BARRIERS TO ADOPTING SIMULATION MODELLING IN CONSTRUCTION INDUSTRY

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Abstract

Research efforts have been proving that computer simulation is a useful decision-support tool for construction projects for more than four decades. Nevertheless, it has not gained widespread adoption by the industry. This paper summarises the barriers to adopting simulation in the construction industry and the level of attention those barriers have received from researchers to date. A systematic literature review was carried out by searching databases and the profiles of the top researchers in this field to identify the journal papers, conference articles, and theses that have addressed the barriers from 2000 to 2019. The search process resulted in 78 documents with 14 barriers recorded. A critical analysis of the barriers was then conducted. The final analysis suggests four areas for improvement to overcome the identified barriers. Addressing the barriers can

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lead to a better realisation of simulation benefits in the industry, thus stimulating the uptake of simulation in construction.

Keywords

Simulation modelling; Construction; Barriers; Systematic literature review.

1 Introduction

Nowadays, construction projects are becoming more complex, dynamic, and risky. Managing such projects in a traditional fashion, which largely depends on trial and error, may lead to undesirable results [1]. This situation calls for the analytical tools and methods that can support an advanced decision-making process [1]. Computer simulation presents one of the most powerful analytical methods to evaluate the effects of different management decisions on a virtual environment [2]. From the operations research point of view, simulation is defined as the imitation of an operating system as it progresses over time and is used to improve the system and to provide a better understanding for stakeholders [3]. It has been proved to be an effective decision-support tool for systems that involve a high level of uncertainty, complexity, and interdependency between system components [4].

Computer simulation has attracted considerable attention from construction researchers since the early 1960s [5]. The first wave of research was mainly focused on developing tools that could support the simulation of construction operations. Halpin [6] led these efforts by introducing CYCLONE, which is a well-established tool that utilises Activity Cycle Diagrams (ACDs) to represent construction operations. During the 1980s, several researchers attempted to follow the lead of CYCLONE by providing other construction simulation tools such as RESQUE, INSIGHT, UM-CYCLONE, and

COOPS [2]. The next generation of construction simulation tools was prompted by the emergence of advanced object-oriented programming in the early 1990s [2]. Stroboscope was introduced by Martinez [7], the first of a series of special purpose simulation tools. These tools were able to model a variety of complex construction systems. Later, Simphony was proposed by Hajjar and AbouRizk [8], a tool that increased model flexibility by allowing the modeller to either follow the traditional code writing technique or using a set of symbols that assist non-expert modellers in building simulation models for several construction applications such as tunnelling, earthmoving, and dewatering. The recent wave of construction simulation studies is more concerned with improving the applicability of simulation modelling in the construction industry. One example is COSYE introduced by AbouRizk and Hague [9], which facilitates collaborative development, interoperation, and reuse of simulation components. Other examples include the integration of simulation modelling with building information modelling (BIM) [10], hybrid modelling [11], data-driven simulation models [12], and virtual and augmented reality (VR/AR)-based simulation models [13].

Despite the extensive research effort to develop simulation tools that model construction operations, the construction industry has consistently shown scepticism in and reluctance to adopting computer simulation [14]. Instead, industry practitioners have preferred to solve problems by making decisions intuitively and in an ad-hoc manner [15]. AbouRizk [2] reported that research efforts to develop simplified construction simulation tools were not successful in changing the negative attitude of the construction industry toward computer simulation. He referred to this problem as a ‘dilemma’ that necessitates more attention by the construction research community. Another alarm for this problem was raised by Lucko, et al. [16] who reported that no single simulation-based tool for construction had been commercialised for industrial purposes (up until the paper's publication date).

Recent studies investigated the determinants that lead to the gap between construction simulation state-of-the-art and state-of-practice using different methodologies. Lee, et al. [17] studied several challenges in construction simulation as identified in a focus group discussion by the Visualization, Information Modelling, and Simulation (VIMS) committee under the American Society of Civil Engineers (ASCE) umbrella. Similarly, Leite, et al. [14] presented 6 grand challenges in construction simulation as derived by the VIMS committee. These challenges were then assessed by a survey on 17 academics and 10 industry practitioners to rank their relative importance. Overcoming some of these challenges, such as the complexity of building simulation models and the amount and nature of simulation input data, has been the primary objective of several construction simulation studies over the past two decades.

The previous studies by ASCE VIMS identified the challenges based on the outcome of a focus group by the simulation expert task force in the VIMS committee. Construction simulation research lacks a comprehensive review on the reported construction simulation challenges in the literature. Therefore, this paper aims at complementing the findings of ASCE VIMS studies by conducting a comprehensive review of literature to address a wider community of interests. Accordingly, future strategies to overcome these barriers by academia and industry can be suggested. Therefore, the first question addressed in this paper is:

RQ1. What are the major challenges in adopting computer simulation in construction?

Once the barriers have been summarised and analysed, the second research question is defined as follows:

RQ2. What are the suggested strategies to overcome the barriers?

The answer to this second question can help researchers to determine ways to change the momentum of the construction industry in the uptake of the simulation modelling as a decision support aid. It is important to point out that the main scope of this paper is on simulation modelling from operations research point of view, which focuses on modelling the behaviour of complex and stochastic systems using simulation approaches such as Discrete Event Simulation, System Dynamics, and Agent Based Modelling. Thus, other types of simulation such as 4D and energy simulations are excluded from this study.

2 Research design

This paper consists of three main phases, as shown in Figure 1. In the first phase, literature was extensively searched to identify the most pertinent studies to the two research questions. A systematic literature review (SLR) was undertaken, which provides a well-recognised method for investigating literature and justifying outcomes in a comprehensive, transparent, and replicable manner [18]. This phase applied the procedure used by Shi, et al. [18] as the primary guidelines to conduct the SLR. The second phase included performing an analysis of the selected literature to describe their attributes and content. The third phase aimed at addressing the two research questions based on the findings of the literature analysis. The details of each phase are discussed in the following sections.

3 Literature search

The first phase of the research involved three major activities, including protocol development, database search, and literature selection.

3.1 Establishing a search protocol

The search protocol embodied the planning document of the SLR. It included a detailed description of the key elements of SLR such as the research questions, relevant databases, keywords, and inclusion/exclusion criteria, based on the recommendations by Borrego, et al. [19]. The protocol was developed within the team of six authors collaboratively. The collaboration helped to refine the document iteratively throughout the review process and assure its validity and replicability. The developed protocol also facilitated discussions between the team members in the early stage of this study.

