between the true stress and engineering stress. This also indicates a very small change in area of the specimens before and after breaking, suggesting that the material is tough as it broke off in a brittle form. Calculations were

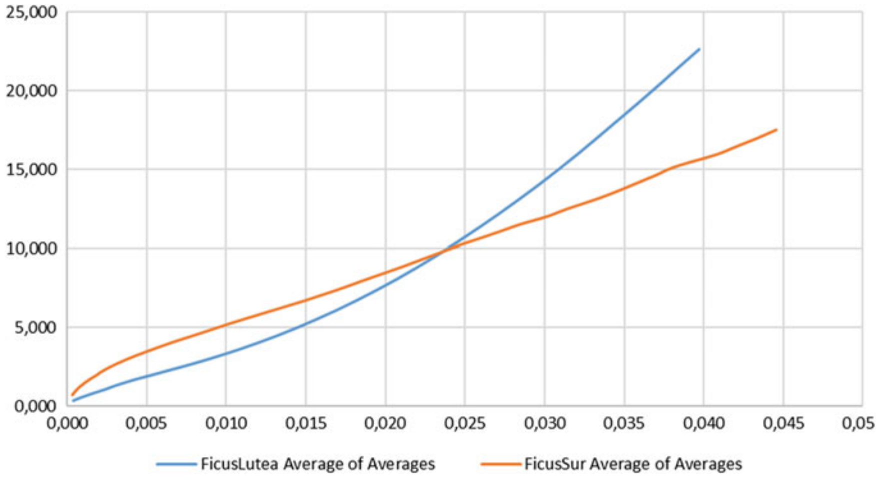

Fig. 4 Stress (MPa) versus strain

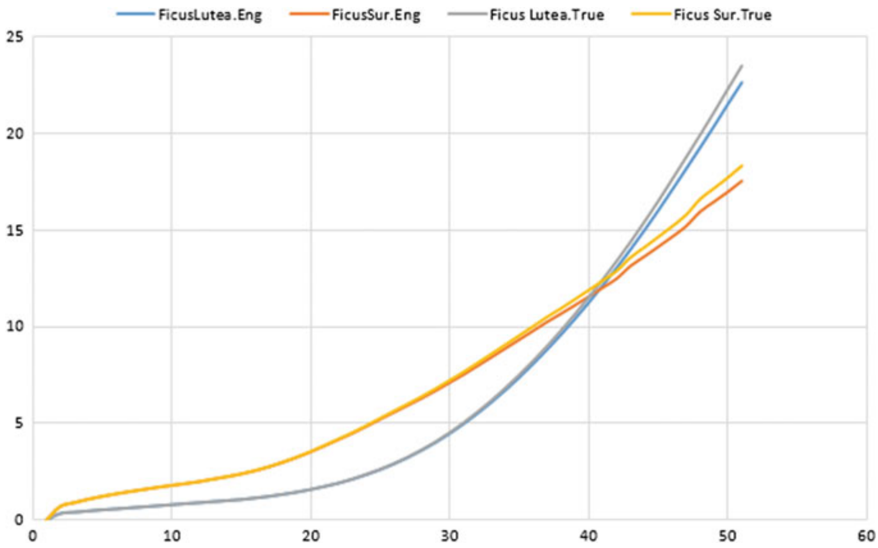

Fig. 5 Engineering stress (GPa)/strain versus true stress (GPa)/strain

Table 3 Young's modulus and tensile test results

Ficus lutea	Ficus sur	Natural fibre composite	Sasil	Borassus fruit	Other plants
0.53	0.412	Young's modulus (Gpa)	9.4	1.63	Young's Modulus (Gpa)
22.6	17.5	Tensile strength in (MPa)	468	53.5	Tensile strength in (MPa)

conducted using the engineering stress, as there results indicate no significant difference between engineering stress and the true stress. Table 3 presents a comparison between Ficus sur, Ficus lutea and other plants.

The plot in Fig. 6 shows the average strains without the stress, giving an expanded view of how the two strains interact and relate. The Ficus sur generates more strain as compared to the Ficus lutea, meaning Ficus lutea is marginally tougher.

Figure plot shows the relationship between crosshead speed and strain. The relationship is almost identical: if the speed is increased, the material will fail. Hence, maintaining the same speed enables a more accurate comparison of the two (Fig. 7).

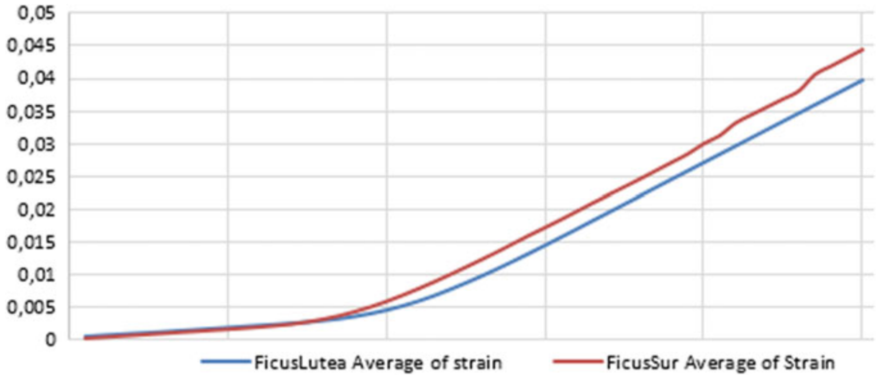

Fig. 6 Strain plot Ficus sur versus Ficus lutea

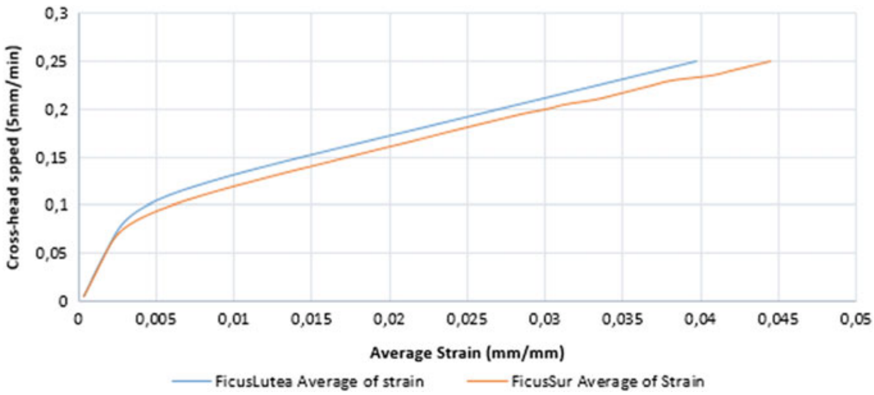

Fig. 7 Strain versus crosshead speed

4 Possible Applications of the New Composite Novel Plant Fibre

Plant fibres offer a variety of benefits; most important is their effect on the environment. Since composites are biodegradable, they become attractive to designers and engineers who desire to stamp out their carbon footprint (Mallick 1997). Composite materials have a wide range of applications. The general idea is to apply them where their major benefits of weightlessness and high strength is applicable.

This composite fibre is suitable for aerospace engineering, automotive industries, sports, and construction engineering, orthopaedic applications, electrical, industrial and marine applications. The potential commercial benefit of such fibre research is yet to be fully explored; however, we know that Africans have been using natural fibre for a long time. Moreover, there is a need to create new industries to contribute to developmental millennial goals of the United Nations and provide livelihoods for many African people. Cotton and wool as main products of natural fibre production contribute to over R300 millions of income annually; surely more can be made by bringing in new fibres (Erasmus 2009).

5 Conclusions

The research objectives were to investigate novel indigenous fibrous plants for use in polymer matrix composites, characterising the performance of these plants. This research found two plants of interest to investigate and stated the findings. What is clear is that a certain type of fibre gives a difference in the tensile strength and elastic limit of the material, indicating that some fibres are better load bearers than others are.

These finding stimulate discussion on which other plant fibres can be sought and used in the composite material, and which plant can compete with Sisal and spark new economic prospects. This research has discovered that it is not easy to get small amounts of fibres for research purposes, and available fibres have already been subject to extensive testing. Hence, this is an opportunity for new local industries of plant fibre production.

There are many possibilities regarding new fibrous plants and their use for fibre-reinforced composites. Hardwood yields a substantial amount fibre without killing the plant itself. The Ficus tree generates very good fibre for fibre-reinforced composites, but it does not generate the best results (as compared to other plants). Moreover, the fibre extraction process is labour intensive.

The use of epoxy over phenolic and polyester is primarily because of the experimental design; it is rated better when judged against environmental degradation effects like flammability, freshwater resistance, salt-water resistance, sunlight resistance and wear resistance.

The statistical analysis yielded very important aspects of the data; it indicated a p-value of less than 0.05, suggesting that this research is statistically important. Furthermore, it was demonstrated that there are no outliers, meaning the samples followed the same manufacturing, cutting and testing processes for both materials. The frequency of values indicated similar results for different tests and other values calculated using the t-test, leaf and stem plot and bell curve.

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Major Influencing Factors of Decision About Alternative Technical Means in Selected Aviation Services

Eugeniusz Piechoczek and Andrzej Hawryluk

Abstract The paper presents general assumptions and continued results of the studies on theoretical and practical aspects of providing selected services with alternative technical means. The study purpose was based on SWOT analyses and research within customers and suppliers. The specificity of the assumptions in the selected areas was illustrated on the basis of examples of completed undertakings. Additionally, the article contains a list of examined factors influencing the adaptation of Unmanned Aircraft Systems as components of the model of conversion of services that could have an impact on decision-making in terms of applications of alternative air platforms. Specific conditions for the chosen area induce the building of the base of rules and the base of knowledge in the range of applying the alternative technical means. It will be essential to preparation of the standards of the approximate inference leaning on insecure or incomplete knowledge. The article bring forward the preliminary results of research and development in this area.

Keywords Aviation · Service provision effectiveness · Unmanned aircraft services · Air services · Remotely piloted aircraft systems

1 Introduction

Constantly and dynamically growing market for unmanned aircraft is estimated at over 120 billion US dollars. According to approximate calculations by the among others PWC circa 30% of the commercial use of unmanned aerial vehicles flying platforms belong to infrastructure sector. The technical means used in the physical movement of products as well as in the logistics information process also directions

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_48

of their utilisation and their application systems creating some kind of infrastructure of logistics processes (Skowronek and Sarjusz-Wolski 1999).

Rapidly growing set of revolutionary solutions, shaping and affecting, for example, the space in which we live. Open the question remains, how many participants indicated above "e-revolution" are ready to function in the created by the revolution conditions. Somebody could also ask, how e-revolution is accepted by final customers, but it seems a reasonable treatment of the listed above processes as objectively existing elements of our surroundings ("technosphere") conceived as an area of human intervention in nature or the area affected by such activities. (EoN https://www.researchgate.net/publication/308076826).

The needs meeting model assumes among others that result of use (technology or product) is set of observations, which are an important element to identify new or significantly alerted needs. This is the starting point for the development of the "new product or the process. Here you can see the relationship with the concepts of "innovation" as process or "innovation" as the technical and technological aspect in this case (Kaźmierczak 2009).

The author presented the assumptions of research at the Conference EPPM 2017. Essential point of the research was to establish, that one of the possible ways to improve efficiency of the provision of the category of services can be use in activities related to such services by alternative technological means. Alternative technical means author understands as substitutional product to actually used. The expected result of the research was the emergence of the model, to assist the overall tasks related to conversion services provided by MAV to UAV. The model development and verification, to supporting a comparative assessment of the selected processes to provide services using alternative technical means, should lead to the development of tools (a set of tools) to facilitation in decision taking concerning the application of the alternative air services platform (Piechoczek and Kaźmierczak 2016). The following article describes the successive stages of the research and preliminary results.

2 Preliminary Research

Research issued within Polish companies only. Selected companies were divided for three groups. Supplier who deliver products or service, they have interest of delivery. Ordered is company who order product or service and pay for that. Third group are researchers or observers who has neutral relations with alternate service. Author delivered questionnaire to companies in the phase of recognition needs associated with the observations of the previous generation's products users effects: information on the extent and how to take into account the data from existing users in the formulation of the description of the new for may be relevant to the decision of the base type—to take or failure to next steps in the cycle (Kaźmierczak 2012). The author of the paper has prepared a questionnaire with questions of SWOT analysis. He expected answer if customer need alternate solution pushed by the market. What is valuation by three different side of the business.

The analysis includes the following areas and subareas:

(1) Benefits of application

- support for protection of critical infrastructure,
- diagnostic of the long distance linear objects (networks),
- monitoring state of power lines preservation,
- costs reduction of maintenance high tension and medium tension power line,
- ability to perform a visual inspection and measurements in populated areas,
- safety of the measurement team.

(2) Unique characteristics

- quick response,
- noise reduction in urban areas and protected,
- possibility of taking administrative decisions on the basis of data,
- choice of platform to a specific task,
- possibility of panoramic observation of linear object and its environment,
- possibility of monitoring and diagnostics of the object from different angles and angular elevation,
- ability to quickly locate anomalies and locations failure,
- possibility of using different measurement methods in minimum time unit,
- ability to apply the new technology (introduction of new diagnostic methods, introduction of new network management tools,
- automation of analysis the collected material,
- ability to reduce staff involved in maintenance process,
- experience and knowledge,
- the international exchange of experiences,
- cyclic training operators.

Rating scale for each question between -10 and $+10$. Survey questionnaires were sent to the selected service providers, recipients of services and research centers. Selection criterion is based on the research of representation referred to as a provider of services, customer services and researchers and reviewers so neutral. Survey were directly addressed to the selected institutions and in the analysis have been used as survey. The scaling method used in the surveys with scaling forced for a nominal scale, which allows only the conclusion of goodies or equality measured characteristics; the basis of allocation are qualitative characteristics of phenomena. You have selected the audience side of the company responsible for the handling of linear objects of critical infrastructure including gas and transmission and distribution of electricity. As vendors were recommended in the market of alternative equipment suppliers and service providers. Neutral it's research institutions and observers of alternative technical means. Selected results of preliminary research presents diagrams below:

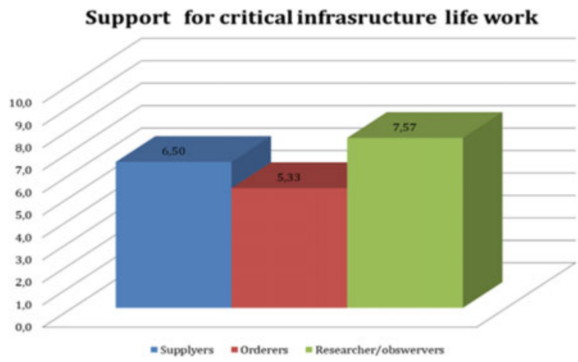

Fig. 1 Support for critical infrastructure

Summary of issue:

- support for safety of critical infrastructure is top rated by a group of observers and researchers. The difference between respond within inquiry groups exceeds 10% (Fig. 1)
- cost reduction of service share responders. We observe large disparity between the assessment of suppliers and customers (Fig. 2)
- sceptical judgement of orderer in the relationship with suppliers and researchers (Fig. 3)
- surprise is pessimism observed within providers in area of long distance monitoring. These capabilities highly evaluate recipient and researchers (Fig. 4)
- the differences in the application of the multidirecton diagnostic methods express responded group. The recipient does not approve the point of views providers and researchers (Fig. 5)
- another surprise is pessimism of suppliers in the immediate location of the anomaly. Optimists are the recipient and researchers (Fig. 6)
- reduction of staff involved in the operation was not accepted by the public. Studies have found big disparities between the opinion of customers and vendors (Fig. 7)
- innovation is accepted by all groups (Fig. 8).

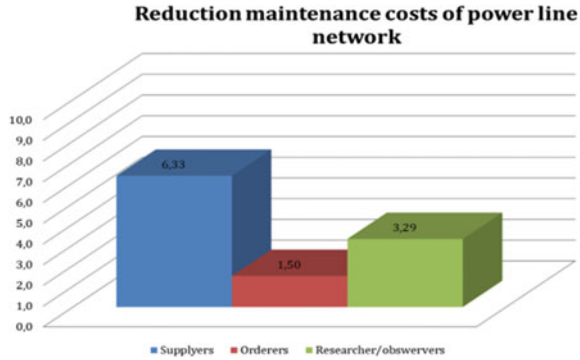

Fig. 2 Decreasing maintenance costs

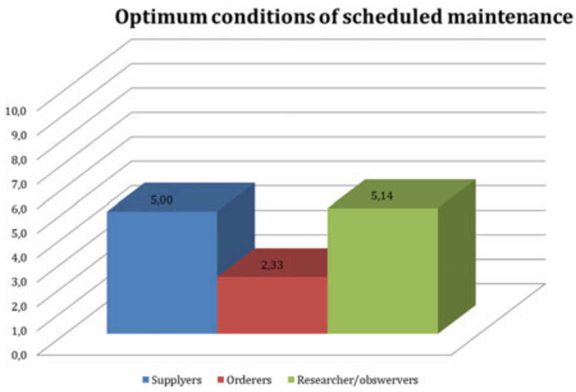

Fig. 3 Optimum conditions of maintenance

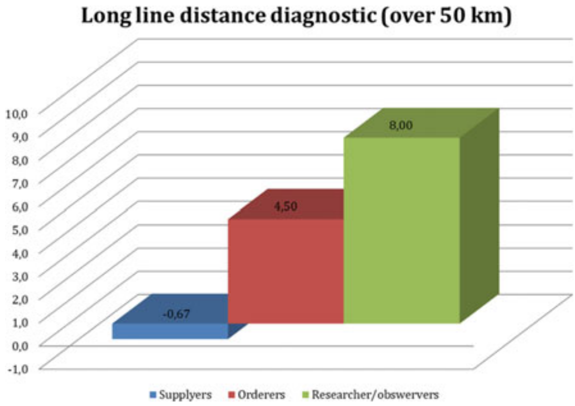

Fig. 4 Long line distance diagnostic

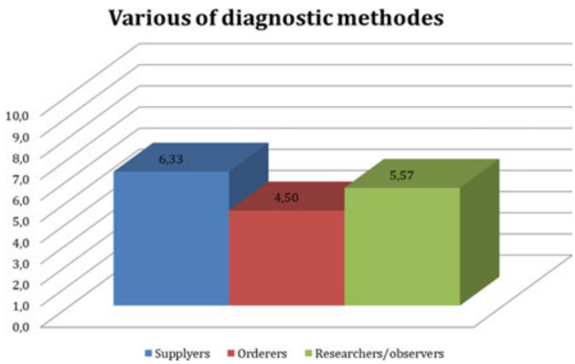

Fig. 5 Various of diagnostic methods

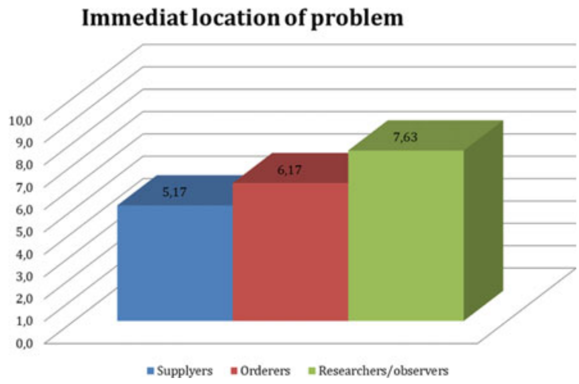

Fig. 6 Snap access mechanism location of problem

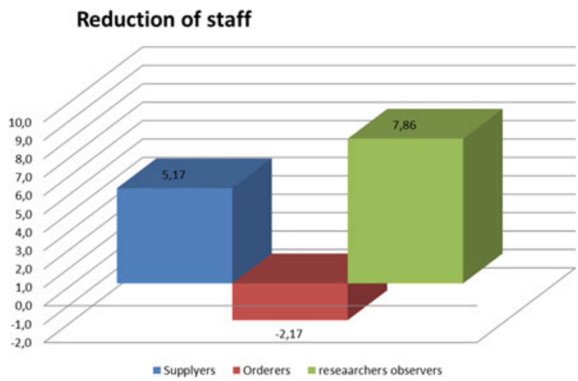

Fig. 7 Reduction of staff engaged

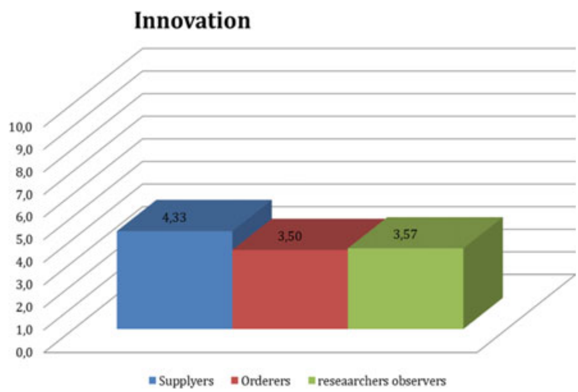

Fig. 8 Innovation

The initial investigation presents acceptance of usage alternative technical means. Therefore, study on new tools supporting their application are appropriate. The results of the preliminary tests confirm the necessity of support the decision-making process by including multi factors tool determining used platform type (Fig. 9).