Scopus was selected as the main database to search for scholarly papers. This database is known to cover most of the leading journals and conferences in the field of simulation [20]. Dissertations and theses were also essential for inclusion in the SLR process [19]. The study used the ProQuest Dissertations & Theses database to address this requirement.

The combination of search keywords was as follows:

(Construction W/3 simulation) AND (project OR management OR process OR operation OR system) AND (gap OR limitation OR issue OR problem OR challenge OR drawback OR barrier)

Since the keywords “Simulation” and “Construction” could be found in contexts other than construction simulation research, the search was limited to the cases in which the distance between the two keywords did not exceed three words, i.e., W/3. This limitation was set to ensure that the keywords were mostly used in the same sentence to decrease the number of out-of-scope results. For instance, this formulation can help to locate cases that may include terms such as “construction process simulation” or “simulation of construction operations”.

The *search fields* included the title, abstract, and keywords. The *publication date* criteria were set to the period after 2000. The main reason to set this search period is that construction simulation research went through three main phases as reported by AbouRizk [2], where the most recent phase in the evolution of construction simulation research started after 2000.

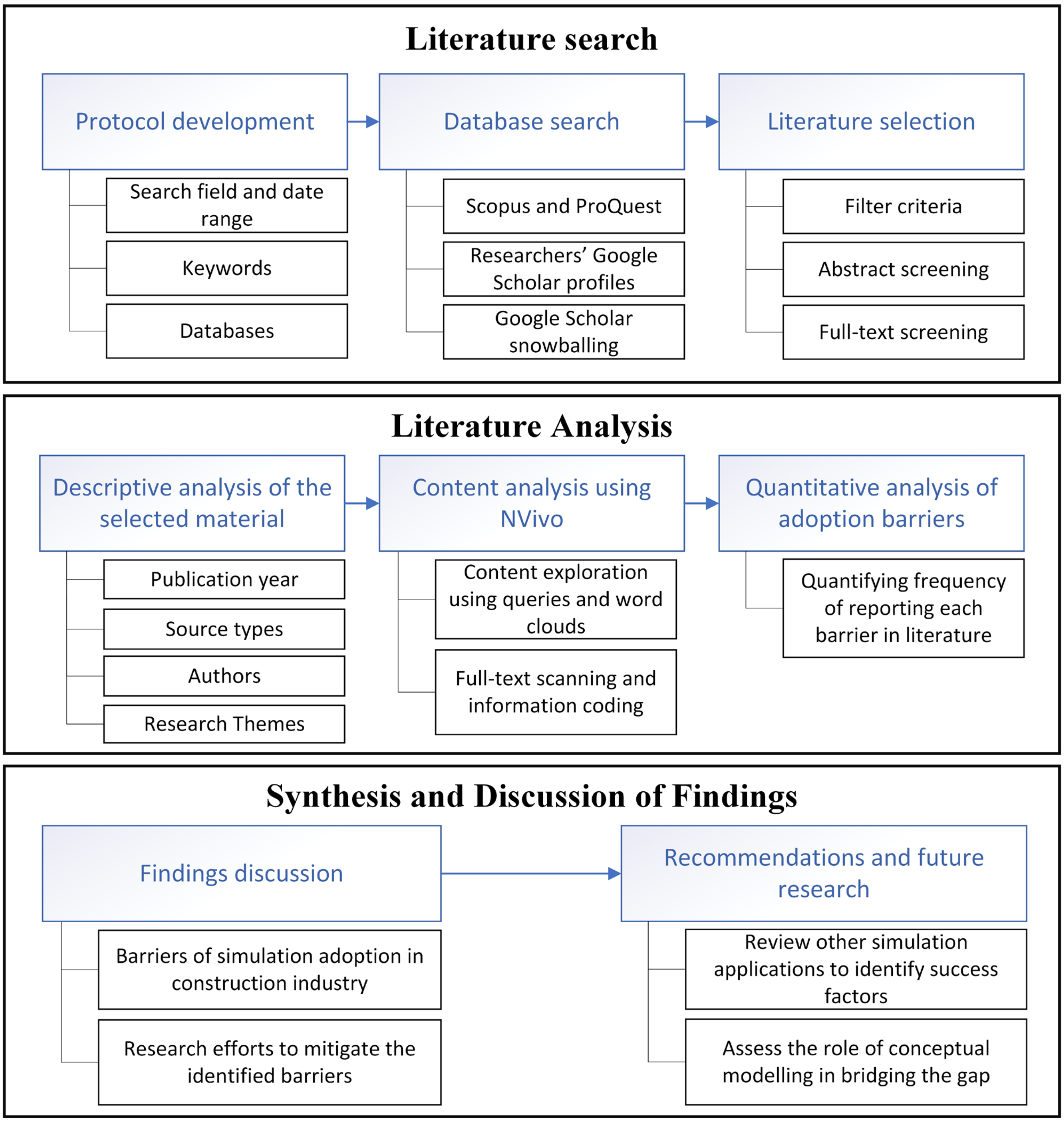

Figure 1: Research design

3.2 Database search

The search returned 750 documents on Scopus and 246 on ProQuest Dissertations & Theses. In addition, author profiles in Google Scholar were searched manually to detect relevant articles that were not included in the database search results. The most recognised authors in the area of construction simulation were identified from Scopus search results analysis and the list of the top ten researchers with most published papers in Panas and Pantouvakis [21]. Google Scholar was used at this stage because it may include other types of literature such as books, book chapters, reports, and unpublished material.

3.3 Literature selection

The last step of the literature search involved a screening process that used a skim and scan technique at two levels. First, the titles and abstracts were screened to limit the selection to documents which included discussion on construction simulation methodologies and/or had presented construction simulation case studies. The number of documents selected was narrowed down to 309 after abstract scanning. Afterwards, a full-text screening was completed that returned documents that had provided an explicit discussion on the barriers to adopting simulation in the construction industry. It is important to note that some publications discussed limitations in current construction simulation research, but these limitations were not necessarily linked to a lack of simulation adoption in the industry. Therefore, even though these publications provide a remarkable contribution to the field such as Martinez [4], they were excluded from the SLR to maintain consistency and eliminate any bias in the screening process.

Forward and backward snowballing was carried out comprehensively during the full-text scanning of the selected documents. Forward snowballing aims at identifying documents that have cited the selected documents. Backward snowballing aims at searching for and identifying relevant documents, which were not found in the searching the databases, in reference lists of selected documents [22]. The newly identified documents underwent the same processes of abstract and full-text screening as the initial ones. Google Scholar was used to performing the forward and backward snowballing during full-text scanning. The final number of selected documents after applying all filtering criteria was 78. These documents were taken to the next research stage for descriptive and content analysis.

4 Literature analysis

The authors analysed the selected 78 documents using descriptive and content analysis. The descriptive analysis summarised the nature of the documents regarding their publication years, sources, authors, and research themes. The content analysis conducted provided an in-depth exploration of the documents. It led to a quantitative analysis of the barriers of adoption. It is important to note that the 78 selected documents include work that could be published more than once in different forms such as journal papers, conference papers, or thesis. For instance, the conference paper by Labban, et al. [23] on simulating asphalt paving operations was incorporated later in the first author's PhD thesis on automating construction simulation [24]. The intentional inclusion of repeated and incremental work was undertaken to measure research activity and authors' interests over time, which can be considered as an unbiased measure as suggested by Robinson [25]. In addition, the literature analysis considered quantifying all reported barriers in the selected documents even if they are cited from previous articles of other authors. The reason for not excluding such barriers is that the cited barriers still represent the point of view of the authors who reported these barriers from previous research.

4.1 Descriptive analysis of the corpus

4.1.1 Chronological distribution of selected documents

Figure 2 illustrates the distribution of the publications over the years. The figure shows a significant rise, especially in the number of conference papers that discussed the barriers to simulation adoption after 2010. This rise can be interpreted as increased awareness among construction simulation researchers regarding the lack of uptake of simulation in the construction industry. Therefore, recent studies are providing more dedicated discussions on the barriers to simulation adoption.

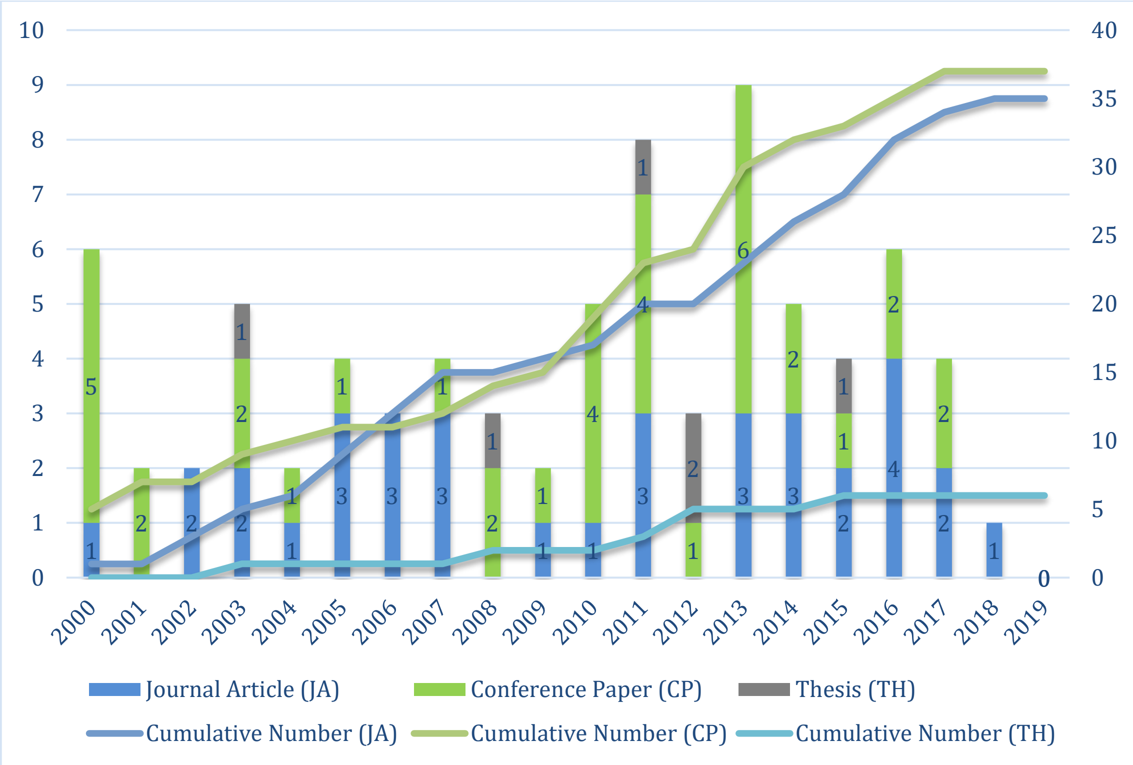

Figure 2: Chronological distribution of findings

4.1.2 Main sources of the documents detected

Figure 3 illustrates the distribution of the documents based on their sources. Among the 78 documents selected, 45% were journal articles (35 documents), 47% were conference proceedings (37 documents), and 8% were theses (6 documents). Automation in Construction (AutoCon) and ASCE Journal of Construction Engineering and Management (JCEM) were the most active journals to publish on the barriers to simulation in construction. These two journals, which are among the most prominent journals in the area of construction management [18], accounted for 22% of the total documents and 50% of the journal articles. The Winter Simulation Conference (WSC) was the most important source to report the barriers as it included 29% (23 documents) of all the documents detected.