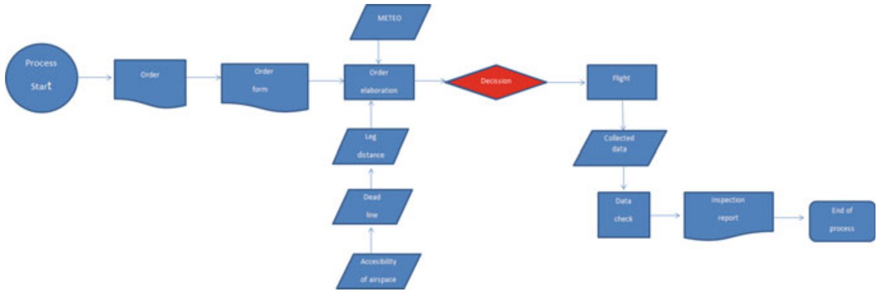

Fig. 9 Decision process model

The model will be placed in decision point marked red. Due to range of network decision point should be transferred to lower level. Lower level of decision required tool to take proper decision. The preliminary model has to fulfil that requirements.

3 State of Knowledge Analyzed

Remotely Piloted Aircraft Systems/Unnamed Aircraft Vehicles should be integrated into the existing aviation system in a safe and proportionate manner and this integration should foster an innovative and competitive European drone industry, creating jobs and growth, in particular for SMEs.

The proposed regulatory framework should set a level of safety and of environmental protection acceptable to the society and offer enough flexibility for the new industry to evolve, innovate and mature. Therefore the exercise is not simply transposing the system put in place for manned aviation but creating one that is proportionate, progressive, risk based and the rules must express objectives that will be complemented by industry standards (EASA 2019).

Machine learning has become an increasingly important artificial intelligence approach for UAVs to operate autonomously. Applying advanced machine learning algorithms (e.g., deep learning algorithm) could help the UAV system to draw better conclusions. For example, due to its improved data processing models, deep learning algorithms could help to obtain new findings from existing data and to get more concise and reliable analysis results (Shakhatreh et al. 2018). One of the necessary information for the flight is the careful evaluation of the weather conditions. Weather conditions are ideal for safe drone operation. Sunny days with calm or weak wind offer less risk to the safety of the operations of this type of equipment. However, it may be necessary to operate a RPAS in weather conditions that do not always fit the ideal operating profile. In this situation, care must be taken not to compromise the safety of the operation and to avoid damaging the equipment and, in particular, the risk of collision with objects, persons and aircraft (ANAC 2019 Doc-1009).

The GNSS satellite technology is an indispensable part of the aircraft's technical infrastructure. In particular, the GNSS satellite technology is used in precise air navigation. The primary products of GNSS applications in aviation are position, time, orientation, and velocity. The position parameter is determined by means of the aircraft coordinates in the XYZ geocentric system, the BLh ellipsoidal system, or the ENU local system. The time parameter allows for precise definition of the moment of determining the aircraft position during the ongoing air operation. The orientation parameter makes it possible to reflect the position of the aircraft in terms of HPR (Heading, Pitch, Roll) angles in 3D space. This system is very useful for UAVs ground station as well. Thanks to it the UAVs parameters delivered for UAV operator can be characterized as highly precise and timely delivered as well. It is very from the point of view safety of the mission conducted by UAVs and its fulfilment (Kozuba and Krasuski 2018).

In recent years, the high demand for UAVs has resulted in quest for technological advancements expected from these systems. Air vehicle, data link, payload, ground control station and other sub-systems require different technologic areas of expertise on their own. System design therefore became an important factor since all these sub-systems, which effect the operational mission directly, require different disciplines of expertise (Torun 1999).

4 Assumption of Direct Research

Shape based on the known data base, verified elements of the decision-making process. Groundwork model project is known data base of the author assessment as expert and his experiences in this regard. Model project contains the following groups of factors influencing decision making, as independent variables:

- current meteorological conditions (wind direction and velocity, precipitation, humidity, temperature, pressure, visibility, cloud base and clouds type
- weather forecast as above
- ambient conditions (village, town, densely populated areas, mountains, plains, forests)
- availability of airspace (limited traffic zone ATZ (Air Traffic Zone), CTR, MATZ (Military Air Traffic Zone), danger areas, prohibited zones etc.)
- the probability of loss of control of BSP-weight-drive type,

dependent variables as well:

- the type of alternate device
- experience the operator.

Source of knowledge acquisition will be current weather information and forecasts, NOTAM (Notice to Air Men) information of ATC (Air Traffic Control) and maps, alternative technical data technical means, the data of the customer.

According to method Value Streaming Map (VSM) created number of alternative scenarios. Generated on about 44,000 scenarios includes factors has influence on the decision-making process.

The decision making process follow heuristic or soft computing methods and tools such as Decision Trees (DT), Fuzzy Interference System (FIS), Belief Networks (BN). The concept of a linguistic variable in the case of FIS provides a means of approximate characterization of phenomena which are too complex or too ill-defined to be amenable to description in conventional quantitative terms. In particular, treating Truth as a linguistic variable with values such as true, very true, completely true, not very true, untrue, etc., leads to what is called fuzzy logic. By providing a basis for approximate reasoning, that is, a mode of reasoning which is not exact nor very inexact, such logic may offer a more realistic framework for human reasoning than the traditional two-valued logic (Kołodziejczyk 2011)

FIS (Fuzzy Interference System) is trying to formalize human reasoning process using natural language using fuzzy logic (that is, through the construction of fuzzy IF-THEN rules).

Fuzzy inference system consists four modules:

- Fuzzification: Converts the entry system, which are acute values (numeric) to fuzzy. This is done by applying a function belonging.
- Knowledge Base: stores a set of IF-THEN rules provided by the experts, which is a formalized, understanding of the addressed problem.
- Mechanism of inference: simulates the human reasoning by fuzzy inference process inputs in, accordance with the logic of the stored in the IF-THEN rules.
- Defuzzification: Converts a set of fuzzy inference resulting from the sharp values (Zadeh 1975).

In the case of uncertain knowledge we are dealing with statements, which in the general case, you can't say with certainty that they are real or fake. A method of characterization of the degree of belief about the veracity of statements is needed for this purpose. Both belonging to the initial knowledge base, as well as obtained in the result of the vote.

The coefficient of adequacy (likelihood of sufficiency-LS), is a measure of belief, that hypothesis (H) will occur if the condition occurs E. Factor of having (likelihood of necessity-LN), is a measure of belief an expert as far as the condition is necessary for the occurrence of hypothesis H. These measures can be given by an expert or derived from conditional probabilities according to designs. In this project the author relied on measures provided by an expert (Marszałek 2018).

To build the model uses probabilistic inference based on Bayes conditional probability given the logic. Independent variables are specified on input. They specify the numeric intervals derived from meteorological information or categories described in AIP (Aeronautical Information Publication). Selected rules that combine harvest limits and sets of numeric values and their mutual relationships.

On the basis of the data from the expert you have created a collection of teaching data. Divided into data on learning and testing. The data-sharing was made at random 70% of teaching and 30% of the testing data. Test data trimming model parameters random data and they are used for verification of the model. In this model, instead defuzzification is created category or module category.

5 Conclusions

Consideration presented above an next stage of research objectives and presented research tools and methods describe present status of investigation. Results of scientific research will be the instrument for decision making and management remotely piloted aircraft systems (RPAS/UAV). Those scientific research determine preparation to doctor thesis “THE STUDY AND VERIFICATION of SUBVENTION MODEL THE COMPARATIVE ESTIMATION of CHOSEN AIR-SERVICE PROCESSES WITH UTILIZATION of THE ALTERNATIVE TECHNICAL MEANS” follow the resolution of Faculty Organization and Management Council branch production engineering. Authors estimate to present progress of research and future results. Research intention is to review if the created model will be an adequate tool for middle level decision point in maintenance system of line critical infrastructure.

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Hedonic Model for Off-Campus Student Housing Around Thammasat University, Rangsit Campus

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Abstract Thammasat University (TU) is one of the oldest and most well-known universities in Thailand. The Rangsit campus of TU has the largest number of students. The area around the campus has continuous development, which convinces people to come for studying and living around this area. With the increasing population in the area, the demand for residences has also increased. The dormitories of the TU Rangsit campus can accommodate a limited number of students. Therefore, the off-campus residences, for instance, an apartment or a condominium is an alternative for students. This research studies the current trend of the facilities provided by apartments and the significant factors affecting the rental price. Thirty-two independent parameters are collected from all apartments around the TU Rangsit campus. Multiple linear regression is employed to analyze the significant factors that affect the rental price. The average rental price per month is 8079.40 Baht (260 dollars), and the average rental price per square meter is 226.85 Baht (7.30 dollars). The results indicate that the significant factors affecting the rental price are free Wi-Fi availability in the shared-common area, convenience store under the building, location, monthly maintenance price, being next to a main road, age of establishment, water heater, fitness facility, recent renovation, refrigerator, swimming pool, laundry and dry-cleaning service, and restaurant under the building.

Keywords Hedonic model · Marginal utility · Multiple regression · Off-campus housing

1 Introduction

Thammasat University (TU) is one of the oldest and most well-known universities in Thailand. There are 4 campuses of TU which are the Rangsit Campus (the largest campus), Thaprachan Campus, Pattaya Campus, and Lampang Campus. Recently, the university has recruited a lot of new students. There has been an increasing

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_49

number of students during 2013–2018 (Office of the Registrar, Thammasat University 2018). Covering the largest area and being near the capital city of the country, the TU Rangsit campus accommodates the highest number of students among all 4 campuses. This campus is located in Pathum Thani province, a prime location just outside of Bangkok. The area has continuous development, for instance, department stores, government offices, schools, and the new construction of a BTS Skytrain Station (Dark Red Line). The station can connect to downtown Bangkok and will be in service in 2021 (Bangkok Post 2019).

The dormitory service within the university can accommodate about 10,000 students (Property and Sport Management Office, Thammasat University 2004), which is only 39.8% of the total number of students at the Rangsit campus. The university cannot meet the demand of living on campus. Hence, more than half of them decide to live off campus in apartments and condominiums. Privately owned off-campus student housing also offers additional comforts to students and provides good facilities that are necessary for them.

In the past, an assessment of off-campus housing around the Rangsit campus of Thammasat University has not been done. This is chosen for research because of the growth of the population and the size of the community. Hence, this is an opportunity to study the characteristics and perceived benefits of off-campus housing. This study applies a hedonic model, where the prices depend on the utility of certain characteristics perceived by customers (Fields 2011). This study identifies the characteristics of off-campus residences that affect their price or monthly rental price. The hedonic pricing model is utilized, and the results from the model indicate the unique coefficients that can be used to estimate the marginal contribution of the characteristics offered by off-campus housing.

2 Research Framework

Surrounding areas of the TU Rangsit campus within 1.5 km from the center of the campus are carefully studied and divided into six different zones, based on the location and the characteristics. Zone 1 is closest to the center of the campus (referred to as the SC building). People who stay in this area can access the university in 3 different ways: by 5-10 min walk, by motorcycle, and by private car. Therefore, the occupancy rate of apartments in this zone is usually 100% due to the proximity to campus and the existing large food center. However, the disadvantage of this zone is that there is a local bar with live music nightly, located at the center of the zone causing noise pollution at nighttime. There is the largest number of apartments in zone 2. By foot, residents have to cross a bridge in order to access the TU campus. By car, residents have to make a U-turn to reach the campus and another U-turn for a return trip from the campus to their apartments. Moreover, road-side maintenance has recently caused traffic congestion during rush hours. In Zone 3, people staying in this zone can travel back and forth in a circle by entering the campus using the Phaholyothin gate and leaving the campus using the Chiang Rak 2 gate. No traffic congestion exists in this zone. Zone 4 consists of 2 major areas. Area 1 is located on the west of Chiang Rak 1 gate, and area 2 is located on the opposite side of area 1. Both areas are similar in that walking to the campus is not recommended because there are no connected footpaths to campus. Apartments in area 1 offer a larger room size with higher rental fees, more room types, and more facilities, for instance, a gym and a swimming pool. Zone 5 has many disadvantages in terms of traveling because there are no footpaths connected to the campus and no motorcycle taxi service; therefore, the residents usually travel by driving to the university. Even though this zone is within a 1.5-km radius from the campus, residents are required to drive up to 10 km to make U-turns to safely travel back to the apartment. To reach zone 6, drivers have to drive approximately 2 km in an alley at the U-turn point of the main road. The road that leads to the apartments in this zone is in poor condition (partially paved and some potholes).

To successfully apply the multiple linear regression model in predicting the rental price of apartments, there are variables that may have an effect on the rental price of apartments around the TU campus. In addition, the variables are arranged into categories which are internal variables and external variables. Therefore, the following are potential variables that may have an impact on the rental price of apartments around the TU Rangsit campus.

2.1 Internal Variables

They refer to the variables that are determined or controlled by the property owners (owners of the apartments or condominiums), for instance, the number of rooms and room size.

Age of Establishment of an apartment or condominium is one of the variables affecting the rental price. According to Manausa (2012), new construction will have a higher price per square foot than a used or old building when considering the same or similar size.

Recent Renovation is the variable that refers to the apartment's or condominium's conditions. Renovation is about maintaining the structure, components, architecture, and ensuring the safety of the property or the residence. In addition, proactive maintenance is important to conserve the value of a property; without maintenance, the property could lose 10% of its value (Riha 2018). Therefore, for some apartments or condominiums, the property owners are concerned about the maintenance of their property which could incur higher costs, leading to a higher rental price.

Room Size is a variable of concern when people make decisions for leasing. The room size and the rental price are closely related, as the value of the real estate includes the value of the area or land that it is built on. Therefore, when other factors are identical, the larger the room, the more area is used, and the higher the value (Lisota 2013).

Furnished is the basic infrastructure that every apartment provides for their renters. It is inconvenient for renters to prepare all necessary furniture by themselves when they are temporarily living in an area. The basic infrastructure or necessary furniture includes beds, desk, chairs, wardrobe, and shelves. The apartments around the campus are fully-furnished. Offering fully-furnished apartments means that property owners have to invest in furnishings. Hence, property owners will incur a higher cost. To recover this cost, property owners will increase the rental price (Craig 2018).

Fitness, Swimming Pool, and Reading/Community Room are also shared amenities that may already be included in the rental price as a hidden cost (Martin 2015). Apartment amenities are features that the property owner has in order to gain a competitive edge in attracting tenants. These amenities require a significant initial investment and an ongoing maintenance cost. Therefore, the property owner can charge tenants a higher rental price to cover these costs and receive a higher return on the investment (Leshnower 2018).

Security System—According to Chianis (2018), "Home security systems are not only for single-family residences—they are for apartments too. In fact, given that renters are historically more likely than homeowners to experience burglaries, it strongly urges people living in apartments to get security systems". An apartment with an existing security system tends to have a higher value than an apartment that does not have a security system. A security system is provided by every apartment around the TU Rangsit campus. However, it is an expense or cost for the property owner. Therefore, this cost may be included in the rental price, making the rental price more expensive.

Free Internet Access/Free Wi-Fi can be provided in the form of in-room free Wi-Fi, free Wi-Fi in the common area, or both. According to the Yorkshire Post (2014), there is evidence indicating that the internet and Wi-Fi access are highly important to people today. The average cost for internet service is about $50 US dollars or 1600 Baht per month, which depends on the provider and the desired level of internet service (CenStar Energy 2017). Hence, when providing free internet service to the tenants, property owners can charge a high rental price to cover this cost.

Electronic Appliances (Air conditioner, Water heater, Refrigerator, Television, or Microwave) refer to electric home appliances that are provided to support the daily living of the tenants. From the field survey at every apartment around the TU Rangsit campus, the fundamental electronics that every apartment provides for their tenants are an air conditioner. However, some apartments provide additional electric appliances to attract more tenants, for instance, an electric shower water heater, television, refrigerator, or microwave. Moreover, the appliances come with a high cost, so the tenants may face a high rental price when renting an apartment with many provided appliances.

Monthly Maintenance Fees refer to the prices paid by tenants for maintaining the public utilities of an apartment; for instance, garbage service and cleaning service. Some apartments may include these prices in the rental price. According to Fuscaldo (2018), maintenance prices can change the property value, as an apartment with low maintenance prices is likely to sell quicker than one with high maintenance prices. Therefore, the tenants would prefer an apartment with low maintenance prices over one with high maintenance prices.

Being Next to a Main Road: According to Mitchell (2016), one of the major concerns when the students have to choose their own apartment is the location. The location where students decide to live will have a huge impact on how they live and how safe they feel. Therefore, an apartment that has its location next to a main road is likely to be more desirable than one located in an alley.

2.2 External Variables

They refer to the outside influences that are uncontrollable by the property owners but can affect the renting decisions of the tenants, for instance, on-site facilities that are operated by a third party.

Restaurant under the Building refers to a restaurant that is located within the area of the apartment. According to Park (2016), food consumption is essential as it is directly related to the survival of human life and closely tied to a human's most basic instincts. Therefore, some people give high attention to their sources of food, which include restaurants. Hence, an apartment that has an on-site restaurant may be a preferable alternative for the tenants.

Laundry and Dry-Cleaning Service refers to drop-off laundry service where the price is not included in the rental price. Clothes are essential things for living, as everybody has to wear clothing every day. According to Ryan (2017), laundry services are convenient, but the cost can be prohibitive for some property owners to provide a drop-off laundry service. Hence, an apartment that provides a good and inexpensive laundry service for tenants is more attractive than one without.

Convenience Store is a facility that supports the daily living of people. A convenience store provides a variety of products or a wide range of everyday items, such as foods, stationery, toiletries, books, etc. According to the National Association of Convenience Stores (2016), "Younger consumers (ages 18–34) are overwhelmingly more favorable toward convenience stores than other age groups". Therefore, when choosing an apartment, the tenants may consider the convenience store, as it supports and facilitates their daily living.

3 Methodology

All variables used in this study and for the data collection are indicated in Table 1. The data were collected by telephone interviews, in-depth interviews, on-site interviews, and the official website of the residences/apartments. In a telephone interview, the telephone number of the apartment is retrieved from the internet or a resident. Through an in-depth interview, the salesperson of each apartment is involved in a face-to-face interview. In an on-site interview, each apartment is visited, where all the data are collected by asking for information from the staff of a particular apartment.

Table 1 Summary of 32 independent variables

Variables	Description
CONVENIENCE	Binary: if there exist a convenience store within 500 m = 1; else = 0
FOODCENTER	Binary: if there exist a food center within 500 m = 1; else = 0
MAINROAD	Binary: if location is located on the main road = 1; else = 0
ZONE1	Binary: if location is located in zone 1 = 1; else = 0
ZONE2	Binary: if location is located in zone 2 = 1; else = 0
ZONE3	Binary: if location is located in zone 3 = 1; else = 0
ZONE4	Binary: if location is located in zone 4 = 1; else = 0
ZONE5	Binary: if location is located in zone 5 = 1; else = 0
ZONE6	Binary: if location is located in zone 6 = 1; else = 0
FULLYFURNISHED	Binary: if a room is fully furnished = 1; else = 0
ROOM_SIZE	Size of a room, measured in square meters
ROOM_PRICE	Rental price per month, measured in Baht
AIRCONDITIONER	Binary: if there is an air conditioner available in a room = 1; else = 0
SHUTTLEBUS	Binary: if there is a free shuttle bus/van service available to the university campus = 1; else = 0
MOTORTAXI	Binary: if there is a motorcycle taxi available = 1; else = 0
FITNESS	Binary: if there is an on-site fitness room/facility available = 1; else = 0
SWIMMINGPOOL	Binary: if there is a swimming pool available = 1; else = 0
SECURITYGUARD	Binary: if there is a 24-hour security guard available = 1; else = 0
REFRIGERATOR	Binary: if a refrigerator is provided in a room = 1; else = 0
WATER HEATER	Binary: if a water heater is provided in a room = 1; else = 0
RESTAURANT	Binary: if at least one on-site restaurant is available = 1; else = 0
WI-FI_COMMON	Binary: if free Wi-Fi is available only in the common area = 1; else = 0
COMMONAREA	Binary: if there is a common area provided for all residents = 1; else = 0
BALCONY	Binary: if there is balcony/terrace in each rental unit = 1; else = 0
LAUNDRY	Binary: if there is a coin operated laundry service available on site = 1; else = 0
COST_ELEC	Cost per unit of electricity
COST_WATER	Cost per unit of water
MAINTENANCEPRICE	Maintenance fee, paid per month
CONTRACT	Minimum rental contract, measured in months
AGE	Age of a property, measured in years since it was built
RENOVATE	Binary: if a property has recently been renovated = 1; else = 0
RENOVATE_AGE	Age of a property, measured in years since it was renovated

Lastly, the internet is also used as a source of information, for instance, the room type and rental price.

3.1 Multiple Linear Regression Model

The multiple linear regression model is one of the most common linear regression analyses. The model explains the relationship between two or more independent or predictor variables and a dependent or response variable, where the independent variables can be dummy coded (as appropriate). The relationship between independent variables and dependent variable can be modeled by fitting a linear equation to the collected data (Department of Statistics and Data Science, Yale University 1997–1998). Using this hypothesis, the article states, "Every value of independent variable x is associated with a value of dependent variable y" (Department of Statistics and Data Science, Yale University 1997–1998). In other words, y depends on more than one x, and the form of relationship or regression model can be expressed as

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon$$

where β_0 is a constant and the intercept, k, is the number of independent variables x, ε is the error of the model which approaches 0 or no error, and β_k is the parameters or regression coefficients for estimating variable x_k. The statistical tests can be performed to assess whether each regression coefficient is significantly different from zero, which means that this independent variable has a significant impact on the dependent variable.

The multiple linear regression model can be used to predict the unit rental price of the apartments or condominiums around Thammasat University (Rangsit campus), where there are many factors influencing the rental price. The unit rental price is stated to be the dependent variable (y), and the influenced factors are stated to be independent variables, x.