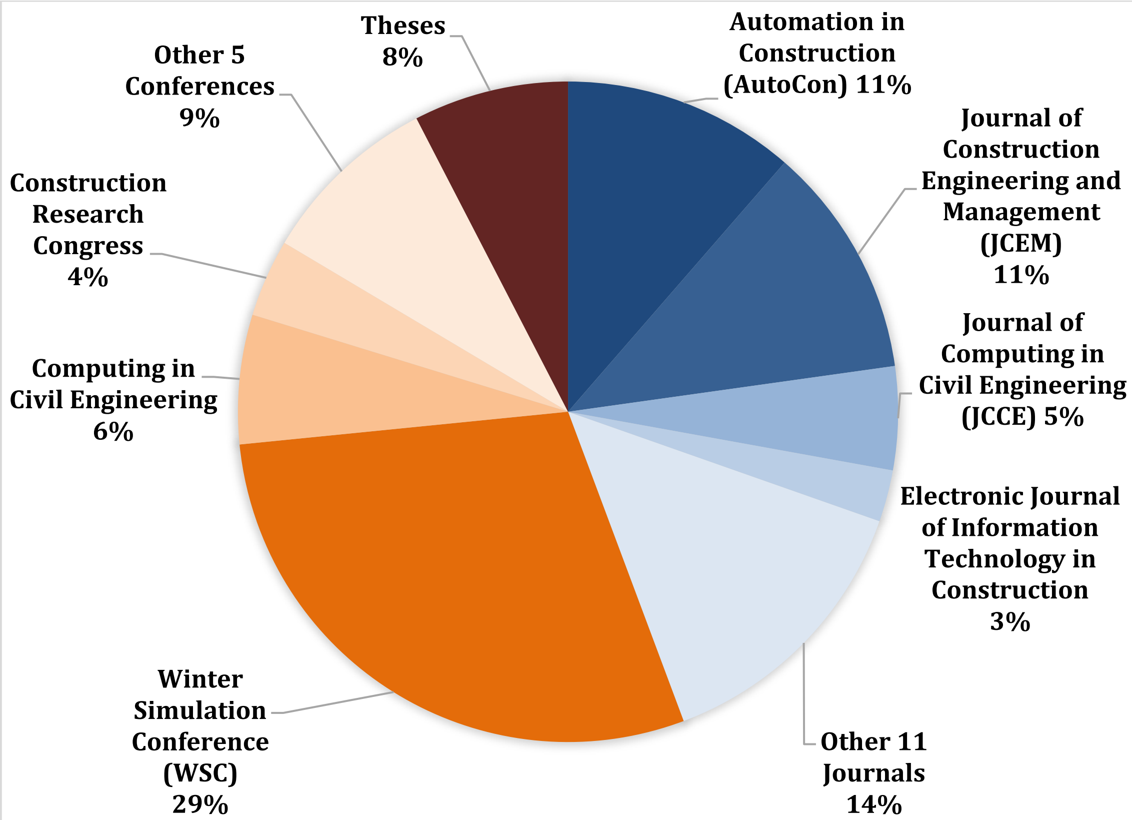

Figure 3: Sources of selected documents

4.1.3 Most published authors

Table 1 lists the top 10 authors with the highest number of publications out of the total of 113 authors identified. It can be concluded that the barriers to adopting simulation in construction have been extensively discussed within institutions in Canada and the USA.

Table 1: Top 10 most published authors of the selected documents

Researcher	Country	Selected documents
AbouRizk, S. M.	Canada	14
Mohamed, Y.	Canada	12
Behzadan, A.	USA	8

Lu, M.	Canada	6
Akhavian, R.	USA	4
ElNimr, A.	Canada	4
Kamat, V. R.	USA	4
Lucko, G.	USA	4
Martinez, J. C.	USA	4
Ruwanpura, J. Y.	Canada	4

4.1.4 Most frequently cited documents

Table 2 lists the most frequently cited documents according to Google Scholar. AbouRizk [2] received the highest number of citations among the selected documents as it provided comprehensive discussions on the gap between construction simulation research and practice as well as the critical factors for the successful collaboration established between the University of Alberta and construction industry in the city of Edmonton, Canada.

Table 2: Most cited documents

No	Author/year	Title	Source	Citations
1	AbouRizk [2]	Role of Simulation in Construction Engineering and Management	JCEM	236
2	Al-Hussein, et al. [26]	Integrating 3D visualization and simulation for tower crane operations on construction sites	AutoCon	146
3	Lee, et al. [11]	Dynamic planning and control methodology for strategic and operational construction project management	AutoCon	131
4	AbouRizk and Mohamed [27]	Simphony - an integrated environment for construction simulation	WSC	113

5	AbouRizk, et al. [5]	Research in Modeling and Simulation for Improving Construction Engineering Operations	JCEM	108
6	Kamat [28]	VITASCOPE: Extensible and scalable 3D visualization of simulated construction operations	Virginia Tech	71
7	Kamat and Martinez [29]	Validating Complex Construction Simulation Models Using 3D Visualization	Systems Analysis Modelling Simulation	71
8	Fente, et al. [30]	Defining a probability distribution function for construction simulation	JCEM	61
9	Akhavian and Behzadan [31]	Knowledge-based simulation modeling of construction fleet operations using multimodal-process data mining	JCEM	61
10	Mohamed and AbouRizk [32]	Framework for Building Intelligent Simulation Models of Construction Operations	JCCE	55

4.1.5 Thematic analysis of the documents

A classification of the papers based on their main objective was performed. Main themes were identified as follows: (1) challenges of construction simulation, (2) construction logistics, (3) data collection and synthesis, (4) hybrid simulation modelling, (5) implementing lean principles with simulation, (6) integrating simulation with BIM, (7) simulation tools and/or methods, and (8) visualization of simulation models. Figure 4 shows the frequency of themes identified for the selected documents.

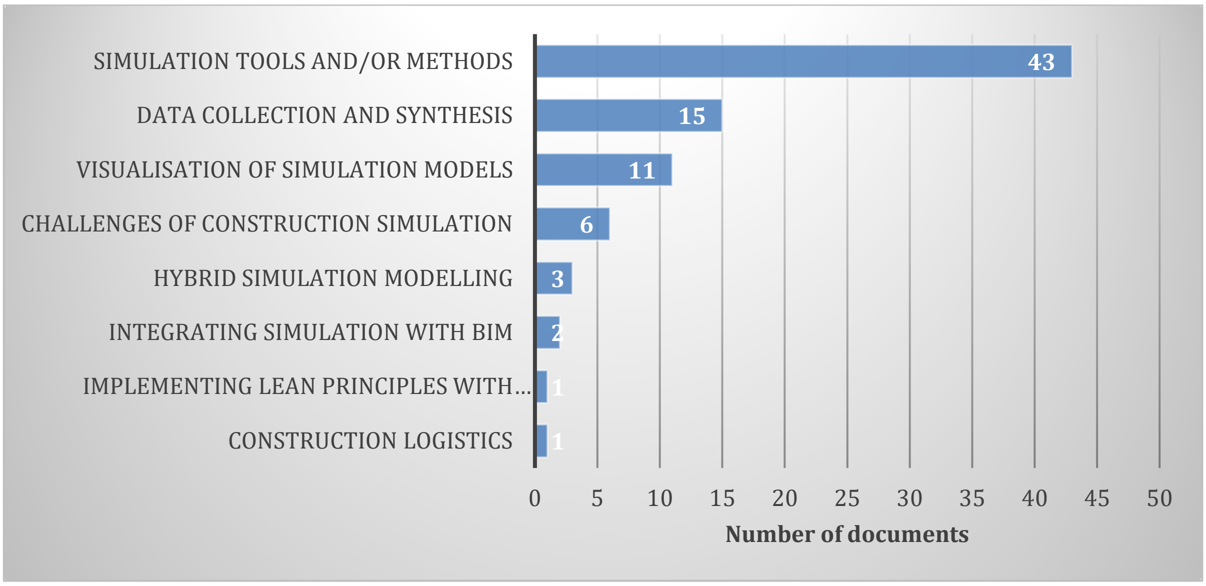

Figure 4: Thematic analysis

"Simulation tools and/or methods" was the most prevalent theme followed by "Data collection and synthesis", and "Visualisation of simulation models". In general, the barriers were discussed in the problem statement section of these documents to justify their scientific contribution to overcoming these barriers.

4.2 Content analysis

Content analysis is a flexible research method that analyses a body of text to identify current research patterns and emerging concepts [33]. It can be combined with qualitative, quantitative, or mixed research methods [33]. Content analysis was conducted using NVivo, which is a software for qualitative data analysis. NVivo is proved very effective with qualitative analysis for SLR as it assists in importing, coding, editing, retrieving and reviewing textual data as well as allowing searching for combinations of words in the text or patterns in the coding [34]. NVivo has been repeatedly used in content analysis of construction review studies such as in Lu and Yuan [35].

For the first research question (RQ1), queries were created using the following keywords: gap, limitation, issue, problem, challenge, drawback, or barrier. The software generated a list of the documents that contained at least one of the keywords or their synonyms. The findings of the queries were scanned to identify all the barriers reported. Each barrier was assigned to a node in NVivo. These nodes were then used as queries to do the second round of content analysis. For each node query, results were manually scanned, and information was assigned to the relative node. Any new barrier found was assigned to a new node. Another query was performed for the new nodes. This process was repeated until all the barriers reported in the documents were identified. Finally, a full-text scanning was completed on the documents to verify the findings from NVivo analysis and to search for any missing information that was overlooked during the process of using queries iteratively to identify barriers. An additional round of scanning was completed by a second co-author to validate the findings of the content analysis and locate any unidentified barriers.

Table 3 lists the findings of the content analysis. Identified barriers were classified into four main categories: (1) Nature of construction projects, (2) Industry practitioners, (3) Simulation technology, and (4) Construction simulation research. This classification aimed at making a distinction between the nature of the identified factors. Such a distinction can help to address barriers individually based on their nature. However, it is important to realise that several barriers within the same category or from different categories are interrelated as they may affect each other. The interrelationship between the barriers is explained in the discussion section of this paper (Section 5).

Table 3: Barriers to simulation adoption in the construction industry

Construction projects (CP)
1. Dynamic and risky nature of construction operations
2. Temporariness and uniqueness of construction projects
3. Time constraints
Simulation technology (ST)
1. The amount and nature of input data requirements
2. The complexity of simulation methodologies
3. The high cost of simulation studies
4. The high level of effort required to build simulation models
5. The long cycle time of simulation studies
6. The sophisticated nature of simulation outputs
7. The special skills required to develop simulation models
Industry practitioners (IP)
1. Industry culture and low confidence in simulation technologies
2. Lack of proper simulation knowledge among construction practitioners
Construction simulation research (CSR)
1. Lack of collaborative construction simulation studies
2. Limitations in construction simulation tools and methods

4.3 Quantitative analysis of identified barriers

The quantitative features of NVivo enabled the enumeration of the results based on the frequency of the findings. Table 4 illustrates the quantitative analysis of the barriers. Figure 5 sorts the identified barriers based on their frequency of reporting in the selected documents.