4 Results

4.1 Descriptive Result

Zones are divided into six zones. There are 42 apartments and 141 room types available. Most of the apartments require at least a 12-month contract. There are only 5 apartments that require a minimum 3-month or 6-month contract. The highest number of rooms provided is about 4000 rooms at the Golf View residence, and the lowest is 50 rooms at the JC Living residence. The oldest apartment is 20 years, and

Table 2 Summary of descriptive statistics

Variable	Total		
	Average	Median	Standard deviation
Number of rooms	466.92	220.00	891.80
Room size (m^2)	35.24	30.00	10.80
Rental price (Baht per month)	8079.40	7500.00	3548.90
Rental price per square meter (Baht per month)	226.85	229.17	60.44
Age (years)	4.74	5.00	3.47
Maintenance prices (Baht per month)	292.24	250	152.64

the age of the newest apartment is about 2 months. The largest room size is 70 m^2, and the smallest is 24 m^2.

The rental price ranges from 2000 Baht per month to 20,000 Baht per month. Also, the apartments vary in rental price per square meter, ranging from 71 Baht to 345 Baht per square meter. The water utility charges range from 4 Baht per unit to 42.8 Baht per unit. In addition, apartments charge the tenants for the electricity from 3 Baht to 8 Baht per unit. There are 29 apartments that do not collect additional maintenance fees from the tenants. The remaining apartments require maintenance fees, ranging from 250 Baht to 500 Baht per month.

All apartments are equipped with standard furniture, for instance, a bed, wardrobe, and table. Also, all rooms have an air conditioner. The apartments provide a security guard (24-hour service). According to Table 1, the average age of apartments is about 5 years. Also, the apartments employ a security guard, apartment cleaners, and staff of more than 10 people (on average). The average rental price per square meter is 226.85 Baht. Since the spaces around apartments are limited, the available parking lots vary. On average, the apartments provide parking lots that can accommodate more than 100 vehicles. Moreover, the apartments charge about 8100 Baht for the rental price (on average). A summary of factors is shown in Table 2.

4.2 Multiple Linear Regression Analysis

The price per square meter is set to be a dependent variable, while the remaining variables are set to be independent variables. The outcome of the model indicated that there are no outliers. Significant independent variables for the model consist of Free Wi-Fi only in the common area, Convenience store, Zones 2–6, Monthly maintenance price, Being next to a main road, Age of establishment, Water heater, Fitness, Recent renovation, Refrigerator, Swimming pool, and Restaurant under the building.

Table 3 provides the results of the statistical values which indicate the fit of the regression model. The *R* squared equals 0.730 or 73%, adjusted *R* squared equals 0.693 or 69.3%, and Durbin-Watson equals 1.708. *R* Squared equals 0.730 or 73%

Table 3 Regression model and their coefficients

Multiple regression analysis	Unstandardized coefficients	Standardized coefficients	*t*	VIF
Monthly rental price per square meter for a room with no additional features	212.949		9.747***	
Location				
• Zone				
Zone 2	−125.670	−0.883	−9.984***	3.565
Zone 3	−103.382	−0.655	−7.187***	3.788
Zone 4	−90.315	−0.713	−7.793***	3.822
Zone 5	−206.485	−0.792	−7.943***	4.540
Zone 6	−249.577	−0.347	−6.439***	1.328
• Being next to a main road	60.908	0.479	8.106***	1.591
Establishment (year)				
• Recent renovation	−24.466	−0.530	−6.959***	2.644
• Age of establishment	−3.361	−0.193	−3.085***	1.777
Amenities				
• Fitness	66.138	0.527	6.638***	2.877
• Refrigerator	39.518	0.327	4.181***	2.796
• Water heater (in-line, tankless)	139.652	0.536	8.224***	1.937
• Swimming pool	53.534	0.384	4.724***	3.008
• Free Wi-Fi only in common area	−40.567	−0.312	−4.491***	2.199
• Monthly maintenance price	−0.036	−0.239	−3.286***	2.412
External facilities				
• Restaurant under the building	−22.220	−0.184	−2.426**	2.616
• Laundry and dry-cleaning service	−55.185	−0.421	−6.064***	2.204
• Convenience store	−47.853	−0.303	−3.692***	3.076

$F = 19.598$***; **$p < 0.05$ and ***$p < 0.01$

indicates that the independent variables explain 73% of the variability of the dependent variable. This value of *R* squared is regarded as an excellent value, as the closer the value is to 1, the better the regression analysis (Boyer 2018). It can be concluded that the independent variables in the regression model have significance for the model or have an effect on the dependent variable. In addition, Durbin-Watson equals 1.708, and it can be considered as a no-autocorrelation problem (Field 2009). Moreover,

Table 3 shows the results of the multiple regression analysis, which indicates the significant independent variables for the model.

According to Table 3, the values of VIF are between 1 and 5. The recommended maximum value of VIF is 5. If it is greater than 5, this indicates a potential multi-collinearity problem (Rogerson 2001). Moreover, the significance values or *p*-values of all significant independent variables are less than or equal to 0.05 which indicates that there is a linear relationship between the significant independent variables and the dependent variables (IBM Knowledge Center, n.d.).

Multiple linear regression is used for estimating the value of each characteristic of the apartment. After conducting the model, 13 out of 32 independent variables indicate a significant effect on the rental price per square meter. The results are categorized for each variable, including location, establishment, and amenities which are the subcategories of internal variables, and external facilities or external variables. From the model, 212 Baht is calculated for the monthly rental price per square meter for a room if the room has no additional features.

Location

Zone 1 is considered to be a prime zone due to its high rental price. Zone 6 has a 250 Baht per square meter difference from Zone 1. Two zones that are located on the opposite side of the campus are zone 2 and zone 5. These zones' rental prices per square meter are 125 and 206 Baht, respectively, which are less than the rental price from the reference zone, zone 1. Zone 3 and Zone 4's rental prices per square meter are only 103 and 90 Baht lower. In addition, being next to a main road is considered to be a more influential variable that affects the rental price than the rental price of the reference zone. An apartment that is located next to a main road can increase its rental price by 60 Baht per square meter.

Establishment

There are two variables which affect the rental price per square meter; recent renovation and age. Both variables are inversely related to the rental price per square meter. Recently renovated properties can increase their rental prices by 35 Baht per square meter. For one additional year of age of the properties, their rental values decrease by 3 Baht per year. This result implies that even though an apartment has been established for many years, keeping up with maintenance is important, to maintain the quality and the structure of the building.

Amenities

A water heater and a refrigerator are in-room features. In contrast, fitness and a swimming pool are facilities in the common area. All 4 variables can increase the value of a property. A water heater has the highest impact among 44 variables and increases the rental price by 140 Baht per square meter. Amenities in the common area are the central facilities where the usage must be shared among the residents. At some apartments, the prices are already included in the rental price or there is an additional cost, mentioned as a maintenance price. Collecting the maintenance price for the apartment will decrease the rental price, but in a small proportion. Having free Wi-Fi only in the common area will also decrease the rental price by 40 Baht per square meter. A possible reason may be because installing Wi-Fi only in common area costs less than installing free Wi-Fi in every room.

External facilities

External facilities are facilities where a property owner can gain additional profits. In the TU area, the property owners always make extra revenue from third-parties by renting spaces for commercial businesses, including convenience stores, laundry and dry-cleaning service, and restaurants. Having a convenience store, laundry service, and restaurant will decrease the rental price by 47, 55, and 22 Baht per square meter, respectively.

As mentioned earlier, all three variables will decrease a room's rental price because they may cause noise. A convenience store is normally open 24-h, which generates day-night noise (Carr 2016). Moreover, it decreases security because everyone can access the store. In summary, even though these facilities will increase the convenience for the residents, they sometimes devalue an apartment's image and reduce the residents' privacy.

5 Conclusion and Recommendations

This research evaluates the marginal contribution of the individual characteristics that comprise off-campus student apartments with an emphasis on each variable. There are 13 significant variables out of 34 potential variables, meaning that each of the significant variables greatly affects the rental price.

The variables are divided into four categories based on characteristics and pricing trends, including location, establishment, amenities, and external facilities. In the location factor, Zone 1 is the prime zone because it is closest to the campus and has the highest rental price rate per square meter among the other five zones. Two zones that have a high rental price are zones that are on the same side of campus. Moreover, being next to a main road is important. In terms of the establishment, recent renovation has more effect on the rental price than the actual age of the building. The rental price of every apartment decreases by 35 Baht per square meter annually, without any renovation. An electrical water heater is an important appliance, as it has the strongest impact on the rental price. If an apartment provides one, it can raise the rental price by 140 Baht. Lastly, external facilities give convenience to the residents, and they are additional sources of income for property owners. They receive leasing revenue each month for leasing the facilities. Therefore, having external facilities or services will likely increase the rental price from 22 to 55 Baht per square meter.

As the off-campus population continues to grow, this research analyzed the property valuation and other factors, to add more overall understanding of student housing decisions. The additional knowledge will help to make more accurate decisions in the prices of the off-campus apartments around TU. In the model, significant factors that are analyzed indicate their relative influential impacts on the price. To add more value to a property, a water heater should be considered as the first priority because it has relatively low investment and maintenance costs. Also, investing in a building swimming pool, fitness, and refrigerator can raise the rental price by a total of 55 Baht per square meter, but the investment cost is much higher than adding a fitness facility or a refrigerator in each room. The location of a property has a high impact on the price. In terms of the establishment, the number of years of renovation is more important than the actual age of the building. This means that if property owners keep maintaining the structure and the quality of the apartment, they can keep charging the same rent. Lastly, external facilities will give the property owners additional income from leasing spaces. Therefore, balancing the number of stores and keeping the quality of third-party facilities will maintain a good image for an apartment building.

Acknowledgements This research is partially supported by the Sirindhorn International Institute of Technology (SIIT), Thammasat University, Thailand.

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The Optimal Initial Buffer and Cycle Time Design for Improving Lean Production Automation Line Efficiency

Duong Vu Xuan Quynh, Chawalit Jeenanunta, Masahiro Nakamura and Fumio Kojima

Abstract Optimizing the size and location of storage buffer between machines is critical issues in designing efficient production automation line. The objective of the study is to propose the optimal design of the initial buffer size as well as the suitable machine cycle time to increase the efficiency of the automation line. In this study, the production system consists of three machines with two buffers are placed between them is considered. There is a regular downtime for maintenance at the second machine, which results in lower production efficiency. The production simulation on cloud is used for modelling and demonstrating the concept. The experimental results revealed the proposed optimal initial buffer and the proposed cycle time of maintenance station could yield the maximum production line efficiency.

Keywords Buffer design · Production line efficiency · Simulation model

1 Introduction

In the current international economic competition, a large amount of industrial products are produced to satisfy an enormous amount of customers every year. Therefore, manufacturing firms put their efforts on improving the production process to cut down

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_50

costs while enhance their production capacity. Lean Automation Production is therefore applied to integrating and continuously improve the production system. Lean Automation arises and becomes the potential trend for improving productivity and the overall performance of the system. However, designing a Lean Automation Production system to have highest efficiency while maintaining low work-in-process is a challenging work.

An automation production line is defined as a system with serially connected machines/workstations by handling system, where parts are transferred from one to another stations. Each part can go through all machines. However, there are interruptions happen between machines due to the difference in downtime and maintenance time of each station, which decreases the production line efficiency. In order to reduce these disruptions, buffers are placed after maintenance workstations in order to reduce the idle time of the next station, which increases the production efficiency.

The Lean Automation approach was successful and well–applied due to its high effectiveness in reducing the waste in production practices. Up to now, developed countries increase their competitive advantages by setting their production site in low labor cost countries. Although, lean automation is a critical solution to avoid non-value-creating process steps, reduce the complexity of the system and improve the productivity, automation systems face various challenges in terms of high investment costs and continuous market fluctuation. Up to now, there are many studies have been conducted applying various methods such as linear programming and heuristics to help reducing the cycle time and optimize automation system. However, there is no standardized formulas that have been accepted among researchers.

In this case, a general buffer design formula is proposed to find the optimal initial buffer size in a given context. The rest of the paper will be presented as follows: literature review, problem description, methodology, case study, result and discussion, sensitivity analysis and conclusion.

2 Literature Review

Studying the design of buffer on production line efficiency has attracted the attention of many researchers in the field of automation system design. Wijngaard (1979) studied the effect of buffer on the production output of two-stage flow production line considering factors such as the production rate, breakdown rate and repair rate. Tiacci (2015) proposed to use the buffer allocation problem (BAP) and the assembly line balancing problem (ALBP) using a genetic algorithm approach. Nahas et al. (2006) proposed a new local search approach for solving buffer allocation problem within an acceptable amount of time and producing a better result. El-tamimi and Savsar (1987) studied automated production lines with two unreliable machines with a buffer and a repairman. The failure and repair rates were different between two machines, whereas the production rates were equal between them. The study illustrated the impact of buffer size on the overall production efficiency and the total cost. Additionally, some mathematical models were designed to find the optimal buffer size with different in operation times and rates (Mohanty et al. 1989; Gupta and Houshyar 1990). Andijani and Anwarull (1997) conducted a research applying analytic hierarchy process (AHP) to identify the most-preferred allocation with three particular objectives: maximizing the average system time, throughput rate and minimizing work-in-process. Sorensen and Janssens (2001) examined a system of n machines to determine the importance of buffer allocation to the availability of the system with the objective of minimizing the total cost of installing and allocating buffers.

Simulation method was an important tool for designing and analyzing as well as improving manufacturing systems. Simulation method was applied to investigate two specific issues: what ideal combination of mean and variances of station processing times will lead to the highest system utilization and how serious it was to deviate from this ideal arrangement. Utilization was maximized when the means and variances of processing time were balanced (La 1994). Alexandros and Chrissoleon (2009) developed a model applying Markovian analysis to generate a transition matrix for any value of intermediate buffer capacity. Therefore, all possible solutions were solved analytically. This method was designed to solve larger production flow lines with parallel unreliable machines at each workstation.

Nahas (2014) studied a serial production line of n unreliable machines with $n - 1$ buffers. The system cost was minimized with a given number of throughput level by determining the optimal preventive maintenance policy and the optimal buffer allocation. Chang (2016) estimated the system reliability for a multistate manufacturing network with parallel production lines (MMN—PPL) considering finite buffer storage. Pathak (2012) used a simulation software to help designing production system to decrease the operation cost and improve product quality of a printing machine product.

Ameen (2018) proposed a simulation model to evaluate the effect of total buffer size on production line efficiency. The study was conducted by generating buffer capacity from 1 to 30 units and measure the system efficiency in each unit case. As a result, a buffer capacity that yields the maximum production line efficiency with various repair rate values was obtained. An increased in buffer capacity could lead to an increased in production output. However, there is limited studies that evaluate how initial buffer effects on the production efficiency. Unlike buffer capacity, initial buffers are put in machines at the beginning of the process to help the system start their production without waiting for parts. Thus, the amount of initial buffer units should be placed so as not to keep many inventories on hand, at the same time help the system to run smoothly will be studied in this case.

Overall, there are many contributions towards buffer allocation topic. However, solving this problem by providing practical formulas to compute the processing time and obtain the suitable initial buffer value accordingly is still fresh within the field. Provided case study is used to bring these formulas into practice. As a result, the gap between scientific research and practical experiences will also be shorten.

In this study, simulation model is designed to investigate the effect of buffer allocation on the production throughput. A practical experiment will be provided in order to reduce the idle time of the system. As a result, the proposed potential processing time formula will be provided. Noticed that this is an experimental research.

3 Problem Description

An illustration of buffer storage is represented in Fig. 1 showing $n - 1$ storages buffer exists between an n-machine line. Although many factors are mentioned in previous studies related to maintenance time, and machine down time, there are limited papers in the field that considered to optimal the machine cycle time. The aim of this research therefore is to propose the optimal initial buffer determination and cycle time design to maximize the Overall Equipment Efficiency (OEE) considering maintenance factor.

Figure 1 describes the general concept of buffering in manufacturing process. Buffers could be considered as a temporary stock station to keep inventories on hand and help to stabilize any fluctuations the system experience during their production process.

In this study, a three-stage flow of automation line with finite buffer storage is investigated. Each stage consists of one machine (M1, M2, M3). The output of machine n will be the input of buffer and machine $n + 1$ at the next station as illustrated below:

Assumption of the production system

The production system is considered in this study is assumed to have the following characteristics:

- Defective products will not be considered in the result of the Overall Equipment Efficiency (OEE).
- Assume machine 1 (M1) is a non-stop working station (no failure occurs to M1).
- Maintenance mode happens at M2 station only with repairment is treated every 100 pieces of products.
- Machine 3 (M3) will stop working due to the following events: the production rate of machine 3 is faster than that of machine 2, experiencing starving mode; machine 2 (M2) is in maintenance mode and buffer 2 (B2) capacity reduces to 0. If buffer 2 (B2) level reaches 0, before the maintenance of the failed machine (M2) is completed, machine 3 (M3) will fall into the idle mode due to the unavailability of the incoming components.
- All buffer capacities are unlimited.

The main objectives of this study is to propose initial buffer and cycle time formulas design, which applies for practical applications in automation line in factories. The case study provided shows the efficiency of the proposed formulas and the way they should be applied in real life problems. Moreover, a new GDfindi simulation

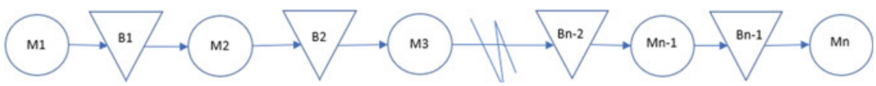


Fig. 1 The production automation line with buffer between each machine

software is used to determine the effects of the buffer storage, the repair time (maintenance) on the production throughput and production line efficiency. Lastly, provide the optimal initial buffer size and optimal machine cycle time to keep the system runs efficiently despite the existence of maintenance events.

4 Methodology

In this section, we will explain in detailed three studied cases as well as how the formulas are applied to solve the problems.

The first case represent a simple system in the factory, with maintenance is treated every 100 products of production. By observing the first case, the common problem of many factories is described in the clearest way with the simplest system of three machines model. The next case proposed a solution to solve the problem by applying the optimal machine cycle time formula. Then, the results are analyzed to see the improvement within the system after applying new machine cycle time value. In the last case, the initial buffer size determination is conducted which bases on the computed machine cycle time in case 2. Result and discussion part is mentioned to provide the deeper understanding about this study.

In the end, sensitivity analysis is provided to evaluate the performance of three cases. Further research will also be discussed at the last section.

GD.findi Production Simulation on Cloud

The simulation model has been developed using GD.findi production simulation on cloud, provided by Lexer Research Inc. which consists of many useful functions that support the simulation design. The floor plan and the process plan are two main functions of this application. Floor plan is used to represent factory layout of production lines, plant and equipment process plan helps to define production processes with the use of Bill of Material (BOM), and describing manufacturing sequences and process specifications. This approach of GDfindi could be considered rare in today simulation software markets, their special features have been tested by many managers from different manufacturing organizations/companies with good impression.

Overall Equipment Efficiency (OEE)

The system efficiency is defined as the proportion of time that the last stage is in operation (Ameen et al. 2018). In this case, it is illustrated by the equation below:

$$OEE = \frac{\sum WT_m}{Total\,time}$$

WT_m is the total work time (WT_m) that m stations spend to produce products in a whole production process, whereas total time consists of total working time (WT_m), total maintenance (MT_m) and total idle time (IT_m) of all stations.

Figures 2 and 3 show the floor plan and the process plan in GDfindi software interface. The Floor plan shows the system layout with three machines and two buffers, whereas the process plan shows the processes that associate to each station.

Optimal Cycle Time for Machine with Downtime

The equation is used to compute the optimal cycle time for machine m with downtime machine. Line Cycle Time is the expected work time needed to produce one unit of product, whereas setup interval (SI_m) indicates the number of products is expected to be produced before maintenance is treated. In other words, maintenance is treated every SI_m products being produced with the maintenance duration is MT_m seconds. Therefore, optimal cycle time of machine m is determined by reducing the work time per unit by exactly the amount of time for maintenance per products before maintenance. As a result, the system can run smoothly without interruptions.