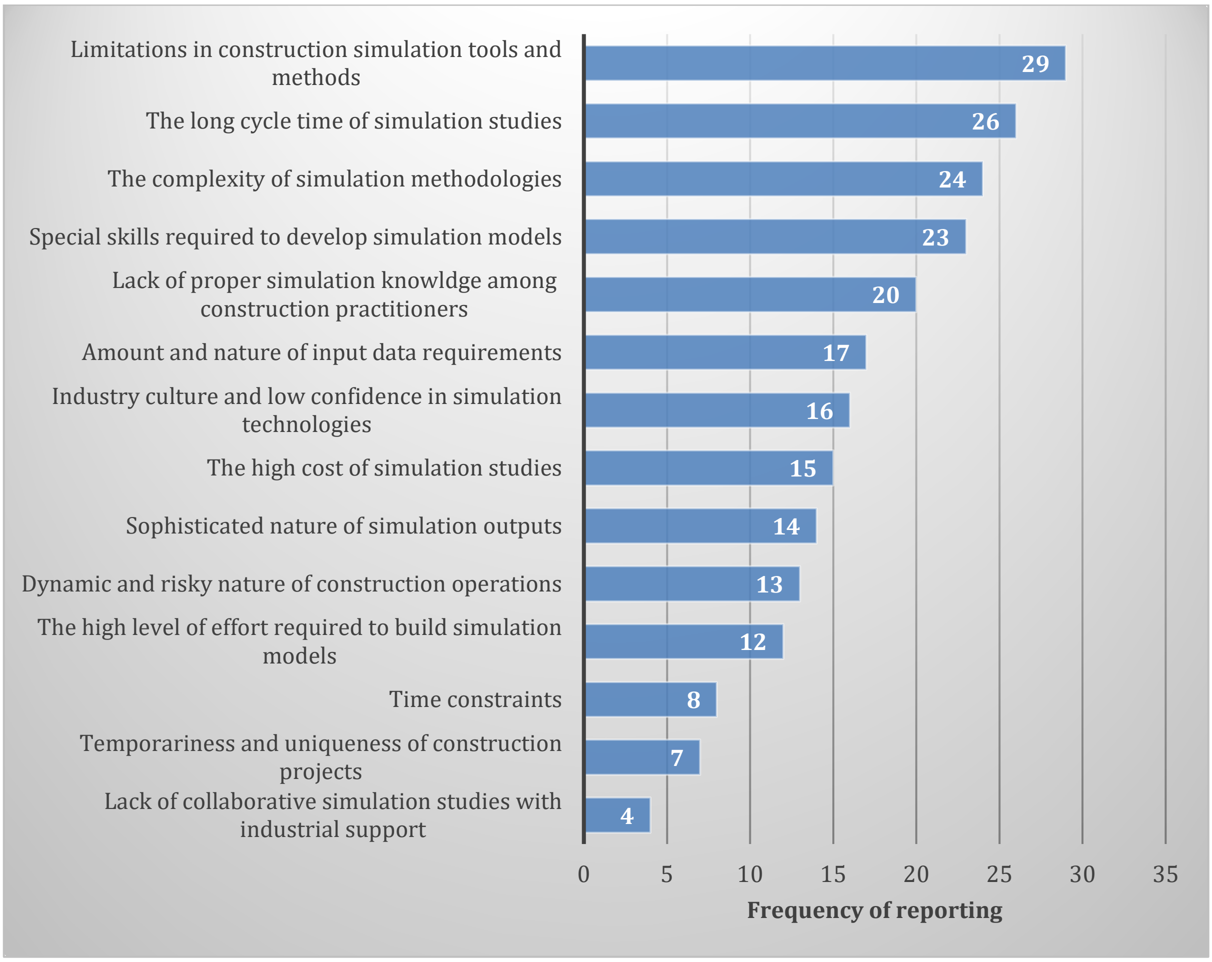

Figure 5: Analysis of barriers to simulation adoption in the construction industry

Table 4: Quantitative analysis of barriers

Barrier	[27]	[30]	[36]	[37]	[38]	[39]	[40]	[41]	[42]	[43]	[44]	[45]	[28]	[29]	[46]	[47]	[48]	[49]	[32]	[50]	[51]	[26]	[11]	[52]	[53]	[54]
CP1		X													X											
CP2																			X					X		
CP3																			X					X		
ST1		X															X			X					X	
ST2	X		X						X	X	X		X		X	X		X			X		X		X	X
ST3								X				X			X						X					
ST4																			X					X		
ST5							X	X	X		X			X	X	X					X				X	X
ST6										X			X	X								X				
ST7						X		X	X	X								X	X		X					X
IP1				X			X					X		X								X				
IP2	X						X	X	X			X		X	X						X					
CSR1					X	X																				
CSR2				X																	X		X		X	

Table 4: Quantitative analysis of barriers (Cont.)

Barrier	**[55]**	**[56]**	**[57]**	**[58]**	**[59]**	**[60]**	**[61]**	**[2]**	**[62]**	**[63]**	**[16]**	**[64]**	**[5]**	**[65]**	**[66]**	**[67]**	**[68]**	**[69]**	**[70]**	**[71]**	**[72]**	**[73]**	**[74]**	**[75]**	**[31]**	**[76]**
CP1					X								X	X					X		X		X	X		
CP2					X						X		X													
CP3					X								X													
ST1		X			X								X						X		X	X		X	X	
ST2		X	X									X		X				X					X			
ST3				X		X	X				X							X			X	X				X
ST4				X																X	X					
ST5			X	X	X	X	X				X						X	X		X		X				X
ST6			X		X					X		X	X		X	X										
ST7	X		X	X		X	X				X							X	X				X			X
IP1		X			X			X					X								X			X		
IP2			X	X	X																			X		
CSR1								X																		
CSR2		X			X	X			X	X					X	X		X			X			X		

Table 4: Quantitative analysis of barriers (Cont.)

Barrier	**[77]**	**[23]**	**[17]**	**[78]**	**[79]**	**[80]**	**[12]**	**[81]**	**[82]**	**[83]**	**[84]**	**[1]**	**[85]**	**[24]**	**[86]**	**[87]**	**[10]**	**[88]**	**[14]**	**[89]**	**[90]**	**[91]**	**[92]**	**[93]**	**[94]**	**[95]**
CP1	X			X																	X		X			
CP2		X												X												
CP3		X				X				X				X												
ST1							X			X		X						X			X					
ST2						X														X	X			X		X
ST3												X							X				X			
ST4		X						X	X					X	X									X	X	
ST5								X									X	X			X					X
ST6	X				X																		X			
ST7		X				X						X	X	X												
IP1	X	X	X		X														X							
IP2		X		X						X				X					X		X			X		X
CSR1																			X							
CSR2	X		X		X						X	X			X	X	X		X	X	X	X	X	X		X

5 Discussion

In this section, we firstly review the identified barriers to simulation adoption in the construction industry based on the findings from the literature review. Secondly, we discuss the main research directions that can help to overcome the barriers.

5.1 Barriers to simulation adoption in the construction industry

The following is a discussion of the 14 identified barriers in descending order based on their frequency of report as found in the qualitative analysis (see Figure 5).

5.1.1 Limitations in construction simulation tools and methods

This barrier was the most frequent problem reported in the literature, which has been discussed from several angles. For instance, the inability of current simulation tools to capture the reality of construction systems was reported in several studies as one of the factors limiting simulation adoption in construction [1,14,56,75,86,87,92]. The inaccuracy of the conceptualisation of the construction operations in the simulation studies has been recorded as another main reason for the gap between academia and industry [17,53,77,84,89-91]. It is typical in construction simulation research to adopt modelling strategies that are borrowed from manufacturing or other disciplines, which force the modellers to tweak construction systems by making unrealistic assumptions and simplifications to fit into these adopted strategies [17,91]. The increased interest in discussing this barrier in literature can explain why the theme of "Simulation tools and/or methods" was recognised as the most common theme in the selected literature.

5.1.2 The long cycle time of simulation studies

The time required to build simulation models has been another major roadblock in adopting computer simulation in construction, reported 26 times by the selected literature. The process of developing a construction simulation model from scratch is highly time-consuming for both modellers and construction stakeholders. Some studies reported time as a barrier in general while other studies were more specific in describing what simulation activities are the most time-consuming. Labban, et al. [23] referred to a case study on an asphalt paving project in which the simulation modelling experiment took five person-months. Such a long duration is not realistic in the production environment of construction projects. In other instances, the lengthy process of data gathering and building the model have been specified as the time-consuming part of the process; which hampers the willingness of the industry to use simulation as a decision-support tool [68,71,81]. Shrestha and Behzadan [95] refer to the conceptualisation as a challenging task that requires a considerable amount of time. The verification and validation of the models have also been addressed as another time-consuming step of the simulation studies [29,40].

5.1.3 The complexity of simulation modelling

This barrier was observed 24 times in the selected literature. Kamat [28] related the complexity of simulation modelling to the nature of the job of modelling, which is a combination of science and art. Lu and Wong [54] referred to the specific analytical aspects of the technique as a major reason for the complexity. Scherer and Ismail [69] also elaborated that this inherent complexity of simulation modelling in comparison with traditional construction planning techniques has been hindering its acceptance in the industry.

5.1.4 Special skills required to develop simulation models

The special aptitudes required to create a simulation model was reported as an obstacle to the adoption of simulation by the industry. To develop a simulation model, a special set of skills in different areas have to be acquired. The skills range from computer programming and statistics to system engineering [43,51,54,80]. In construction, to utilise the powerful features of simulation modelling tools in their decision-making process, the simulation modellers need to develop cognitive skills to observe, analyse, and conceptualise site operations [54]. These skills have steep learning curves and can take months or even years to be adequately mastered [39]. This barrier was reported 23 times in the selected literature.

5.1.5 Lack of proper simulation knowledge among construction practitioners

This barrier was mentioned 20 times in the selected literature. Construction engineers typically lack the knowledge required to develop a simulation model [83]. This problem can be mainly traced back to the lack of simulation education in construction curricula [14]. In their questionnaire survey to investigate the grand challenges in the construction industry, Leite, et al. [14] found that integrating simulation into construction curricula was identified as the most critical challenge by both academic and industry participants. This finding suggests the lack of proper simulation education as the main reason for this barrier.

5.1.6 Amount and nature of the input data required for a simulation study

This barrier was recorded 17 times. A significant amount of production data is required from the site to create the model, which is rarely available and its collection is associated with a tedious process [5,53]. Moreover, there is a lack of practical methods to provide updated and meaningful data during construction to keep the model current as the system evolves [1,31]. In the absence of the data that is specific to the project, most construction simulation models depend on historical data collected either from other projects or from expert judgement. This data will not necessarily suit the situation under study, which may affect the reliability and credibility of the model [12,83].

5.1.7 Industry culture and low confidence in simulation technologies

The construction industry has been known to resist and doubt modern technologies in general, with several examples such as their approach to the visualisation and information modelling technologies [14]. Construction practitioners often consider simulation as a “black art” that only a computer expert can understand [26]. In this sense, it closely ties to the lack of simulation knowledge discussed in 5.1.5. This cultural problem has been persistently reported over two decades with no compromise, so far. It was observed 16 times in the quantitative analysis of literature.

5.1.8 The high cost of simulation studies

This barrier was recorded 15 times. The high cost of simulation studies can be associated with the cost of acquisition and training to get a simulation software running for in-house simulation studies [45,60,92]. An alternative way is to hire external simulation consultants to undertake simulation studies which can be highly expensive and difficult to justify for stakeholders.

5.1.9 Sophisticated nature of simulation outputs

The selected literature contained 14 references to this barrier. Typically, the outputs of a simulation model are presented in statistical tables and charts. Such representation of outputs may be seen as impractical findings of the simulation study, especially with complex systems. This problem has been reported as one reason for the “black-box effect” perceived by construction practitioners towards simulation modelling [5,37]. This barrier is closely linked to the barriers discussed in 5.1.5 and 5.1.7 as it can be concluded that simulation outputs do not fit current data management systems and visualisation techniques for construction.

5.1.10 Dynamic and risky nature of construction operations

Construction projects are well known for their high level of risk and dynamicity [5]. Moreover, construction projects include diverse parties with different and sensitive inputs to the project. Fente, et al. [30] indicated that this barrier is the same reason why there is a research interest in using simulation for construction. Even though the complex nature of construction projects necessitates the need for the advanced analytical capabilities of simulation modelling [4], these characteristics have been repeatedly reported as an impediment to simulation adoption in the construction industry. The difficulty involved in abstracting such complex and uncertain operations can be considered as the primary factor leading to this barrier [74,77]. The selected literature contained 13 references to this barrier

5.1.11 High level of effort required to build simulation models

Carrying out a complete simulation study requires a considerable amount of effort for problem definition, system conceptualisation, data collection and synthesis, model design and coding, experimentation, verification and validation, and model implementation. Given the distinct nature of construction projects, this effort may seem infeasible to construction stakeholders [52]. Therefore, 12 studies in the selected literature argued that the amount of effort required for simulation modelling has been hindering simulation adoption by the construction industry. Even though effort can be expressed in terms of time and cost which can be related back to the barriers discussed in 5.1.2 and 5.1.8, we reported this barrier separately in the same way it was reported in the selected studies to maintain impartiality inherited in the practices of SLR.

5.1.12 Time constraints

This barrier was reported 8 times in the selected literature and it is fundamentally linked with the long-time requirements of simulation modelling discussed in 5.1.2. Since construction projects have a relatively short life cycle [5,23,83], construction decision-makers may not have sufficient time to run complete and valid simulation models [5]. Therefore, they may have to base their decisions on their experience and intuition by acting as “firefighters” to seek instant solutions to problems when encountered [96].

5.1.13 Temporariness and uniqueness of construction projects

Each construction project is considered “one-of-a-kind” due to the unique nature of its attributes[96]. Compared to other operations research disciplines such as manufacturing, construction production systems are temporary [59]. Therefore, in most cases, a construction simulation model is only used for the case it was built to solve. Going through a complete simulation study to produce a single and non-reusable simulation model may seem like an unjustifiable investment for construction stakeholders [32]. This barrier was recorded 7 times in the quantitative analysis of selected literature.

5.1.14 Lack of collaborative construction simulation studies

Even though simulation modelling is a major topic in the area of construction engineering and management [4,97], construction simulation research lacks collaborative studies that combine people from different research areas with strong industrial support [2,14]. The need for higher collaboration in conducting simulation research was recorded only four times in the selected literature with the oldest by [38] 19 years ago. Surprisingly, this barrier is ranked as the least frequent barrier in the selected literature.

5.2 Trends of the appearance of the barrier in the literature

Figure 6 depicts the cumulative frequency for each barrier against the publication year. It can be found that barriers related to “Simulation Technology” (ST in blue) have high frequency over the years in general, especially long development time, special skills, and complexity of simulation methodologies. Barriers that belong to the category of “Industry Practitioners” (IP in red) have fluctuated frequency, but in general, they received average interest compared to other barriers. Barriers of “Construction Projects” (CP in green) have low frequency and are of the least interest to researchers. Finally, the two barriers related to “Construction Simulation Research” (CSR in orange) have different results. It seems that the lack of collaborative studies did not catch the attention of most researchers in general as it has the lowest frequency for most years. On the other hand, the barrier of limitations of current construction simulation methods was the most frequent barrier by 2019.