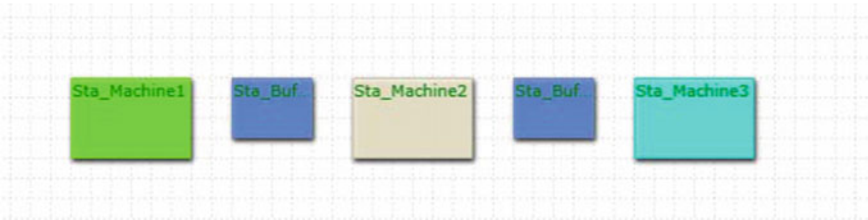
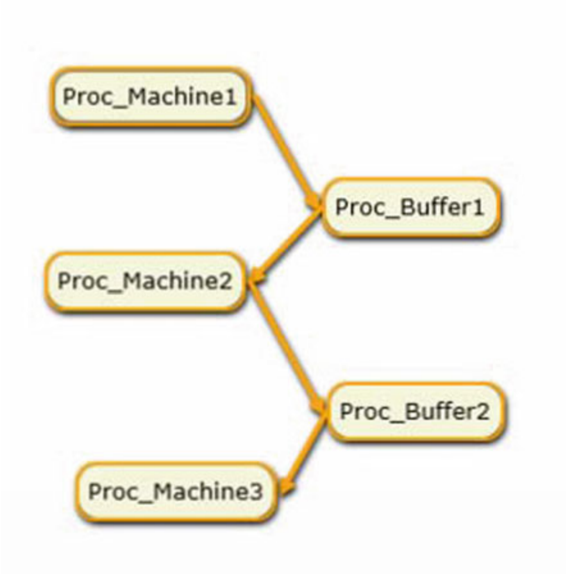


Fig. 2 GD.findi floor plan for the case study

Fig. 3 GD.findi process plan for the case study



$$Machine\,Cycle\,Time_m = Line\,Cycle\,Time - \frac{MT_m}{SI_m} \quad (1)$$

Initial Buffer Design

In general, if the maintenance machine m has a faster Machine Cycle Time (MCT_m) compare to the previous machine (MCT_{m-1}). Then we need to prepare initial buffer at buffer $m-1$ by the following amount:

$$Initial\ Buffer_{m-1} = \frac{MT_m}{MCT_m} \quad (2)$$

Case Study

In this case, a three machines model is built as to demonstrate the effect of initial buffer size on the overall production efficiency. There are three machines, two buffers with one maintenance at machine 2 (M2) with the production goal of 500 products. Work time of three machines are 10 s per unit. There are two buffer placements B1 and B2 which are placed between machine 1, 2 (M1, M2) and machine 2, 3 (M2, M3), respectively. Maintenance is treated every 100 products being produced with the duration time of 120 s. The formula (1) is applied to obtain the optimal Machine Cycle Time of machine 2 (M2) station with the value of 8.8 s. As machine 2 (M2) reduces its Machine Cycle time (MCT_2) to 8.8 s, thus it will be faster than that of the previous machine (MCT_1). As a result, machine 2 (M2) will be starved due to the lack of incoming product. Therefore, the initial buffer needs to be prepared to avoid idling time of machine 2 (M2). This $\frac{MT_m}{MCT_m}$ units of buffer are used to prepare enough initial buffer to use before maintenance is treated on machine 2 (M2). Then during the maintenance time, more products will be produced to save for the next maintenance time. The initial buffer is then obtained using formula (2) with 14 units of optimal initial buffer capacity.

There are three scenarios will be discussed in this section.

Case 1: Basic model with no initial buffer.
Case 2: Reduce M2 cycle time.
Case 3: Set initial buffer.

Detailed parameters including maintenance time (MT_m—seconds), Machine Cycle Time (MCT_m—seconds) and initial buffer (IB—units) will be provided in the following Table 1.

5 Result and Discussion

In this section, simulation results will be presented including operation rate, idle time, working time, average production rate. In each case, the operation rate of machines increases due to the work time improvement of machine 2 and the initial buffer

Table 1 Operation time in cases

Station	Case 1			Case 2			Case 3		
	MT_m (s)	MCT_m (s)	IB (units)	MT_m (s)	MCT_m (s)	IB (units)	MT_m (s)	MCT_m (s)	IB (units)
M1	0	10	0	0	10	0	0	10	0
B1	–	–	0	–	–	0	–	–	14
M2	120	10	0	120	8.8	0	120	8.8	0
B2	–	–	0	–	–	0	–	–	0
M3	0	10	0	0	10	0	0	10	0

determination. Therefore, the Overall Equipment Efficiency (OEE) is also enhanced (Table 2).

Table 3 reveals the general view and the improvement in three cases. The maintenance time in three cases are the same, whereas the idle time and working time have a significant improvement. In particular, idle time reduced to 296.4 s in the last case which is 70% reduction compare to the first case and 50% compare to the second case, respectively. Besides, the Overall Equipment Efficiency is also improved by 3 to 4% in the last two cases and the production rate per hour has enhanced by 20 units in the second case and 30 units in the last case. In general, the required time needed to spend for production has been reduced (work and idle time reduction), which follows by the improvement of OEE value.

Inventory Analysis

In the first case, the production automation line with maintenance is treated every 100 products being produced is observed and evaluated. Interestingly, the result indicates that the operation ratio of the three machines is considered equal with the value of 90.90%. Table 4 represents the inventory level of three machines for three cases. For Case 1, Machine 1 is stable maintaining the value of 1 unit in the whole production process, whereas the second machine has to deal with the climbing units of buffer level. Lastly, machine 3 facing the starving condition (reaches 0 unit). In brief, the inventory level of three machines in the first case indicates the inventory cost will rise significantly without managing the work-in-process inventory.

Figure 4 captures the machine's status as a Gantt Chart from GD.findi software. The yellow bar indicates the maintenance mode of machines. The blue bar indicates the busy or working mode of the machines, whereas the red one illustrates the idle mode. The grey area is the amount of work-in-process waiting at the buffer in front of each machine. It can be observed that, every time machine 2 falls into the maintenance mode, machine 3 is also idle. There is a large amount of work in process parts is

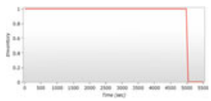
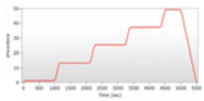
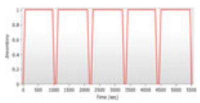
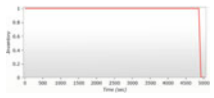
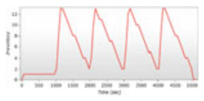
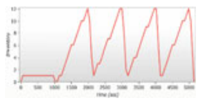
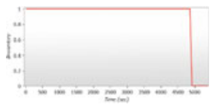
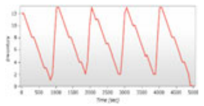
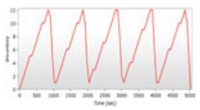
Table 2 Operation rate and over equipment efficiency

Scenario	Operation rate in stations			OEE (%)
	Machine 1 (%)	Machine 2 (%)	Machine 3 (%)	
Case 1	90.90	90.90	90.90	90.90
Case 2	97.30	85.62	97.30	93.40
Case 3	97.03	87.85	99.82	94.90

Table 3 Simulation results for each case

Model	Idle time (s)	Maintenance time (s)	Working time (s)	Average production rate (/h)
Case 1	1020	480	15,000	327.27 units
Case 2	536.4	480	14,400	350.26 units
Case 3	296.4	480	14,280	358.64 units

Table 4 Inventory level in cases

Scenario	Inventory level		
	Machine 1	Machine 2	Machine 3
Case 1			
Case 2			
Case 3			

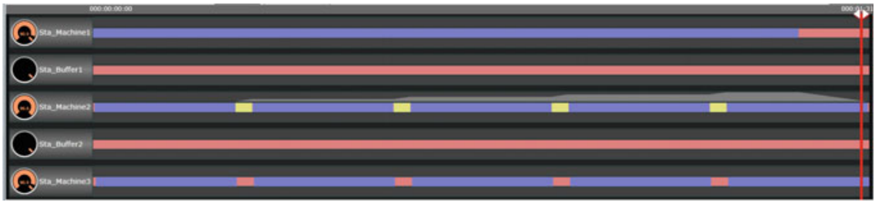


Fig. 4 Material flows of machines in case 1

waiting in front of machine 2 that causes the grey area above machine 2. In particular, despite machine 1, 2 and 3 have the same cycle time, due to maintenance is treated on machine 2, the production rate of machine 2 is slower than that of machine 3 and 1. Therefore, the level of inventory in machine 2 will be increased dramatically due to the overwhelming of incoming parts of the previous station (M1). As a result, machine 2 cycle time needs to be faster.

For Case 2, Table 2 indicates the operation rate of machine 2 reduces to 85.62%, whereas the operation rate of machine 1 and 3 increases by almost 6% in this case (97.30%). The overall equipment efficiency rises 2.4% compares to the previous case.

Interestingly, idle time at Machine 2 can be observed from Fig. 5. At the first stage, the production rate of Machine 1 is slower than Machine 2, so M2 falls into the "starving mode", which causes some idle time. During maintenance mode of M2, the work-in-process build up at buffer 1. Once, M2 becomes available, the work-in-process accumulate at buffer 2 due to the faster Machine Cycle Time of M2, which helps to supply parts for M3 during the next maintenance in M2. Although there are some idle times appear at Machine 3, the inventory level at buffer 2 is accumulated because Machine 2 is faster than Machine 3. As a result, the inventory level in

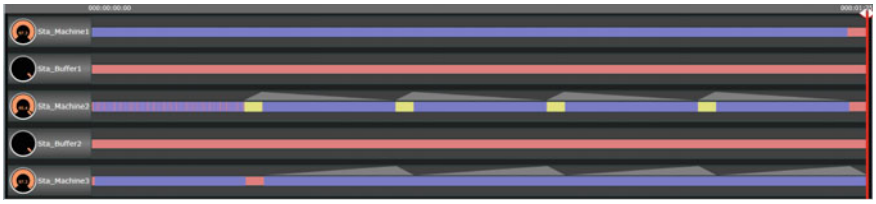


Fig. 5 Material flows of machines in case 2

three machines are enough for the whole production process, which helps to prevent "blocking" and "starving" mode and enhance the Overall Equipment Efficiency. Moreover, the idle time of machine 3 after the first downtime has been eliminated.

In order to overcome the idle times of machine 2 station, initial buffer of 14 units will be placed in buffer 1, which is computed based on the Machine Cycle Time (8.8 s). It can be seen in Fig. 6, after adding 14 units of buffer capacity at buffer 1 station, the idle times in the M2 have been eliminated. Moreover, the idle time of M3 is also eliminated.

From Table 2 in case 3, the operation rate of machine 1 maintain the rate of 97%, whereas 2% has been added for the two last machines (from 85 to 87% and 97 to 99%). Therefore, the overall equipment efficiency has increased by 1% (from 93.4 to 94.9%).

According to Table 4 in case 3, machine 1 buffer level is stable at 1 unit, which always keep the system at the working mode. Similarity, Machine 2 also maintains the WIP with the range of 1 to 14 units. Lastly, the idle time of Machine 3 causing by maintenance of M2 has been eliminated.

It can be said that, determining the optimal cycle time for machine 2 and optimal initial buffer has improved the overall production average. In brief, balancing the production rate within stations plays an important role for the improvement in the production line efficiency.

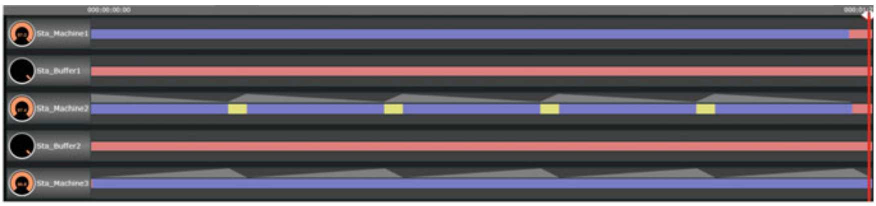


Fig. 6 Material flow of machines in case 3

6 Sensitivity Analysis

The following line charts provide the evaluation of production rate average/hour of the experiment (Fig. 7).

Since there is no initial buffer or optimal machine cycle time is applied on case 1, the average production rate per hour reduces from 327 units/h to 322 units/h. However, the reduction rate reduces then remain nearly constant after 4000 units of production goal (Fig. 8).

After determining the optimal machine cycle time, the production rate average at the starting point is also improved, which is 10 units greater than that of case 1. Then, continue to rise from 350 units to almost 360 units/h (Fig. 9).

Applying both formulas, this case obtain the greatest beginning data point compares to the others with 359.4 units. However, the improvement speed in this case

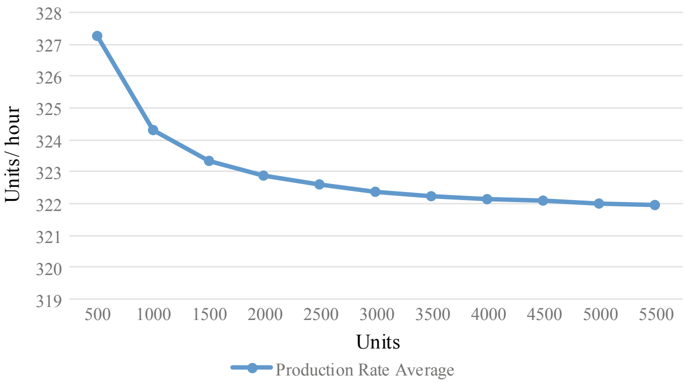


Fig. 7 Production rate average/h case 1

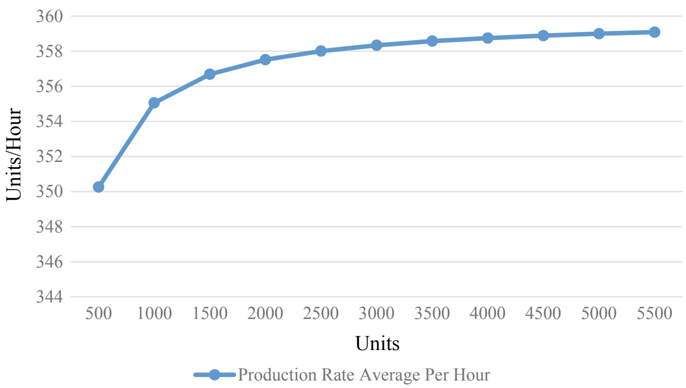


Fig. 8 Production rate average/h case 2

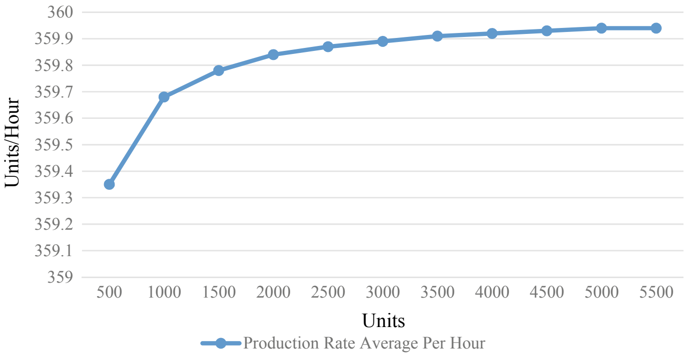


Fig. 9 Production rate average/h case 3

is reduced. In particular, only 0.2 units/h increases for every 500 added units of production goal.

Interestingly, the common point of three cases is that, they all get into the constant stage after a certain amount of added production goal. Moreover, case 2 production rate rising speed is faster than that of case 3. Therefore, at the last point of 5500 units of production goal, case 2 achieved value is almost equal to that of case 3. This reveals that, the improvement of machine cycle time has a greater impact on the production output of the overall system, whereas, the initial buffer size determination keeps the system stable.

7 Conclusions

In this study, the optimal initial buffer size and machine cycle time are provided to improve the production line efficiency. Moreover, the machine with the regular maintenance need to find optimal cycle time so as to reduce the effect of idle time on the production line efficiency. The result demonstrates the significant improvement on efficiency placing the optimal buffer before maintenance station. This research shows the important role of buffer capacity, allocation as well as line balancing in designing and enhancing the efficiency of the production line in a practical way.

Lastly, the proposed optimal initial buffer size and optimal cycle time for maintenance machine formulas may also be applied to more complicated production system. However, the positive effect may be reduced due to the involved of many other factors towards a complicated system. Further investigation should be provided to extend these practical formulas within a more complicated system. Advanced techniques and some heuristics such as Genetic Algorithm and Tabu Search could also be investigated.

Acknowledgements We would like to show our gratitude to Lean Automation System Integrators (LASI) Project, Denso Corporation. We would like to thank Dr. Masahiro Nakamura and Mr. Teruo Oohashi, from Lexer Research Inc. for their kindly support in this research. We want to send our deepest appreciation to Sirindhorn International Institute of Technology (SIIT), Thammasat University (TU), Thailand as well as Logistics and Supply Chain Systems Engineering Research Unit Center for Demonstration and Technology Transfer of Industry 4.0 for financial support our research. This study was also partially funded by Studies for Science and Technology Foundation (STF).

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Combining Takt and Deming Cycles at Operator Level—Practical Study

Jon Lerche, Hasse H. Neve, Søren Wandahl and Allan Gross

Abstract Few empirical studies have previously been reported on implementation of takt planning and controlling the workflows continuously. This paper presents a case study from the offshore renewable industry, which is closely related to construction. The paper aims to develop and trial a conceptual model for combining takt planning and PDCA, also known as the Deming cycle in construction environments. The conceptual model has furthermore been modified for a visual board implementation that covers a specified process with a fixed number of technicians per performing team. The conceptual model draws on knowledge of takt planning implementation from the lean construction community and PDCA implementation from the lean production community. The main contribution of this paper is the conceptual model combining takt planning and Deming cycle in a construction environment. This conceptual model has potential implications in the construction and refurbishment industry.

Keywords Construction · Deming · Management · Offshore · Takt

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_51

1 Introduction

1.1 Offshore Wind Turbine Construction Projects

From a turbine provider perspective, a project starts with a contract negotiation and customers choosing expected power output of the turbines. The project then formulates the design interfaces between cabling, foundation, and turbines. At the same time as the design formulations are prepared, the larger installation vessels are booked for installing foundations and turbines, as these hold a major contingency of the overall construction cost. When these parameters are defined, the turbines are set in production and later received at a designated harbor port facility. Here towers, nacelles, and blades are prepared for later offshore installation (Barlow et al. 2014) where the turbines will move into operation and start the power production. Various studies have focused on offshore wind project planning. Alla et al. (2013) focused on the overall project planning, including cabling, foundations, and turbines. Backe and Haugland (2017) investigated port and vessel configurations for the project plan, emphasizing the potential effects from the weather. Ursavas (2017) further developed the understanding of offshore wind farm installation planning and how calculations for this are highly affected by the changing weather conditions and how this is seen as a critical factor in the plans.

Wind turbine construction operates with repetitive tasks which have minor differences, similar to the case study presented by Heinonen and Seppänen (2016) from cabin refurbishment in a cruise ship. Hence, wind turbines can be perceived as standard products or modules that are manufactured and later constructed within the project-based production paradigm. In construction, modulization has had increasing attention (Peltokorpi et al. 2018) and the increased standardization makes it ideal for takt planning. The project shifts from land to offshore, which increases the importance of continuous improvements and a thorough plan. Liker and Meier (2006) described a combination of Deming cycle and takt planning within the car manufacturing industry (Liker 2004). Frandson et al. (2013) developed the understanding of takt applied in a construction setting with repetitive activities, which is also a known practice in location-based scheduling (Seppänen 2014).

Even though planning of wind farm installation is a developed topic, takt is not yet seen as it is in manufacturing (Liker 2004) or construction (Frandson and Tommelein 2014). Neither takt nor the Deming cycle (Deming 2000) had previously been introduced to the planning of offshore wind farm installation. In this study, we will present a case study of the installation processes for turbines in an offshore construction project and the implementation of takt and PDCA in a combined conceptual model. The project and the results from the implementation of the lean methods are presented. Finally, results are compared with existing takt literature, and the implication possibilities for lean construction are discussed. For academics and practitioners, this paper presents a conceptual model for takt planning and PDCA combined in a construction environment.

2 Case Study

2.1 Case Project

The case data was gathered in collaboration with an offshore wind turbine construction site, located in the British sector of the North Sea. The project organization is considered temporary, as the teams are brought together for executing this specific project for a known client to fulfill a contract as turbine supplier with a total expected power output above 400 megawatts for the complete wind farm. The project team had, prior to the construction phase, focused on planning of the construction works and generated takt workflows to understand the risks and identify improvement potentials. These initiatives and schedules are to meet contractual targets for various processes and milestones in the project. The selected process for this case study is part of the offshore installation requiring a large jack-up vessel (Barlow et al. 2014). The daily vessel charter rate is at approximately 200,000 EUR. The contractual target is 19 h of lead time per installation run throughout the project. Besides defining the takt, the vessel charter cost also motivated the project organization to continuously improve their processes. This makes the vessel and equipment the main cost drivers during the installation phase. The available number of vessel cabins limits the number of available technicians during the voyage and processes. The process studied here is considered similar to takt operations seen in manufacturing and construction. During the installation, the components are relocated to their final assembly positions by utilizing the vessel crane, and the technicians go through the product as if it were a high-rise building. The workstations are defined by the interface assembly points of the turbine: foundation—tower, tower—nacelle, nacelle—blades. The process planning and control system include the following three steps and will be described below:

- Standard installation process workflows
- Conceptual model for takt and PDCA
- Operational roles and responsibilities.

2.2 Existing Workflow

The workflows define the planned durations for the team of technicians executing the construction process together. Each complete run-through would then be considered an actual duration and here referred to as a lead time. The formalized workflows are based on the takt planning methodology and had previously been mapped and organized. But they are based on the team of multiskilled technicians working together, in contradiction to how Frandson et al. (2013) organized it per trade. The takt system here is developed on a team level in similarity with the structure described by Frandson et al. (2014). The turbine installation processes have a low variation and complexity, which enables organizing activities among specialists, assuring the processes are commenced systematically in the various locations. The locations here are defined by the vessel deck or main components—foundation, tower, nacelle, and blades—but these are not directly reflected in the individual workflows. Each row is divided between the team roles and gives a clear illustration of the tasks and the structure which must be performed. The role could potentially be exchanged with locations. If locations would be more applicable to the overall project planning methods such as location-based scheduling (Kenley and Seppänen 2010), this would require considerations of the operational level and trades. The columns in Fig. 1 display the timeline at top and then give the time stamps for when the activities are organized to be performed by each individual technician. The task headlines and durations are directly marked in the schedule, and if multiple technicians are required for individual activities, this would be reflected by similar task descriptions. Color segregation could also be used to create an easy overview of the processes for the technicians and managers. The project teams are familiarized with this way of working, enabling further development of a conceptual model.

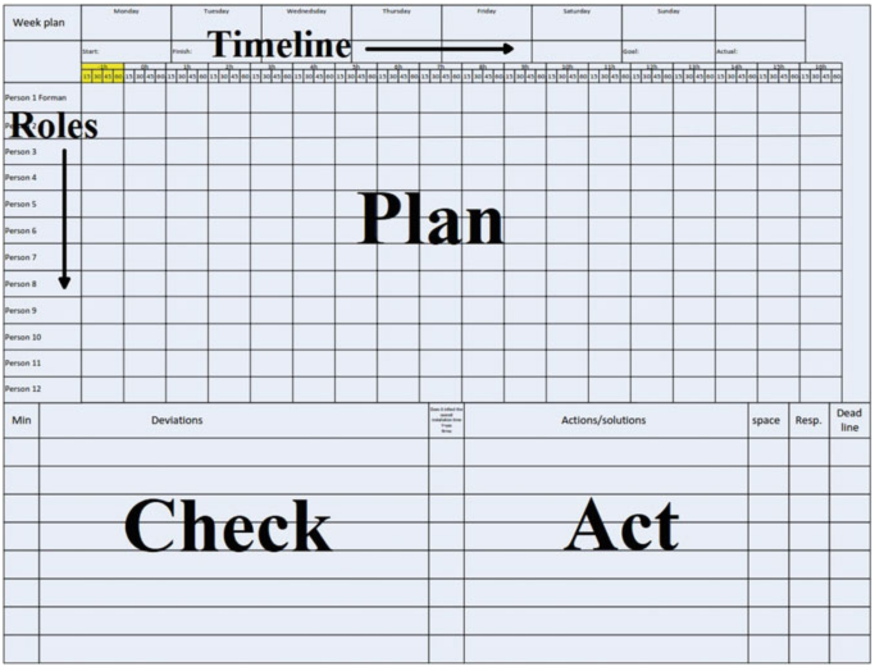

Fig. 1 Takt table design with the PCA

2.3 Conceptual Model Development

The following section shows the findings and development of the conceptual model for combining takt planning and Deming cycle in a visual board solution intended for the team levels. This was initiated with understanding of the activities and structuring these between the individual roles as described above. The Deming cycle (Deming 2000), also commonly known as the Plan-Do-Check-Act (PDCA) cycle, has been widely utilized in industry standards and management systems (ISO 2018; Liker 2004).

- Plan—Describing *how* and *what* and ensuring processes are aligned with the objectives.
- Do—Performing the processes or tasks according to the plan.
- Check—Measuring the performance, deviations and results of the processes compared to planned.
- Act—Acting to eliminate deviations or improvements to the existing processes.

PDCA has been a method for improving work processes, handling issues, and improving the business or organization. The four steps have also been presented by Liker and Meier (2006) as a driver of continuous improvements and key element in a learning culture (Frandson et al. 2014). The utilization of the PDCA in this case was motivated by the continuous improvement potentials and understanding how or if this could affect the workflow durations. Teams could use it as a communication method and structure for meetings concerning deviations or corrections in the flow. This streamlined the decision process. A workshop in collaboration with the operational team was organized to uncover the potentials and to further understand how the workflows in combination with PDCA could be displayed for the teams.

The case owner agreed to create a visual and adjustable solution for the daily interactions within the team that could assist them in their decision making. During the workshop, visual management was discussed in the construction context, referring to "why" manufacturing had chosen to utilize visual management (VM) through years. Koskela et al. (2018) argued that "Mental operations, such as communication and decision-making are strictly seen waste in production; they are not adding value to the customer. Through VM, communication and decision-making can be sped up." The operational team agreed to develop the conceptual model around their existing workflows and with a systematic way to handle deviations or improvements. The product of the workshop is described here and illustrated in Fig. 1. The fields are as shown in Fig. 1 and marked as "check" and "act," which both relate to the PDCA cycle (Liker 2004; Deming 2000). These inputs are then used for adapting the workflow if required and reducing the waste in the daily operations by making deviations visible for operators. Figure 1 is then illustrated in Fig. 2, which comes from the case project. Here the tasks are organized for the operators. The visual display of the workflow is then as illustrated in Fig. 1, combined with rows for deviations marked "check" on the left and actions marked "act" on the right. Between check and act there is a column for whether the deviations affect the lead time, indicated by "Y" for yes and

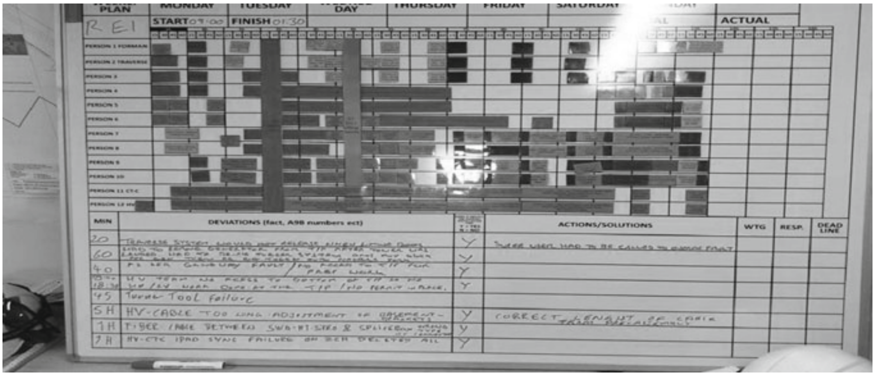

Fig. 2 Takt table picture from implementation

"N" for no. Float in the schedule is reflected by "N," as these deviations don't affect the overall performance. "Y" is considered similar to stopping a production line and thereby affecting the lead time. Next to the actions, a "space" column illustrating the location which is affected by it. The following columns organize the solution owner (responsible) and deadlines for the action. Each item is listed in individual rows to ensure that deviations, actions, etc., are linearly connected.

2.4 Resources and Responsibilities

The operations supervisor ensures coordination with team and vessel interfaces such as technicians, crane operators, deckhands, master, and client representatives. Further, the supervisor handles the interface toward the project organization, logistics, equipment, and tools. As a shift starts and ends, the operative supervisors conduct a briefing and debriefing of the team about their performance and occurrences throughout the shift. The supervisor has the responsibility of following up on deviations and actions, in addition to assisting the foremen in the implementation of changes to the workflow.

The foreman has the responsibility of organizing and leading the team. This consists of multiple specialized roles, such as mechanical, electrical, or specialized operator. Together, these technicians form a united work force, which in comparison with construction would require carpenters, electricians, bricklayers, and plumbers to be engaged simultaneously and work together under the team umbrella. Each role in the workflow is organized according to the individual's competences, trade, and profile. Figure 2 shows the daily tasks during the construction phase for the technicians. During the performance of the tasks, the team members register obstruction or optimization potentials, which are by the end of each shift registered as deviations. All deviations are listed in the "check" area, and at the end of each shift, the team is debriefed about performance and issues or improvement suggestions. The board

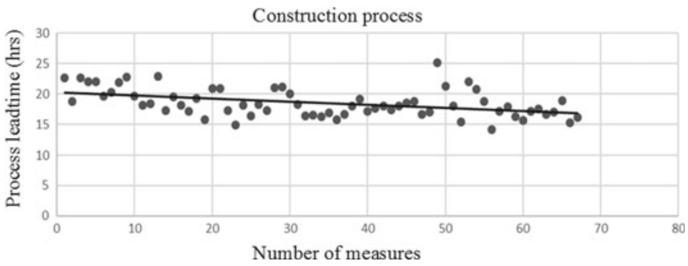

Fig. 3 Registered process lead times and trendline

ensures visual overview and traceability for the on-signing shift, reducing decision making time for them as they have a clear overview of the situation and performed.

3 Achieved Results

The case owner agreed to implement the conceptual model, with continuous performance measures afterward. These performance measures were conducted by operational managers taking pictures (Fig. 2) of the visual board after each run-through. The process lead times include preparations, lifting operations, assembly of main components, and ensuring the turbine is at a certain stage for the commissioning teams that follows.

Each process run-through for the installation was cleaned for adverse weather delay registrations, as these were not contractually included. The data are presented here in a scatter diagram with a trendline. Figure 3 illustrates the multiple lead times for the installation processes registered during the case study. The trendline illustrates a downward tendency. The trendline illustrates a trend from 20 to 16 h lead time, giving a 20% reduction by utilizing this conceptual model with takt time planning of the activities. This reduction was generated through stabilization of the workflow, by continuously adapting minor improvement adjustments and removing obstacles in the flow. Every deviation was registered on the board and transferred to an Excel register for later follow up and potential analysis of occurring errors. These data registration could be used to improve future project executions.

4 Discussion

4.1 Workflow Comparison

Wind turbine construction is similar to construction in multiple aspects: the project-based production, pre-fab elements, and fixed position manufacturing. This is also reflected in the external conditions of the turbine construction sites being subject to weather conditions (Alla et al. 2013; Ursavas 2017), which is also seen within regular construction (Koskela 1999). These flow conditions enable the workflows and performance of the teams if they are prepared, no matter if constructing wind turbines or pre-fab buildings. Trades are organized and move through the products (Tommelein and Riley 1999). The foundation for the wind turbine construction here was the formalized workflow illustrated in Fig. 2, which defined the movements through the products. Tommelein and Riley (1999) described the deviations in the workflows as variabilities which in construction have registered implications. The lack of possibilities for protecting the flow with buffering and potential deviations emphasizes the importance for workflow readiness prior to each turbine installation.

4.2 Combined Takt and PDCA in Comparison

The conceptual model has implications as a method for visually displaying PDCA with different forms of plan. This could apply to process meetings like week plans and lookaheads (Ballard 2000). The check areas could potentially be adapted further with the flow conditions for planning and control purposes. The control of the flow allows technicians and site management to increase focus on deviations or variabilities that affect the workflow. It could also be argued that the registration of deviations gives the technicians a voice when or if the takt time is not realized, allowing them to be part of the solution for stabilizing the flow. A similar voice is heard when the foremen, as part of the Last Planner System (Ballard 1999), coordinate and together formulate their process plan across trades based on the master and phase plan. Obstacles and challenges are brought to surface, easing the decision making for managers and peers during repetitive planning sessions. Besides this, a combination of takt and PDCA can be used as a continuous method for improving the parade of trades through workflow improvements, encouraging the teams to reconsider approach and methods.

4.3 Takt Results in Comparison to Construction Takt Results

Chauhan et al. (2018) argues for prefabrication and takt as way of industrializing the construction industry. This could be argued to support takt applied in offshore wind construction with its multiple identical products in each project. Heinonen and Seppänen (2016) achieved a 73% cycle time reduction during the refurbishment of 126 identical cruise ship cabins. This indicates that the potential is greater than the presented results here, which could be related to learning curves as presented by Thomas et al. (1986) for construction productivity. Frandson et al. (2013) showed how takt and daily management led to 5 months completion instead of the original 11 months planned.

5 Conclusion

This case revealed a potential positive relation between takt and PDCA in a construction environment. Furthermore, measures illustrated a downward tendency in the process lead times for the teams. The 20% reduction of lead time is perceived as a substantial reduction. The impact on decision-making was not registered, and neither was the time from a deviation occurred until a solution had been implemented. The conceptual model presented can potentially be further developed for various levels of site management, using the planning and control as an opportunity for learning. Furthermore, the case illustrates a potential for further development or adaption into the construction domain.

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An Overview of Potential Application of Acoustic Emission in Machining Processes

Joanna Krajewska-Śpiewak and Agnieszka Żyra

Abstract The paper presents the potential application of acoustic emission method (AE) in conventional and unconventional machining processes. To reduce the probability of production defects more attention is paid to the manufacturing processes monitoring. According to the basis of acoustic emission method, which allows for analyzing material destruction in the entire volume of the analyzed sample in real time were described. An overview of potential application of AE method in conventional machining processes such as cutting and also during electro discharge machining were presented.

Keywords Acoustic emission · Decohesion · Electro discharge machining · Machining zone

1 Introduction

In order to reduce the probability of production defects, more and more attention is paid to monitoring production processes. This is particularly important when manufacturing components which are used in specific operating conditions, where the technological properties of the surface layer play a key role (e.g. elements of aircraft engines, gas turbines, high-pressure turbines). In a later stage of quality control, effective, non-destructive inspection methods are important which can guarantee a higher degree of detection of existing damages.

There are few important aspects of all kinds of treatments such as accuracy, stability and their quality. For the machining processes monitoring, time series of selected quantities are used which are measured on-line, in order to extract important events from the point of view of the process diagnostics. These quantities are subjected to various transformations, which allow for proper interpretation of signals

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_52

and extracting from them the most important information about the course of the process.

The most popular methods of process diagnostics include:

- Thermos-diagnostics—measurement and analysis of temperature are used to determine the condition of the tool. Thermometers (contact measurement) or thermovision cameras, infrared thermometers etc. (non-contact measurement) are used.
- Tribo-diagnostics—information contained in the lubricants and cutting lubricants which are used in the treatment are used to determine the condition of the tool.
- Vibro-diagnostics—in which a vibration signal is used to assess the tool condition. Obtained signal is developed and analyzed. The speed, acceleration and deviation caused by vibration are used to measure.
- Measurement of cutting forces—it is based on deformations' measurement of elements subjected to forces. Cutting forces are registered by sensors, the obtained signals are converted into readable quantities.
- Acoustic-diagnostics—the method is designed to extract an acoustic signal which is later analyzed and evaluated (Krajewska 2014).

Due to the measurable benefits associated with the use of AE signal for machining processes monitoring this method is introduced in this article.

2 Basics of Acoustic Emission

Acoustic emission is defined as the physical phenomenon of sending energy (in the form of wave radiation) by an energetically excited body, with its simultaneous transition to a state of lower energy (Banaszak and Kowalski 2011). Increasing energy is transformed into a mechanical impulse that travels along the material as a resilient wave. Once the surface of the material is reached the wave is transformed into a surface wave. An electrical AE signal is obtained by piezoelectric AE sensors which are used to detect elastic waves on the workpiece. Such a signal goes through the preamplifier to the measuring apparatus for its processing (Banaszak and Kowalski 2011).

There are two types of signals: continuous and discrete. The first one is associated with continuous or permanent processes. The discrete signal appears in the moments when the cohesion of the material is destroyed, for example, when the chip influences the machining process. The frequency of the AE signal is in the range from 50 to 400 kHz.

Due to the types of processes taking place in the material (Banaszak and Kowalski 2011; Witos 2008), the following sources of acoustic emission can be distinguished:

- motion of crystal lattice defects;
- movement of: dislocations, vacancies, interjected atoms;
- transition of molecules and atoms between energy states;

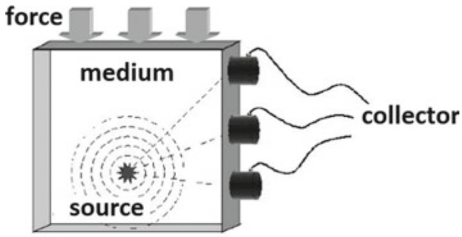

Fig. 1 The measurement of the acoustic emission signal (Grosse and Ohtsu 2008)

- formation of cracks and microcrack and its spreading;
- local movements of the center which can cause internal friction;
- phase transitions and chemical reactions related to local phase changes;
- incomplete electrical discharges (electric discharges occur locally in the dielectric between the electrodes, are revealed by the presence of a current pulse and the emission of an electromagnetic wave (Witos 2008);
- selected biological processes.

Processes which generate acoustic emission signals may occur as a result of: chemical or thermal changes, the operation of external mechanical load, or changes in technical objects during their utilization (Banaszak and Kowalski 2011). The measurement of the acoustic emission signal (Fig. 1) is based on the registration of elastic waves generated by the acoustic emission source.

Elastic waves propagate radially in all directions in the volume of the analyzed material as a result of a change in the internal energy distribution which is caused by an external stimulus (Banaszak and Kowalski 2011). The waves are registered by acoustic emission sensors placed on the surface of the analyzed object. AE sensors convert AE signal into alternating electrical voltage.

3 AE Signal Processing

The purpose of AE signal processing is to detect "explosions" that are evidence of the sudden emission of energy produced inside the material. The task of AE is to estimate: the time and location of explosions, oscillation frequencies and to properly describe the overlapping structures.

Extraction of physical parameters from the received AE signal is one of the problems associated with the processing of the AE signal. This problem is related to the fact that the signals are non-stationary whose waveforms are unknown and include changes in time and frequency. Figure 2 shows the general signal processing structure.

One of the methods of AE signal processing is Fast Fourier Transform (FFT). Its task is to divide the signal into components of particular frequencies. FT is used to convert rare signals that contain relatively few frequency components with a significant amplitude. During the processing of the raw signal into the frequency domain, the signal loses information in the time domain. During the processing of the raw

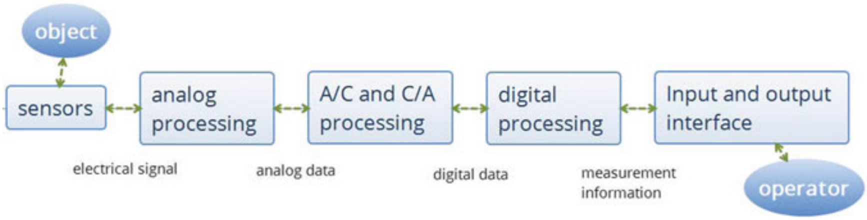

Fig. 2 General signal processing structure

signal into the frequency domain, the signal loses information in the time domain. In this case, the received signal should be filtered. In order to overcome this problem short-time Fourier Transform (STFT) is proposed to use. This method is mainly used for non-stationary signals. The data window in STFT is focused in time. The spectral coefficients are calculated for data of short lengths, then the window is transferred to the new position and is recalculated.

Wavelet analysis is another method of signal processing. It allows the use of long periods of time when very precise data and low frequency data are needed. It also allows the use of short periods when high-frequency data is needed. Falki to matematyczne funkcje, które dzielą dane na różne składowe częstotliwości. Each fragment is analyzed with the appropriate resolution suited to its scale. The main difference between FT and wavelet analysis is that a single wavelet function is located in space, while the sine and cosine functions in the Fourier Transform are not. The basic function on the time-frequency plane in Fig. 3 allows to see the differences in the time-frequency distribution between these two methods.

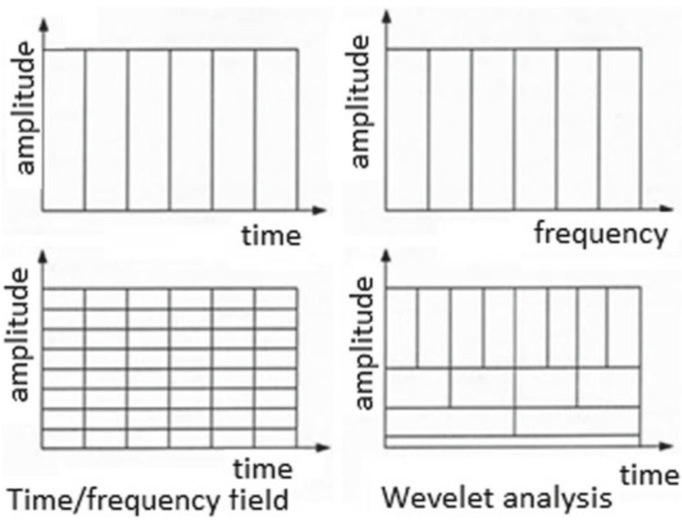

Fig. 3 Time function and time-frequency function of fourier transform and wavelets

The key point of wavelet analysis is the extraction of information from the original signal, by the distribution of this signal into a series of approximations and the distribution of data on different frequency bands. The time and frequency characteristics are preserved. The next step in signal processing is to select several distribution sequences that are appropriate for the application.

4 AE in Cutting Process

A complex process of cutting blade wear occurs during materials cutting. A worn tool has a negative effect on the work surface. In order to reduce the unwanted phenomenon, certain methods were developed to monitor the wear of cutting tools. These methods can be divided into two groups: indirect and direct (optical, radioactive, measurement of cutting forces, measurement of vibrations, AE, etc.). Indirect methods are based on measurements of the effects of wear. The results obtained by indirect methods are subject to uncertainty which results from disturbances of unknown nature. The implementation of direct methods is very difficult in many technical aspects, but the results obtained reflect the actual state of tool wear. AE signal method is considered as the most effective direct method. The most important advantage of this method is the ability to monitor the cutting process in a real time (on-line monitoring). An additional advantage of the AE signal is the frequency range, which significantly exceeds the range of natural vibrations of the machine and noise from the surroundings.

The basic sources of acoustic emission during cutting were characterized by (Dornfeld 1999; Xiaozhi and Beizhi 2007) and include:

- plastic deformation of the workpiece in the shear zone;
- plastic deformation and friction between the chip and the rake surface of the tool;
- friction between the workpiece and the flank surface of the tool;
- forming and tangling of a chip breaking;
- chip breakage;
- shockwave, which arises at the entrance of the tool into the workpiece;
- sudden chip breakage at the tool output from the workpiece.

The last two sources of AE occur during milling and are associated with the dynamism of this process. Figure 4 show the location of acoustic emission sources during cutting process.

The acoustic emission signal registered during the cutting process is complex. It is classified as ultrasound in the frequency range from 50 kHz to 2 MHz. The main advantage of such high frequencies is (Jemielniak 2000) that they are distant from the frequencies of free, forced and self-excited vibrations (including noise) associated with machining.

The acoustic emission phenomenon has been used to monitor the cutting process for a long time. The use of acoustic emission signal to monitor the cutting process and cutting tool has been described by Dornfeld (1999), Jemielniak (2000), Xiaozhi

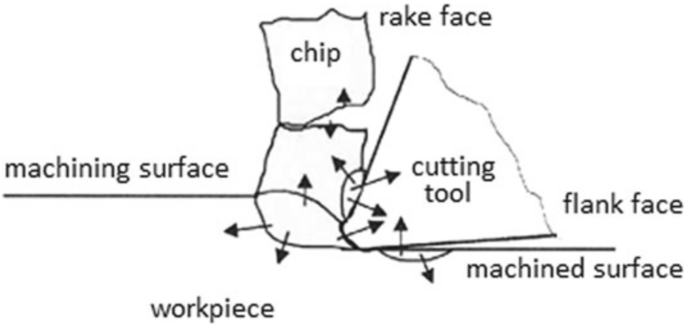

Fig. 4 Sources of AE signals (Xiaozhi and Beizhi 2007)

and Beizhi (2007). The work carried out by Jemielniak (2000) focuses primarily on the application of AE signal to monitor the wear process of cutting tools during turning. Few people (Dornfeld 1999; Jemielniak 2000) used the AE phenomenon to monitor the workpiece.

The authors (Dornfeld 1999) attempted to use the AE signal to monitor the machined surface during cutting. They used elements made out of nickel and titanium based alloys. A piezoelectric 4-component Kistler 9272 dynanometer (Fx, Fy, Fz, Mz) with a frequency of <5 kHz response was used for monitoring. AE sensor—Kistler 8152A with a response frequency of 50–400 kHz was attached directly to the workpiece. The signals were recorded by the synchronized National Instruments PCI package and then processed in the Matlab environment. Torque and power were recorded at a rate of 10 samples per second (10 kHz), while AE at 800 samples/s (800 kHz). The most difficult part of the research was to connect the sensor signal with anomalies arising on the machining surface. After the tests, there was a weak relation between the noise signal ratio and the strength signal. The authors concluded that it is necessary to improve the signal-to-noise ratio by selecting the appropriate filtering technique for digital signal, which will enable its better interpretation. The authors concluded that the analysis of the frequency of the AE signal can play an important role in monitoring not only the condition of the tool, but also the workpiece itself.

In another research (Olufayo and Abou-El-Hossein 2013) AE signal was used to monitor the ultra-precise cutting process of an aluminum alloy (RSA 905) used for the production of optical molds. Diamond tolles were used in the research. Dynamometers or vibrations sensors used in conventional monitoring techniques have a significantly lower sensitivity to the machining process, although AE sensors have shown higher sensitivity at higher frequencies. The use of AE sensors allows the identification of micro strain mechanisms in a relatively loud machining environment. A cylindrical element with a convex radius of 100 mm, a thickness of 40 mm and a diameter of 15 mm was machined. The machining parameters were as followed: feed rates of 25, 15 and 5 mm/min; cutting speed $v_c = 2000$ [rpm] and depth of cut $a_p = 10$ μm/transition. The treatment was carried out at a room temperature and the air was a coolant. The moderate increase from the initial to the final step in each feed rate reflects changes in the tool and the workpiece. These changes may be cause by tool wear, surface damage or poor surface structure. These phenomena were observed during conventional method monitoring of the cutting process, which reflects the sensitivity of the AE signal to the wear of cutting tools. The authors of the article also believe that the AE signal can be used to monitor and evaluate changes in surface topography.

Many information on the detection of surface defects during: turning or drilling can be find in a literature. Unfortunately, the amount of information regarding the detection of anomalies arising on the machined surface during milling is small. This is mainly due to the dynamic nature of the milling process associated with the entry/exit of the blade into the workpiece/from the workpiece. This results in a greater difficulty in detecting anomalies occurring on the work surface during milling (Jemielniak 2000).

5 Identification of Decohesion Process by AE Signal

Decohesion is also known as a minimal thickness of the cutting layer (a_{min}) and it is defined as the minimum undeformed value of the machining allowance which can be removed from the machined surface with the use of cutting tools with defined stereometry. The problem of a_{min} determination was carried out by Brammertz in (Brammertz 1961). He proved that the surface roughness created during milling process depends on the minimal thickness of the cutting layer.

Existing methods for a determination are based on the knowledge of the value of the coefficient of friction and cutting edge radius. Friction coefficient is determined with the use of vibratory cutting. Vibrating tool is an effective way of increasing the stiffness of the cutting contact point. Contact stiffness between the tool and the workpiece is closely related to the maintenance of the contact surface during machining process.

Methods for a_{min} determination in the industrial conditions are difficult because they require determination and knowledge of many different parameters which can include: hardness, coefficient of friction, yield strength, Young's modulus, hardening of material, fracture toughness, elasticity (Nowakowski and Miko 2013).

Authors (Gawlik et al. 2016) used AE signal for identification of the decohesion process. Acoustic emission signals were registered by measuring Wallen 6 system.

After milling process harmonic components (peak amplitude [dB], energy [ae]) of AE signal were extracted and were used to determine the beginning of decohesion process (a_{min}).

Figure 5 shows registered AE signal during entire cutting process for selected sample.

Based on the registered AE signal (Fig. 5) characteristic stages of cutting process can be distinguish: moment of first contact between cutting tool and the workpiece, elastic and plastic deformation that occur in the workpiece, stabilization of machining

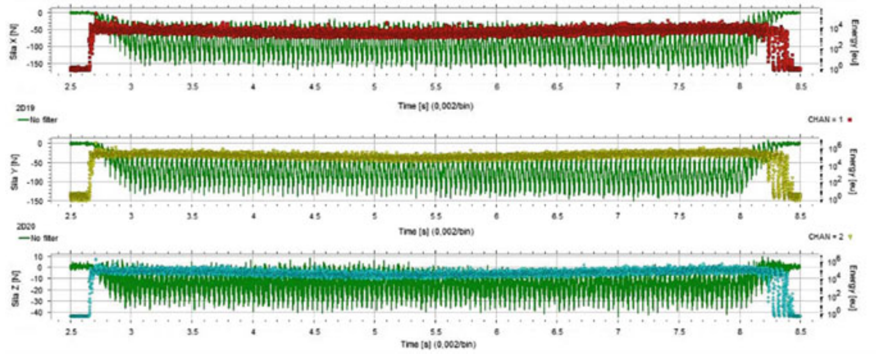

Fig. 5 Registered AE signal for selected sample (N1): $v_c = 46.7$ m/min, f = 280 mm/min, $a_p = 0.35$ mm (Gawlik et al. 2016)

process, relaxation of material and the end of cutting process. In order to identify the minimal thickness of the cutting layer time of decohesion process (t_d) and time (t_p) of assumed depth of cut (a_p) were determined (Fig. 6).

The values of time (t_d) and $\left(t_p\right)$ were used to calculate the value of the minimal thickness of the cutting layer. Based on the similar triangles, the formula (1) was developed in order to determine the minimal thickness of the cutting layer a_{min}:

$$a_{min} = a_p * \frac{t_d}{t_p} \quad (1)$$

where: t_d—time from the first contact between cutting tool and the workpiece to the moment of decohesion process; t_p— cutting time of the assumed depth of cut a_p.

Carried out research showed the possibility of use of energy extracted of AE signal. An important feature of AE energy is that its value changes with the change

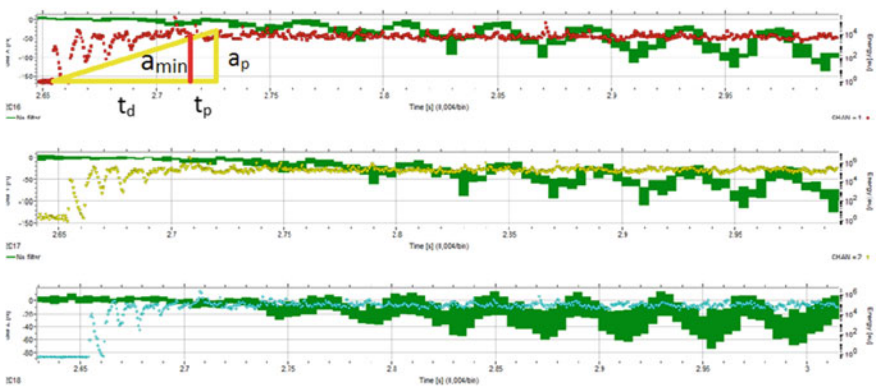

Fig. 6 The principle of decohesion process (a_{min}) determination (Gawlik et al. 2016)

of cutting conditions (cutting parameters). It has not been shown in current methods that the values of the minimal thickness of the cutting layer strongly depend on the cutting parameters.

6 AE in Electro Discharge Machining Process

Unconventional machining is an alternative to traditional production methods, especially when machining difficult-to-cut materials, and when it is necessary to obtain very high dimensional accuracy of the workpiece, without introducing significant changes to the structure of the surface layer (Torres et al. 2015).

One of the most popular unconventional methods of machining is electrical discharge machining (EDM) in which the material is removed as a result of electrical discharges. Due to the relatively low machining costs, it is especially used when small-sized elements or complex geometry are needed (Kunieda et al. 2005).

During the spark erosion machining, the material allowance from the machined surface is removed as a result of electrical erosion that occurs as a result of phenomena accompanying pulsed electric discharges (evaporation, melting and tearing of the material) between the working electrode and the workpiece (Kunieda et al. 2005; Żyra 2017). The working electrode and the workpiece are connected to the generator of electric voltage pulses. The machining gap is usually filled with a hydrocarbon dielectric (in case of electro erosion drilling) or with water based dielectric liquid (in the case of wire cutting—WEDM). In the machining zone, a forced dielectric flow is ensured all the time, which causes cooling, solidification of the molten material and its removal from the machining zone.

There is a high probability of occurrences which disturb the stability of the machining process during electrical discharge machining. Incomplete discharges, mobility of detached particles of material, dielectric contamination by processing products, melting of the working electrode material these all have a negative effect both on the condition of the machining surface and the working electrode (Kozochkin et al. 2016). Therefore, it seems to be important to monitor both the EDM machining process itself and to check the surface quality of the workpiece.

Due to the wide application of AE for both continuous process monitoring and for analysis of changes in the workpiece which appear after machining process, the authors (Aggelis et al. 2011; Smith and Koshy 2013) indicate the possibilities of the application of AE in EDM.

Ydreskog (1989) and Muto et al. (1989) showed the possibility of AE application to locate electric discharges on the machined surface based on the analysis of time delays of acoustic emission waves. Between the moment of the discharge and the feedback response which come from the sensor, in relation to the speed of sound in the machining material in which the acoustic wave propagates. It was possible to locate the occurrence of electroerosion discharges on the machining surface with an accuracy of 0.3 mm with the use of two AE sensors with a resonant frequency of 20 MHz. Unfortunately, this method is suitable for analyzing single, isolated discharges. Currently, it is impossible to locate the source of discharges based on the estimation of AE signal delays during a series of sudden discharges which occur during the real EDM machining process due to the overlapping of subsequent AE signals (Muto et al. 1989; Smith and Koshy 2013; Ydreskog 1989).

Based on the increasing frequency of AE signals from electrical discharge and their localization Smith (Smith and Koshy 2013) considered two problems associated with the industrial application od AE in EDM. These are the estimation of the length of the working electrode during drilling and the cutting height during cutting. The experiment was conducted in two stages. The first stage involved conducting the experiment during a single discharge, in order to determine the propagation speed of the acoustic emission in the electrode and the wire. Information about speed propagation of the wave was used to map electroerosive discharges in the second stage of the experiment. Standard AE sensors were used with a sensitivity range of 100–900 kHz. The AE signal was collected at a sampling frequency of 10 MHz. The AE signal was collected at a sampling frequency of 10 MHz. Hall sensors were used to collect current reference signals of electrical discharges.

7 Summary

There are many systems used to diagnose the machining process and condition of the tool. In this paper the acoustic emission method which is an inspection global method based on gathering information from AE sensors located on the tested object was presented.

AE method enables to localize the damage based on the incoming AE signal to the individual sensors. AE is also a visual technique that can identify, locate and display errors based on the real time signal which also allows monitoring objects at a distance (Grosse and Ohtsu 2008; Żyra 2017).

It should be noted that this method does not allow for repeatability of the measurement results. There is also a problem associated with estimating an appropriate noise cut-off level and external interference. During progressive wear blades in cutting process, the conditions of decohesion processes change, which may create additional problems with the selection of the signal components responsible for the individual processes (i.e. decohesion and wear) (Żyra 2017). The undoubted advantage of the AE method is the possibility of analyzing material destruction in the entire volume of the analyzed sample in real time. It is also possible to indicate the locations of the signal sources. Moreover, acoustic emission allows continuous testing, without interfering with the tested object. Research in a wide temperature range is possible (with the use of waveguides), as well as research in various environments (including water). Because of the fact that sensors are installed outside the cutting zone, there is no risk of its destruction. The AE signals which come from the cutting process are free from external disturbances due to the fact that the AE frequency range is higher than the corresponding vibrations of the machine and it is above the noise of the surrounding environment.

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State-of-the-Art in Product-Service System Design

Mariusz Salwin, Andrzej Kraslawski and Jan Lipiak

Abstract Since the 1990s, a Product-Service System (PSS) has been seen as a concept that helps businesses in building their competitive advantage and allows them to increase the added value provided to customers by expanding product offer with dedicated services within an environmentally-friendly model. The needs voiced by practitioners and theoreticians concerning the development of new PSS models for different industries have not been met satisfactorily as many theoretical, methodological, and practical aspects involved in the process remain unresolved. The paper proposes a comprehensive classification of PSS design methods. The latter have been classified against criteria, such as industry and size of a company in which PSS models can be applied, product and service development paths or types of contacts with customers. In addition, the paper reviews literature on PSS design published over the recent 18 years. Its primary purpose is to identify the major aspects of PSS design, features common to different design methods, and their limitations. By examining the existing design methods, we hope to facilitate the adaptation of business models to specific PSS problems. This publication addresses and analyses 60 PSS design methods.

Keywords Product-Service system · Product-Service system design · Product-Service system method

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_53

1 Introduction

Over a longer perspective, companies will no more acquire competitive advantage only by designing and manufacturing products (De Zan et al. 2015). The last twenty years witnessed a clear gain in popularity of research devoted to Product-Service Systems (PSS) (Annarelli et al. 2016; Park and Yoon 2015). Recently, traditionally oriented manufacturing companies have decided that services linked to products can be innovative and provide added value to customers, which ultimately translates into higher profits (Roy and Cheruvu 2009; Biotto et al. 2012). On top of that, growing interest in sustainable development and meeting customer needs are central to enterprises. Hence, the PSS attract increasing attention of business practitioners and researchers (Boons and Lüdeke-Freund 2013).

In order to develop diverse PSS models, manufacturers must develop new PSS design methods starting from product-oriented through service-oriented up to result-oriented ones (Tukker 2004; Muto et al. 2016). Within the last eighteen years, we observed a rapid expansion of research on the development of PSS design methods.

Conducted analyses revealed that a few traditionally operating manufacturers can work out and select a PSS model that would be adequate to their business. They find the task difficult as opportunities offered by PSS are far from what they have come across so far (Muto et al. 2016). That is why the development of PSS models needs to be supported by specific methods, techniques and tools (Gokula Vijaykumar et al. 2013). Available literature proposes a number of methods dedicated to developing such solutions. Even though each method aims at working out a new PSS model for an enterprise, proposed ways leading to achieve this goal differ in terms of the scope, industry and tools used to support contacts with customers. The selection of an adequate PSS design method is therefore not a trivial issue.

Literature on the Product-Service Systems offers a wide array of reviews of design methods (Becker et al. 2010; Vasantha et al. 2011; Cavalieri and Pezzotta 2012; Qu 2016; Idrissi et al. 2017). Becker et al (2010) demonstrated that the creation and offering of value bundles are crucial in a service-based economy. They also showed that it is a complex undertaking which can be accomplished in value networks of different business units or companies and cannot be separated from a broader context of the integration of business processes involved in services and manufacturing. The review worked out by Clayton, Backhouse and Dani (2012) was motivated by the reflection on how representative literature can be in specifying industrial practices in PSS design. Authors focused particularly on recommendations formulated for PSS design. Vasantha et al. (2011) carried out literature review based on eight methods to identify needs in future studies. The analysis covered authors' views, definitions of services and PSS. Gokula Vijaykumar et al. (2013) examined nine design methods and concluded that the role of actors involved in PSS design is not specified clearly enough and, more precisely, that there is not sufficient information about the possibilities of engaging the stakeholders in cooperation at subsequent PSS design stages. Literature review by Boehm and Thomas (2013) addressed the integration of three disciplines: the information system (IS), business management (BM), and engineering and design (ED) to ensure uniform definition of PSS and terms within the three disciplines. Tukker (2015) focused mainly on engineering and design and dealt with aspects of PSS concept, PSS design methods, business and environmental advantages and drawbacks of PSS. He strived to assess the PSS contribution in efficient resource management. Reim et al (2015) reviewed literature to find out how companies implement PSS business models. They investigated the links between business models and tactics deployed by companies with respect to: drafting contracts, marketing, using network relations with external partners, designing products and services, as well as operational practices concerning sustainable growth. Qu et al (2016) aimed to understand the state-of-the-art knowledge concerning the design, assessment and operating methodologies. Authors focused on three research areas: PSS design methodologies (PSS-DM), PSS evaluation methodologies (PSS-EM), and PSS operating methodologies (PSS-OM). Idrissi et al (2017) drew attention to the gap in PSS modeling to support the decision-making process in the design stage. Their analysis considered seven methods that apply the Unified Modeling Language (UML) procedure.

The paper is structured as follows: the first section is an introduction. The next part introduces the research methodology. The third part contains analyses of the literature devoted to the existing PSS design methods. The final part is discussion and conclusion.

2 Research Methodology

2.1 Research Aim

The paper aims at identifying, analyzing, and classifying the existing body of knowledge on Product-Service System design by highlighting the major features of PSS design methods, their similarities and boundaries.

We have formulated the following research questions in the paper:

1. What is the state-of-the-art in PSS design?
2. What are the major limitations of PSS design methods available in literature?

This analysis also presents the suggestions for possible future directions of research on PSS development. By exploring existing design methods, we hope to facilitate the adaptation of business models to specific PSS problems.

2.2 Systematic Review

The methodology adopted in the article is a systematic review (Pittaway et al. 2004). This method has been chosen as it uses a scientific and transparent process aimed at minimizing prejudice through a detailed search for works published in literature (Annarelli and Nonino 2016). The authors used the suggestions of Tranfield (2003) and his collaborators and took three main steps:

1. Planning the review: In this paper, the authors focused on PSS design and analysis of available methods, which is the main goal of this article. It was decided to search only for the articles that explicitly use the term "Product-Service System design" or indicate it as a synonym.
2. Conducting the review: The authors searched (in title, abstract and keywords) for the term "Product-Service System design" or its synonyms in a database such as ProQues, Springler Link, Science Direct, Taylor & Francis Online, EBSCOhost, Scopus, Emerald, Insight, Web of Science, Ingenta, Wilma, IEEE Xplore Digital Library and Google Scholar. The databases used in the review are a tool to search for literature sources in electronic form, particularly useful for works published after 1995, with a wide range of topics and journals.
3. Reporting and dissemination: In this phase, the available methods of PSS design were examined in detail. According to the presented guidelines, we obtained 400 articles covering the period from 2001 to 2017. The selection based on title and summary led us to a limited set of 64 articles covering articles, conference materials, monograph chapters and books, in which 60 methods of PSS design were found.

3 Literature Review

This section reviews PSS design methodologies proposed in literature. The main goal of this paper is to classify the available technologies. The analysis of 60 approaches to PSS design provides an extensive literature review. All methods available in literature can be divided into two categories: methods validated in industrial practice and methods proposed by researchers without any validation (Fig. 1).

Having examined the available literature, we can conclude that out of 60 PSS design methods, only 12 have been successfully implemented in industrial practice and continue to be used (Aurich et al. 2006; Shimomura et al. 2009; Sundin et al. 2009; Ziout and Azab 2015; Andriankaja et al. 2017; Halme et al. 2004; Kim et al.

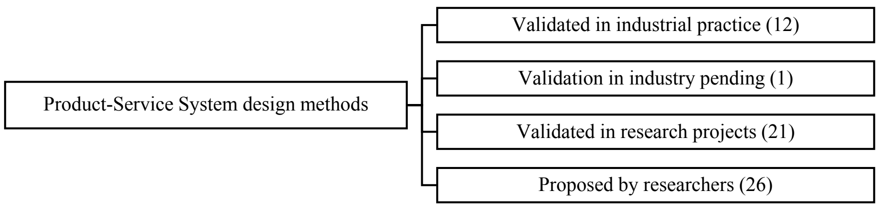

Fig. 1 Classification of PSS design methods

2015; Tuan and Park 2014; Barquet et al. 2015; Maxwell and Vorst 2003; Moser et al. 2015; Wood and Tasker 2011). Validation of one of these methods is still pending (Idrissi et al. 2017). Another 21 methods have been validated in research projects; however, they have not yet been used in practice (Abdalla 2003; Rexfelt and Hiort af Ornäs 2009; Tukker and Tischner 2006; Tukker and van Halen 2003; van Halen et al. 2005; Engelhardt et al. 2003; Muto et al. 2016; Brezet et al. 2001; Luiten et al. 2001; Marques et al. 2013; van de Kar 2010; Evans et al. 2007; Green and Vergragt 2002; Manzini et al. 2004; James et al. 2001; Müller et al. 2009; Adrodegari et al. 2017; Matzen and McAloone 2006; Muto et al. 2015; Morelli 2002, 2003; Vezzoli et al. 2014; Tuan and Park 2014). We distinguished 26 methods, which have the status of the researchers' proposals (Weber and Deubel 2003; Alonso-Rasgado and Thompson 2006; Alonso-Rasgado et al. 2004; Lindahl et al. 2009; Morelli 2006; Uchihira et al. 2007, 2008; Chiu et al. 2017; Komoto and Tomiyama 2008; Tan et al. 2009; Welp et al. 2008; Maussang et al. 2009; Kimita et al. 2009; van de Kar 2010; Geum and Park 2011; Lee et al. 2011; Kim et al. 2012; Akasaka et al. 2012; Gokula Vijaykumar et al. 2013; Dimache and Roche 2013; Pezzotta et al. 2014, 2015; Chiu et al. 2015; Medini and Boucher 2016; Trevisan and Brissaud 2016; Scherer et al. 2016; Sassanelli et al. 2016; Campos et al. 2017).

In the next stage of our analysis, we focused on how these methods emerged and have developed over the years (Fig. 2). Such a presentation helps in capturing a precise chronology of all developments linked to the launching of individual methods and providing a picture of the scale of the occurrence by the end of May 2018.

After examining how the methods developed over time, we can conclude that the first methods used to design a PSS emerged back in 2001 (DES, AEPSS, the PSS Innovation Workbook, the Kathalys method).

In the next stage of the analysis, we focused on the industries for which the methods have been developed and are in use, as shown in Fig. 3.

Some PSS design methods target several diverse (sometimes completely different) industries. On the one hand, this testifies to the versatility of solutions available in literature which can be adapted for different industries but, on the other hand, it means we need to develop new methods tailored specifically for specific industries. Most methods target mechanical engineering. They include solutions for cutting devices,

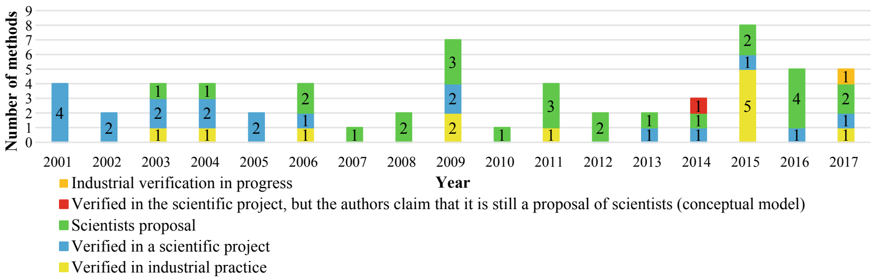

Fig. 2 Development of PSS design methods

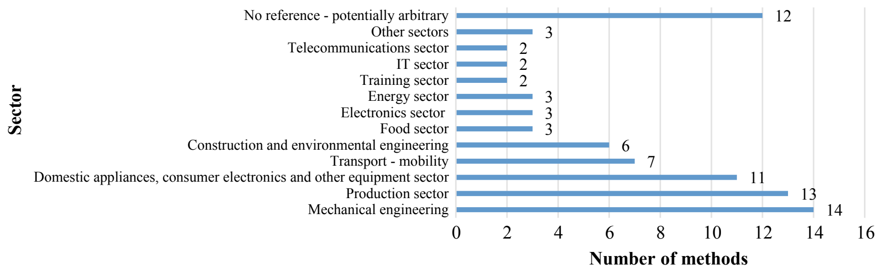

Fig. 3 Classification of PSS design methods by sector

angle grinders for cutting steel, heavy road construction machinery, valves, and tank gauging systems (Alonso-Rasgado and Thompson 2006; Alonso-Rasgado et al. 2004; Aurich et al. 2006; Matzen and McAloone 2006). Among them, we can find solutions for cooling devices, cranes, compactors, laser systems, and agricultural machinery (Dimache and Roche 2013; Sundin et al. 2009; Gokula Vijaykumar et al. 2013; Ziout and Azab 2015). Moreover, these methods include solutions targeting CNC machine tools, lifts, manufacturing machinery, and aircraft industry (Adrodegari et al. 2017; Campos et al. 2017; Shimomura et al. 2009; Wood and Tasker 2011).

Next, we considered the size of companies to which available design methods of Product-Service Systems are addressed. This classification shows we may select a method that is appropriate for the size of a business (Fig. 4).

As many as 48 methods out of the total analysed pool are not size specific and can potentially be used by a company of any size. Literature distinguishes one method, each with a precise focus on small enterprises (Evans et al. 2007; Manzini et al. 2004), medium-sized enterprises (Aurich et al. 2006) and large enterprises (Sundin et al. 2009). In literature, four methods are addressed to SMEs (Abdalla 2003; Engelhardt et al. 2003; Medini and Boucher 2016; Tukker and Tischner 2006), and four methods target small, medium and large companies (Lindahl et al. 2009; Luiten et al. 2001; Tukker and Tischner 2006; Tukker and van Halen 2003). One method is dedicated to small and large enterprises (Dimache and Roche 2013).

The next stage of examining PSS design methods focused on the paths of product and service design within the system (Fig. 5). This stage was intended to indicate the number of design methods in which products and services within a PSS are jointly developed and the number in which the process takes place separately.

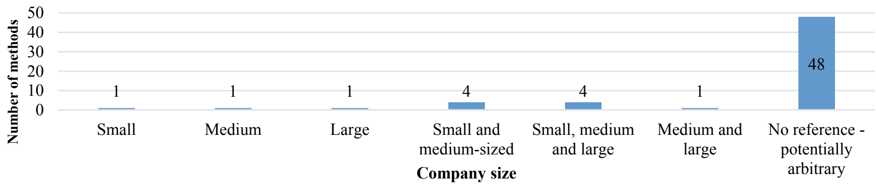

Fig. 4 Proposed PSS design methods by company size

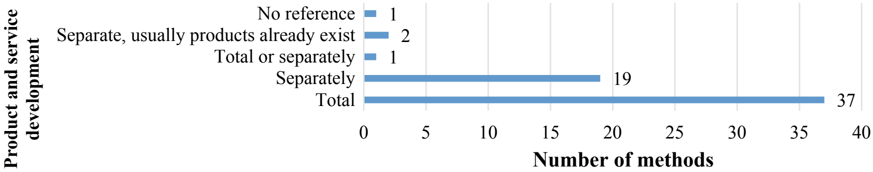

Fig. 5 Product and service development in PSS design methods

The development of products and services takes place together in 37 methods while these are separate development paths in 19 methods. Maxwell and Vorst (2003) gave plenty of leeway to develop products and services either jointly or separately. The methods developed by Morelli (2002, 2003) and Manzini et al. (2004) as well as Evans et al. (2007) enable adding services to already developed products. The method developed by Barquet et al. (2015) made no specific recommendations.

The next stage of the analysis of PSS design methods focused on the tools that support available design methods for such systems (Fig. 6). Our goal was to make an inventory of tools used when designing Product-Service Systems.

In total, we found about 150 tools that support the 60 PSS design methods. Figure 6 shows that seventeen of these tools are used more frequently than others, with blueprinting being the most frequently used tool in designing PSS. It is applied in 9 methods out of which only one has been validated in industrial practice. TraPSS is a design method that uses the biggest number (26) of tools (Dimache and Roche 2013). The literature review indicates that about 6 methods use no tools (Barquet et al. 2015; Moser et al. 2015; Tran and Park 2015; Müller et al. 2009; Rexfelt and Hiort af Ornäs 2009; Gokula Vijaykumar et al. 2013).

A further stage of analysis was devoted to contacts with customers when developing new PSS (Fig. 7). We wanted to find out whether the final user is involved and remains in touch with the company when a new system is being developed.

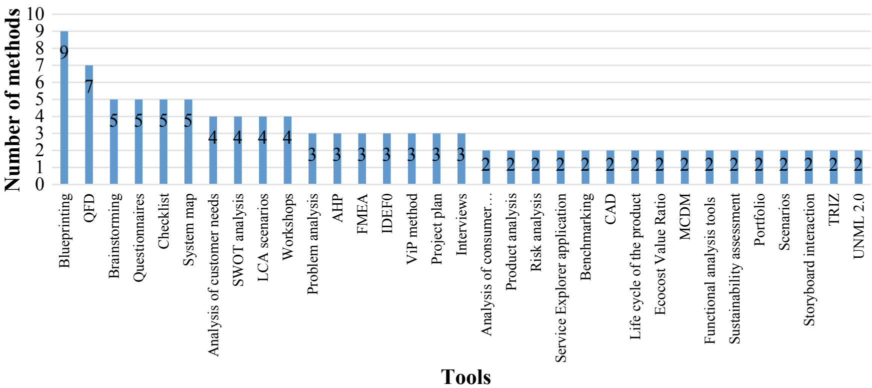

Fig. 6 Tools that support PSS design methods

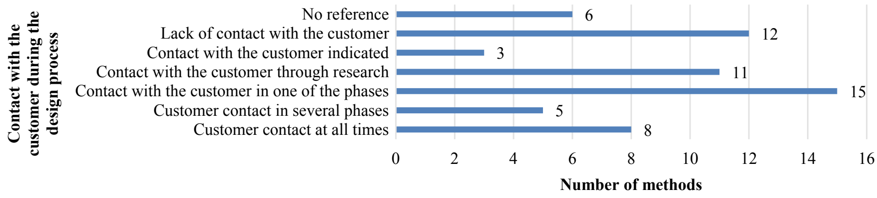

Fig. 7 Contact with the customer in PSS design methods

From the literature review, we have learnt that 42 PSS design methods address customer contacts in developing a new system. Out of these 42 methods, 8 provide for direct continuous contact throughout the process. In 6 methods, customer contacts while developing PSS are not specified precisely.

Subsequently, our analysis concentrated on the types of PSS that can be designed based on the methodologies available in literature (Fig. 8). Literature distinguishes between 5 types of PSS (integration, product, service, use, and result-oriented) (Neely 2008).

Our investigation shows that out of the 60 design methods for PPS available in literature, 30 can be used for the development of integration-oriented PSS and 39 for product-oriented PSS. Most design methods (45) can be used in developing service-oriented PSS. As shown in Fig. 8, there are 31 methods for a use-oriented PSS and 33 methods for a result-oriented PSS. We need to stress that some methodologies available in literature are intended for designing systems of specific types. Some methods can be used in designing several types of PSS (Geum and Park 2011; Lee et al. 2011; Vezzoli et al. 2014; Pezzotta et al. 2015; Chiu et al. 2017).

The next part of the analysis highlights environmental, economic and social aspects (Fig. 9). We aimed at finding out whether PSS design methods available in literature consider these aspects in developing a new system.

Whereas the environmental aspect is considered in 36 PSS design methods, the economic aspect is taken into account in 47 PSS design methods and the social aspect in 23 PSS design methods.

The structure of product system design methods available in literature is then examined. In most methods, a new system is developed in consecutive stages. Each stage comprises a series of actions that must be completed. We need to stress here that in the majority of methods, each stage is described in a rather imprecise manner; basic operations are just listed without any profound explanation. In some methods besides

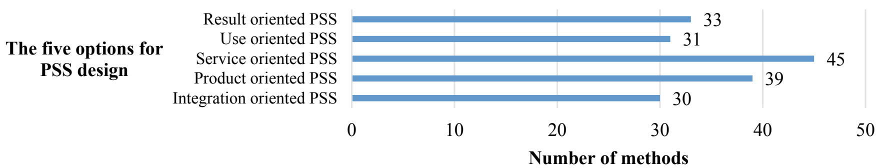

Fig. 8 Types of PSS

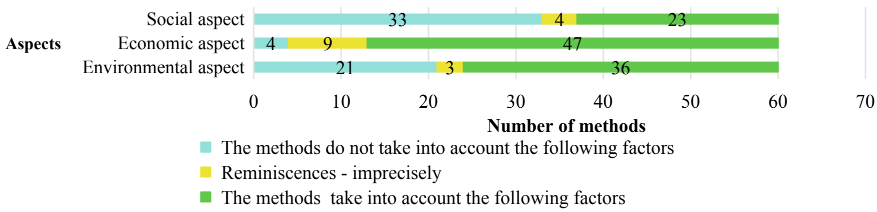

Fig. 9 Sustainable development aspects considered in PSS design

the main phases we can identify additional ones, such as: paths (Luiten et al. 2001), division into two spaces: problem space and the space of solutions (Morelli 2002, 2003), additional modules: diagnostic module, opportunity recognition module, and an implementation module (Tukker and Tischner 2006), division into two spaces: product design space and technical service design space (Aurich et al. 2006), DFACE-SI procedure (Uchihira et al. 2007, 2008), model of interdependence between the implementation of Product-Service Systems and customer satisfaction (Akasaka et al. 2012), business model dimension (Barquet et al. 2015), customer area and company area (Scherer et al. 2016), and additional steps in model building (Idrissi et al. 2017). In the PSS Innovation Workbook method when developing a new system, a company does not take any steps but answers the questions (James et al. 2001). The Service Thinking method brings together the conceptual side of developing a Product-Service System based on customer wishes and the social dimension as a competence of the expert team to perform services (Wood and Tasker 2011). Several methods available in literature include feedbacks that enable revisiting each previous design phase. Feedbacks are a crucial and useful functionality (Kim et al. 2015; Gokula Vijaykumar et al. 2013; Weber and Deubel 2003).

4 Discussion and Conclusion

Studies discussed in the paper were undertaken to identify the main PSS design areas, their limitations, and industries in which they are deployed most frequently.

We managed to identify 60 PSS design methods in literature, with 12 of them implemented in economic practice. Analyzed literature, available examples and case studies have led us to the conclusion that PSS design methods are not presented in too much detail, which significantly limits their practical application. The majority of available methods focus on three aspects: design processes that integrate products and services, definitions of new terms, and considerations on planning and design stages of a product lifecycle. Another relevant issue that needs to be considered is the flexibility and versatility of methods available in literature, which can be applied in several industries and by enterprises of different sizes to develop many PSS.

Each stage of available methods needs to be described in greater detail. For each method we should precisely identify costs and financial flows. More examples of practical applications and case studies could help in providing a fuller picture of a given PSS. Literature should provide practitioners with examples telling them how they could potentially design new PSS in their organizations. We also lack details that could help develop new methods from old ones in an iterative approach geared towards continuous improvement and working out new solutions.

Literature review allows identifying the research gap in available PSS design methods to focus further actions on bridging this gap. The major shortcomings of PSS design methods include:

- No available method addresses the Canvas Business Model—further studies are needed to find out how methods available in literature may impact the corporate business model and how the business model changes before and after a PSS has been developed in an enterprise.
- No available method informs how a PSS should be implemented in a company.
- Methods available in literature are very imprecise about economic aspects, which are described superficially without any details as to costs or cash flows from manufacturer or customer viewpoint while these aspects are crucial for assessing the PSS performance. There are no methods to assess economic efficiency of PSS.
- No precisely specified stages of risk analysis for PSS design. The process is not systematic and does not facilitate risk identification, planning and management intended to eliminate risk or minimize it to acceptable levels.

Existing literature informs that only a handful of methods have been validated in industrial practice. Vast majority have not been evaluated for industrial organizations that seek such solutions.

The range of tools that support Product-Service System design methods is also important. It only confirms how complex exercise it is to develop a new system. In addition, tools used for that purpose are generally known and widely used in industrial and academic practice.

Moreover, the analysis provides solid foundations for working out new design methods for new industries and reveals for which industries such methods have already been developed and what aspects should be considered.

Business practitioners can also benefit from results shared in the paper. By looking at different aspects of methods available in literature they acquire a useful basis for the selection of method that best fits their respective activity field. The definition of Product-Service System design and literature studies are good points of departure for developing new PSS design methods in new industries.

The analysis shows that PSS design continues to develop and there is a constant demand for new design methods for new industries. Fundamental conclusions from the research suggest that the existing PSS design process described in literature does not fully reflect the industrial practice of PSS design. The analysis is the starting point for the development of a new method that will fill in the gaps in PSS design.

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A System Dynamics Model of Multimodal Transportation of Rubber Products in Thailand

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Abstract Thailand is the world's leading natural rubber exporting country, accounting for 36.8% of the world market. In addition, the country is a member of the ASEAN Economic Community, aiming to be the center of the transportation in the region. Multimodal transportation is then encouraged to enhance the transport efficiency and reduce the logistics cost. This study develops the system dynamics model of multimodal transportation of rubber product in Thailand, utilizing the system dynamics modeling approach. Six savings and five costs related to the multimodal transportation are considered in the model. The simulation results show a negative cash flow at the beginning of the simulation years due to high investment in the multimodal-related facilities and infrastructure. With continuous use of multimodal transportation, the net cash flow becomes positive, and the project reaches the internal rate of return of 12% at the end of year 13. The results also show that the saving in truck rental cost and the product damage cost are the most important benefit and cost of multimodal transportation, respectively. The study results can be used as a guideline for the rubber and exporting companies, as well as the government, to effectively plan for the multimodal transportation in the long-term.

Keywords Multimodal transportation · Rubber · System dynamics modeling · Thailand

1 Introduction

Thai economy is growing, specifically in the exporting area that rises to 9.7% in 2017 (Workman 2019). After joining the ASEAN Economic Community (AEC), Thailand gains the benefits of tax reduction within the AEC countries, bringing even more export products to the market (NESDB 2015). Main export products include

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K. Panuwatwanich and C. Ko (eds.), *The 10th International Conference on Engineering, Project, and Production Management*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1910-9_54

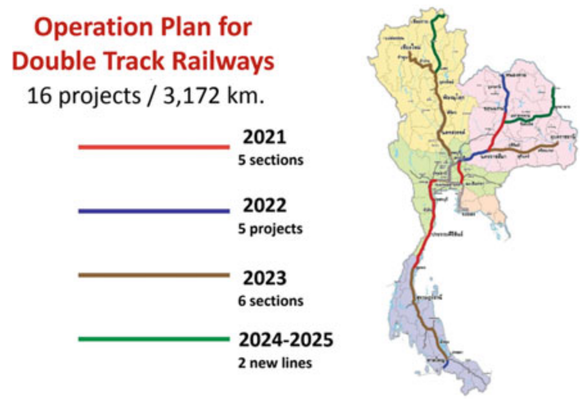


Fig. 1 Double track system project (Thongkamkoon 2017)

automobiles, electronic devices, rubber, rice, and cassava. Currently, Thailand is the world's largest producer and exporter of rubber products, accounting for 36.8% of the world market. The southern part of Thailand is the largest latex plantations area, accounting for over 70% of the country's supply. Major partner countries are China, United States of America, and Malaysia with 26.7%, 11.7%, and 9.3% of the total imported amount, respectively (Workman 2019).

Thailand aims to be the center for logistics and transportation in the AEC countries. Motor mode is the major mode of transportation in Thailand. It is, however, the most expensive mode among the three modes, with an average logistics cost of two to three times higher (Wongsanguan 2018). The government, therefore, initiates a number of projects to encourage the use of multimodal transportation to reduce logistics and transportation cost. This includes the double track system project throughout the country to promote social stability, augment economic stability, promote transport security and safety, and boost competitiveness (Thongkamkoon 2017). Sixteen sub-projects are planned with around 15,000 million dollars budget (see Fig. 1). It is expected that the double track system project, more of multimodal transportation will be initiated, thus reducing logistics cost in the long-term.

To enhance the transportation effectiveness and reduce logistics cost, this study aims to examine savings and costs of multimodal transportation of rubber product utilizing a system dynamics modelling approach. It is expected that the study results will provide a guidance to the rubber and transportation industries to effectively plan for rubber transportation in the long-term.

2 Multimodal Transportation of Rubber Product

Multimodal transportation is the coordinated use of two or more modes of movement in transferring goods. It can be a combination of truck, rail, air, or ship modes. It provides convenient and economical connections of various modes to make complete journey from origin to destination. Several studies have been conducted in the area of multimodal transportation of rubber product in Thailand. Santha (2015), for example, examined the transition from single-mode to multimodal transportation of rubber in the southern part of Thailand using multimodal regression method. The results show that multimodal transportation minimizes time loss at transshipment points, provides faster transit of goods, reduces burden of documentation and formalities, and saves cost. Luathep et al. (2016), similarly, studied the impact of transport infrastructure development on a modal shift for rubber product transport in the southern Thailand. The multimodal transport model was developed to evaluate the impact, and the results show that if all government projects, including the improvement and expansion of major roads to have at least four lanes along with the development of rail and water transports, are implemented, the transport time and cost could be reduced. BOI (2018) provided information regarding 10 trading and multimodal transportation centers, including Songkhla province, to aid the export of rubber and other products.

In this study, the multimodal transportation is considered in the rubber product transportation using the combination of truck and train modes. The origin of the study is at the major rubber export company located in Songkhla province (the southern part of Thailand), and the destination is at Laemchabang port, which is the major export port of Thailand located in the eastern part of Thailand. The products are to be delivered using the truck mode from the origin to Thung Pho railway station, where the container yard (CY) is provided for temporary storage. They are then transferred to the trains to continue their journey to Laemchabung port for the final exporting process.

3 System Dynamics Model of Multimodal Transportation of Rubber Product

System dynamics (SD) modelling approach is used to examine multimodal transportation of rubber product in Thailand in the long-term. It has been applied in many studies. Lewe et al. (2014), for example, developed a system dynamics model for multimodal intercity transportation that integrates socioeconomic factors, mode performance, aggregated demand and capacity. Perez-Lespier (2013), on the other hand, developed an SD model to identify and understand major elements and disruptions that, altogether, affect the efficiency of the multimodal transportation system in USA.

In this study, the SD modelling is utilized to develop the SD model of multimodal transportation of rubber products in Thailand. Various literatures have been conducted to extract key savings and costs of multimodal transportation. Rinsatitnon et al. (2018), for example, mentioned that by using multimodal transportation, the company can save fuel cost. Transport Corporation of India Limited (2018) added that by using multimodal transportation, accidents can be reduced, leading to less accident cost. Muangneua (2013), in contrast, stated that multimodal transportation requires a longer transit time than that for road transportation. Kruse et al. (2017)

Table 1 Data for the SD model of multimodal transportation of rubber product

Benefit and cost	Data
Saving in accident cost	• Accident cost = 20,715.20 baht/accident
Saving in reimbursement cost	• Chances of getting accidents: minor = 96.69% major = 3.31%
	• Reimbursement cost: minor = 80,000 baht/accident major = 300,000 baht/accident
Saving in truck driver cost	• Truck driver cost = 216,000 baht/person/year
Saving in fuel cost	• Diesel price = 30 baht/L • Fuel consumption rate for truck = 3.50 km/L • Fuel consumption rate for train = 0.12 km/L • Capacity: truck = 20 tons/truck train = 2000 tons/train
Saving in truck rental cost	• Truck rental cost = 3.65 million baht/truck/year
Saving in carbon dioxide tax	• Carbon dioxide tax = 500 baht/ton-CO_2 • CO_2 emission rate: truck = 107.37 g-CO_2/ton-km train = 13.37 g-CO_2/ton-km
Product return cost	• Train delay time = 0.75 h/round • Product return rate = 4.31%
Lift-on and lift-off cost	• Lift-on and lift-off cost = 850 baht/round
Tariff cost	• Tariff cost = 0.81 baht/km
Product damage cost	• Product damage chance = 2.37%

Note References include J&P Transport (2018), Road Accident Victims Protection Company Limited (2018), Transport Corporation of India Limited (2018), NESDB (2015), Kruse et al. (2017), Pornchai (2017), Protopapas et al. (2012), Wattanakuljarus (2012)

mentioned that the use of multimodal transportation requires lift on and lift off activities during transshipment processes.

A total of six savings and five costs are used for the development of SD model of multimodal transportation of rubber product in Thailand. Savings include (1) saving in accident cost, (2) saving in reimbursement cost, (3) saving in truck driver cost, (4) saving in fuel cost, (5) saving in truck rental cost, and (6) saving in carbon dioxide tax. Five costs, on the other hand, include (1) investment of the container yard, (2) product return cost, (3) lift-on and lift-off cost, (4) tariff cost, and (5) product damage cost. Both secondary and primary data used to develop equations for the SD model of multimodal transportation of rubber product are as shown in Table 1.

3.1 *Saving in Accident Cost*

According to the Transport Corporation of India Limited (2018), chances of getting road accidents can be reduced with the utilization of multimodal transportation, as it reduces the number of trucks in the transportation processes. According to the

Ministry of Road Transport and Highways (2016), the accident rate (AR) is averaged at 3.5 accidents/truck/year. Less trucks, then, tend to reduce the accident cost, which is averaged at 20,715.20 baht/accident. Equations 1–3 are used to calculate saving in accident cost, where SAC = saving in accident cost (baht/year), ACTT = accident cost of truck mode only (baht/year), ACTM = accident cost of multimode (baht/year), TT = trucks used in the truck mode only (trucks/year), TM = trucks used in the multimode (trucks/year), AR = accident rate (accidents/truck/year), and AC = accident cost (baht/accident).

$$\text{SAC} = \text{ACTT} - \text{ACTM} \tag{1}$$

$$\text{ACTT} = \text{TT} \times \text{AR} \times \text{AC} \tag{2}$$

$$\text{ACTM} = \text{TM} \times \text{AR} \times \text{AC} \tag{3}$$

3.2 *Saving in Reimbursement Cost*

A smaller number of accidents also leads to less reimbursement cost. In this study, the reimbursement cost is separated into minor and major cases, with chances of 96.69% and 3.31%, and the reimbursement cost of 80,000 and 300,000 baht per reimbursement, respectively, as shown in Table 1. Equations 4–6 are used to calculate saving in reimbursement cost, where SRC = saving in reimbursement cost (baht/year), SRCMN = saving in reimbursement cost based on minor cases (baht/year), SRCMJ = saving in reimbursement cost based on major cases (baht/year), MNC = chance of having minor cases (%), MNR = reimbursement cost of minor cases (baht/accident), MJC = chance of having major cases (%), and MJR = reimbursement cost of major cases (baht/accident) (Road Accident Victims Protection Company Limited 2018).

$$\text{SRC} = \text{SRCMN} + \text{SRCMJ} \tag{4}$$

$$\text{SRCMN} = (\text{TT} - \text{TM}) \times \text{AR} \times \text{MNC} \times \text{MNR} \tag{5}$$

$$\text{SRCMJ} = (\text{TT} - \text{TM}) \times \text{AR} \times \text{MJC} \times \text{MJR} \tag{6}$$

3.3 Saving in Truck Driver Cost

The use of multimodal transportation results in less trucks used. This implies less labors, especially truck drivers, used for transport, assuming one truck driver per one truck. Equation 7 is used to calculate saving in truck driver cost, where STD = saving in truck driver cost (baht/year) and TDC = truck driver cost (baht/truck/year).

$$\mathrm{STD} = (\mathrm{TT} - \mathrm{TM}) \times \mathrm{TDC} \tag{7}$$

3.4 Saving in Fuel Cost

With less trucks used, fuel cost can be saved. In this study, saving in fuel cost is calculated based on the average fuel price, fuel consumption rate, distance from the origin to the destination based on the transportation mode, hauling capacity, and number of transport rounds per year. Equations 8–10 are used to calculate the fuel cost savings, where SFC = saving in fuel cost (baht/year), FCTM = fuel cost based on the truck mode only (baht/year), FCMM = fuel cost based on the multimode (baht/year), DTM = distance traveled by truck mode only (i.e. from the rubber company to Laemchabang port) (km/round), RTM = number of rounds per year based on the truck mode only (rounds/year), FCTTM = fuel consumption rate based on the truck mode (km/L), FC = fuel cost (i.e. diesel price in this study) (baht/L), DTMCY = distance traveled by truck in the multimode (i.e. from the rubber company to Thung Pho railway station) (km/round), RTMCY = number of rounds per year of truck in the multimode (rounds/year), DRMLC = distance traveled by train in the multimode (i.e. from the Thung Pho railway station to Laemchabang port) (km/round), RRMLC = number of rounds per year of train in the multimode (rounds/year), and FCTRM = fuel consumption rate based on the train mode (km/L).

$$\mathrm{SFC} = \mathrm{FCTM} - \mathrm{FCMM} \tag{8}$$

$$\mathrm{FCTM} = (\mathrm{DTM} \times \mathrm{RTM})/\mathrm{FCTTM} \times \mathrm{FC} \tag{9}$$

$$\begin{aligned}\mathrm{FCMM} = {} & [(\mathrm{DTMCY} \times \mathrm{RTMCY})/\mathrm{FCTTM} \times \mathrm{FC}] \\ & + [(\mathrm{DRMLC} \times \mathrm{RRMLC})/\mathrm{FCTRM} \times \mathrm{FC}]\end{aligned} \tag{10}$$

3.5 Saving in Truck Rental Cost

In this study, it is assumed that there is no investment in trucks. As a result, all trucks used in the transportation are rented (J&P Transport 2018). With less trucks used in the multimodal transportation, truck rental cost is reduced. Equation 11 is used to calculate the saving in truck rental cost, where STR = saving in truck rental cost (baht/year) and TRC = truck rental cost (baht/truck/year).

$$STR = (TT - TM) \times TRC \tag{11}$$

3.6 Saving in Carbon Dioxide Tax

Saving in CO_2 tax is based on the emission rate of each truck mode, with the CO_2 tax of around 500 baht/ton-CO_2. Equations 12–14 are used to calculate saving in carbon dioxide tax, where SCT = saving in CO_2 tax (baht/year), CTTM = CO_2 tax based on the truck mode only (baht/year), CTMM = CO_2 tax based on the multimode (baht/year), TKMTM = total tons-kilometers of truck mode only per year (i.e. from the rubber company to Laemchabang port) (tons-kilometers/year), ERTM = emission rate of the truck mode (ton-CO_2/ton-kilometers), CT = CO_2 tax (baht/ton-CO_2), TKMTMCY = total tons-kilometers of truck in the multimode (i.e. from the rubber company to Thung Pho railway station) (tons-kilometers/year), TKMRMLC = total tons-kilometers of train in the multimode (i.e. from the Thung Pho railway station to Laemchabang port) (tons-kilometers/year), ERRM = emission rate of the train mode (ton-CO_2/tons-kilometers) (Wattanakuljarus 2012).

$$SCT = CTTM - CTMM \tag{12}$$

$$CTTM = TKMTM \times ERTM \times CT \tag{13}$$

$$CTMM = [(TKMTMCY \times ERTM) + (TKMRMLC \times ERRM)] \times CT \tag{14}$$

3.7 Investment in the Container Yard

To accommodate the multimodal transportation, the investment in the container yard is required at Thung Pho railway station. In this study, the investment cost of 50 million baht is incurred at the beginning of the simulation year.

3.8 Product Return Cost

The use of multimodal transportation may reduce the transportation cost, but increase delay, thus causing the product return cost. In this study, the delay of train mode is estimated at 0.75 h per round, and the product return rate is 4.31%. With the rubber price of 54,472 baht/ton, the product return cost can be calculated, with Eq. 15, where PRC = product return cost (baht/year), TDL = total delay hours per year (hours/year), PRR = product return rate (%), HPR = time used per round (hours/round), TPR = capacity transported per round (tons/round), and RBP = rubber price (baht/ton) (Office of the Rubber Replanting Aid Fund 2015).

$$\mathrm{PRC} = (\mathrm{TDL} \times \mathrm{PRR})/\mathrm{HPR} \times \mathrm{TPR} \times \mathrm{RBP} \tag{15}$$

3.9 Lift-on and Lift-off Cost

The use of multimodal transportation requires the lift-on and lift-off processes. The lift-on and lift-off cost (LLC) is then based on the cost per round (LL) and the number of rounds per year (RRMLC) (see Eq. 16).

$$\mathrm{LLC} = \mathrm{LL} \times \mathrm{RRMLC} \tag{16}$$

3.10 Tariff Cost

Tariff is paid when train mode is used. Tariff cost is calculated based on the tariff cost per kilometer (TF), distance from Thung Pho railway station to Laemchabang port (DRMLC), and number of rounds per year (RRMLC) (see Eq. 17).

$$\mathrm{TFC} = \mathrm{TF} \times \mathrm{DRMLC} \times \mathrm{RRMLC} \tag{17}$$

3.11 Product Damage Cost

The use of multimodal transportation may cause product damage during the transshipment processes. According to NESDB (2015), the rubber product has a product damage chance of 2.37%. The product damage cost is calculated with Eq. 18, where PDC = product damage cost (baht/year), TPY = total tons transported per year (tons/year), and PDCH = product damage chance (%).

$$PDC = TPY \times PDCH \times RBP \tag{18}$$

4 Simulation Results

The SD model of multimodal transportation of rubber product is simulated, and the simulation results are as shown in Fig. 2. At the beginning of the simulation, the net cash flow is negative due to the investment in the container yard at Thung Pho railway station. After that, the savings of multimodal transportation start to increase, raising the net cash flow to be positive at the end of year 2.

Closer examination of savings and costs, as shown in Figs. 3 and 4, reveals that saving in truck rental cost and product damage cost are the most significant. This is consistent with MacAndrews (2019), who stated that the rise of truck costs and increase in regulation regarding drivers' hours shift the single transportation to multimodal transportation modes. Solistica (2018), on the other hand, mentioned that product damage, resulting from accidents and mishandling during storage, transport, and transshipment, represents not only financial loss, but also delays for the manufacturing or commercial operations of the company.

The internal rate of return (IRR) is further used to examine the feasibility of the project. According to Bonzanigo and Kalra (2014), the minimum acceptable IRR for

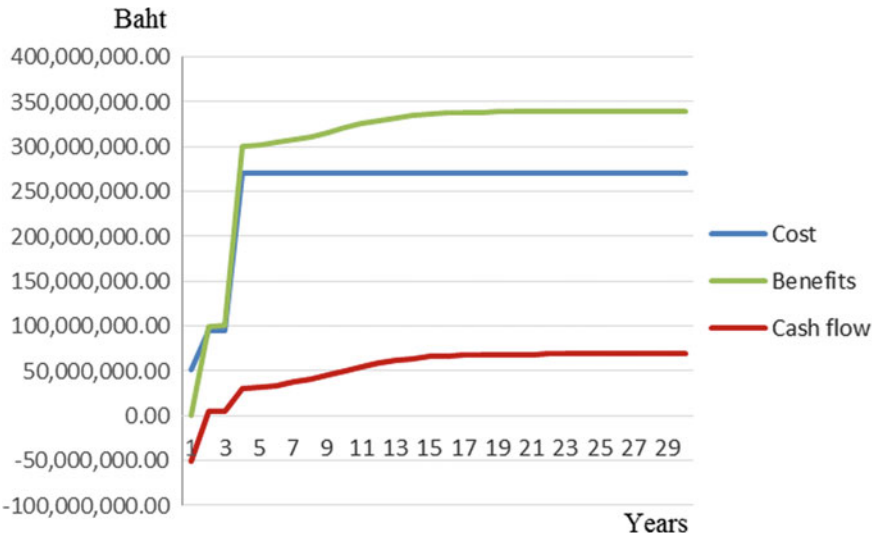


Fig. 2 Simulation results of savings, costs, and net cash flow

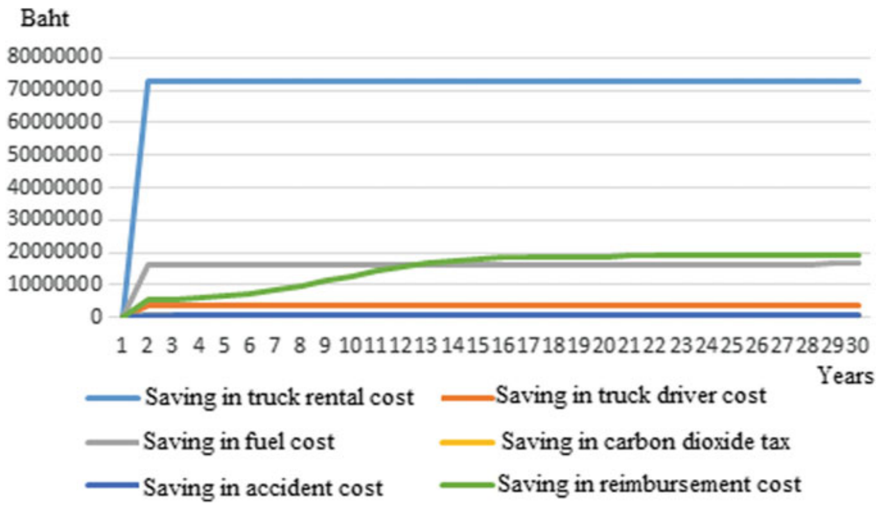


Fig. 3 Simulation results of saving factors

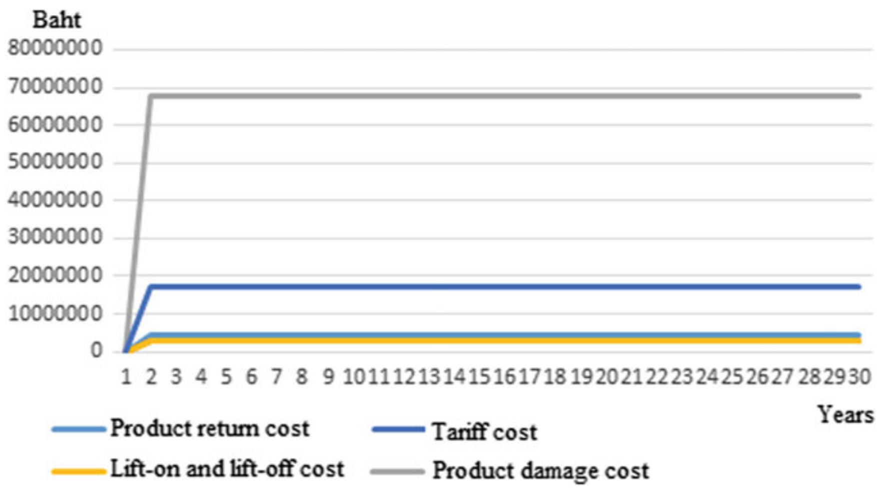


Fig. 4 Simulation results of cost factors

most of the government project is set at 12%. Figure 5 shows that with the continuous use of multimodal transportation, the project reaches the IRR of 12% at the end of year 13. The IRR keeps increasing afterwards and reaches 17% in 30 years.

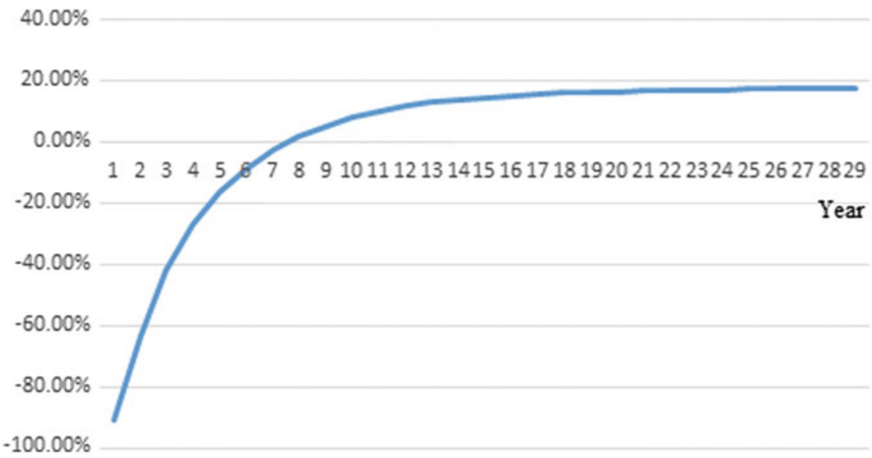


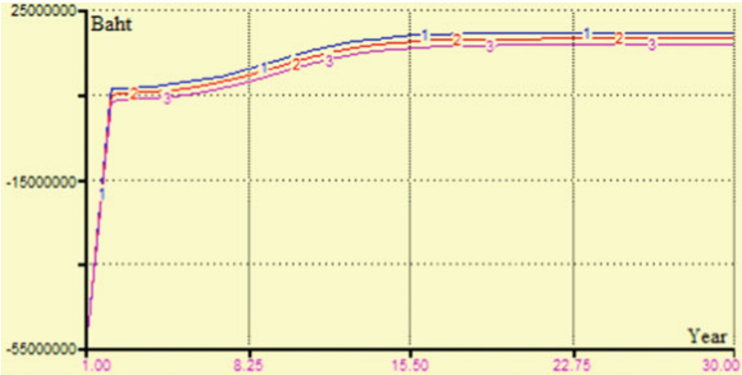
Fig. 5 Simulation results of internal rate of return

5 Sensitivity Analysis

To validate the model, this study uses the sensitivity analysis. Based on Fig. 3, the saving in truck rental cost is the most important saving factor. It is thus used to perform the sensitivity analysis to detect the sensitiveness of the developed SD model by changing the truck rental costs from 3.65 million–4.2 million baht (J&P Transport 2018). Figure 6 reveals that when changing the truck rental costs, the behavior of the model does not change, proving the non-sensitiveness of the model. The results also show that the multimodal transportation is effective when the current truck rental cost is very high. This is because high saving in truck rental cost is achieved when modal shift is utilized.

6 Conclusion

Becoming the center of transportation in the AEC, Thailand aims to utilize more of multimodal transportation to enhance the transportation effectiveness and reduce the logistics cost. This study develops the SD model of multimodal transportation of rubber products in Thailand, utilizing the SD modeling approach. Six savings, namely saving in accident cost, saving in reimbursement cost, saving in truck driver cost, saving in fuel cost, saving in truck rental cost, and saving in carbon dioxide tax, and five costs, including product return, lift-on and lift-off, tariff, and product damage costs are considered in the SD model. The simulation results reveal that the net cash flow is negative in the beginning years due to high investment in the container yard at the railway station to accommodate the transportation of rubber



Note: 1 represents the net cash flow when the truck rental cost is 4.20 million baht/year
2 represents the net cash flow when the truck rental cost is 3.92 million baht/year
3 represents the net cash flow when the truck rental cost is 3.65 million baht/year

Fig. 6 Sensitivity analysis results when truck rental cost is changed. *Note* (1) represents the net cash flow when the truck rental cost is 4.20 million baht/year, (2) represents the net cash flow when the truck rental cost is 3.92 million baht/year, (3) represents the net cash flow when the truck rental cost is 3.65 million baht/year

products in the long-term. The net cash flow becomes positive after the multimodal transportation is effectively used, with the IRR reaching 12% at the end of year 13.

It is found that with the use of multimodal transportation, less trucks are required, leading to high savings in truck rental cost and low carbon dioxide emission. The products, however, may have a higher chance of being damaged during the transshipment processes. Sensors may be installed to the packaging to warn rough handling and possible contents damage (Solistica 2018). The study results can be used as a guideline for the rubber and exporting companies to effectively plan for the multimodal transportation in the long-term. The government can also use the study results to plan for the infrastructure project to support the multimodal transportation.

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