Two patterns of barriers can be identified in Figure 6. First, most of the barriers under the categories of 'Construction projects' and 'Simulation technology' consistently concerned researchers as they received regular attention over the reviewed period (2000-2019). Second, some other barriers that are related to industry practitioners and construction simulation research received higher attention recently. This higher attention for the second pattern can be interpreted as an increased awareness of the most critical barriers that need more research efforts. A clear example of the second pattern is the barrier of "limitations of current construction simulation methods" which received a rapid increase in frequency and became the most frequent barrier by 2019.

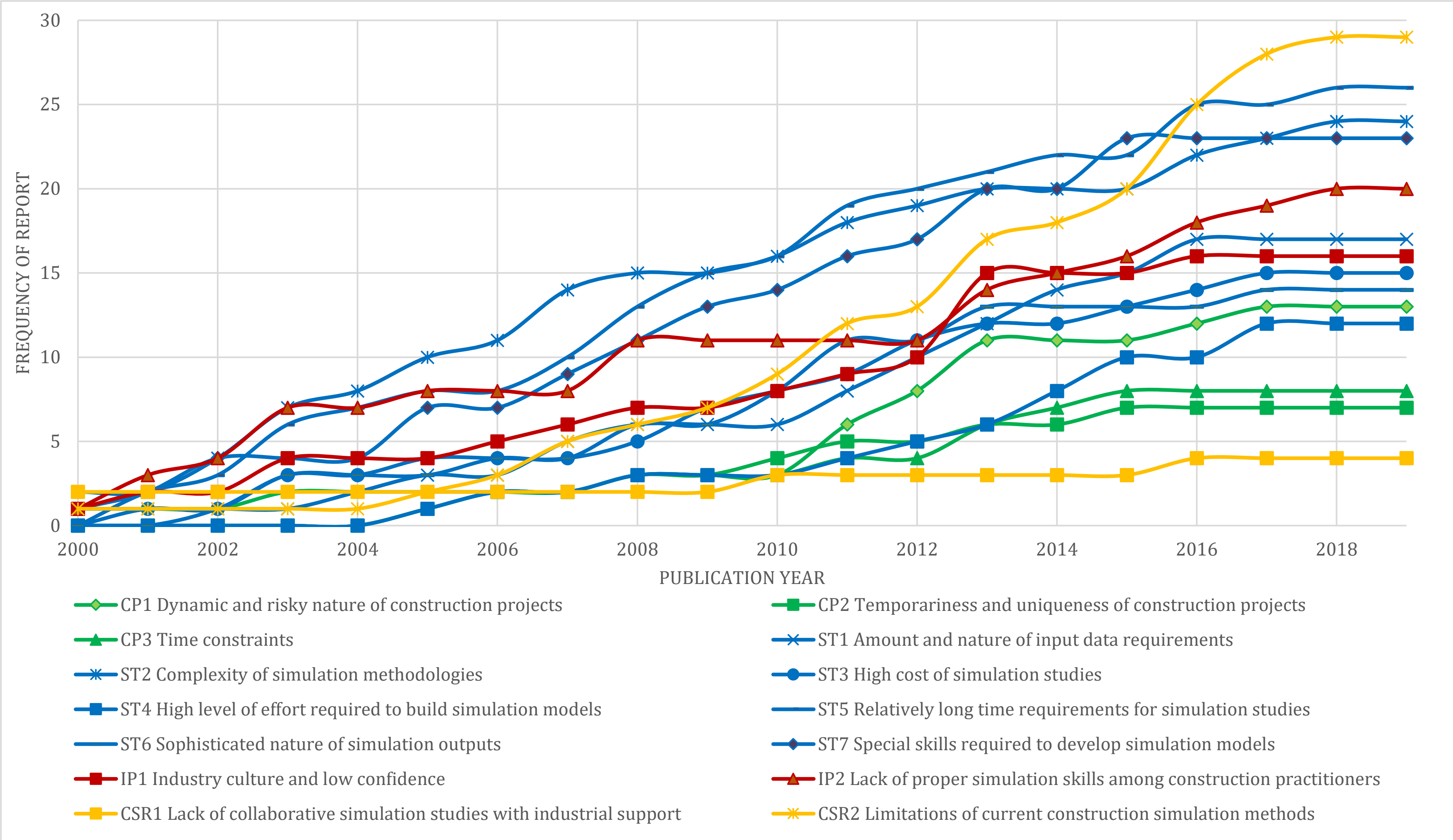

Figure 6: Trends in barriers

5.3 Research directions to overcome construction simulation adoption barriers

Several initiatives have been launched to bridge the gap between construction simulation state-of-the-art and state-of-practice. Building on the ASCE's VIMS committee mission reports by Lee, et al. [17] and Leite, et al. [14], this study summarises four main directions as recommendations for future research.

5.3.1 Reducing the skills, efforts, and time required to build simulation models

As discussed, building a construction simulation model necessitates acquiring multidisciplinary knowledge such as industrial engineering, computer science, and construction management, which is often unavailable for most construction engineering practitioners [14]. Thus, mainstream research efforts have been focused on developing construction simulation tools that do not require the users to obtain extensive knowledge about simulation modelling. The development of simulation systems for construction applications, such as CYCLONE [6], Stroboscope [7], and Simphony [8], featured outstanding contributions to the area of reducing the required skills and development efforts. These systems require a minimal simulation education to support non-experts in building simulation models. Additionally, through the use of predefined construction-specific objects, these systems can save a considerable amount of simulation conceptualisation and coding time. The challenges associated with reducing skills, efforts, and time can be summarised by the question of "Can simulation be made as simple as the Critical Path Method (CPM) without sacrificing its functionality?" [98]. This question is based on the notion that CPM is considered the most popular tool in the 20th century for construction management practitioners [99]. However, efforts spent on simplifying model development were not enough to yield successful deployment of simulation in the industry [2]. Therefore, these efforts should coincide with other research aspects as discussed in the following subsections on research directions.

5.3.2 Improving the quality of computer simulation studies

New advancements in computer simulation technologies can facilitate the generation of simulation models with higher quality [14]. For example, sensing devices and smartphones can be used in conjunction with Agent-Based Modelling (ABS) to incorporate social aspects and human behaviour in construction simulation. Additionally, partnering construction simulation models with real-time data from the site has been proposed in recent studies to develop dynamic models that adapt to the real world [1,95]. It was found that more accurate and reliable simulation results can be obtained by the efficient use of sensors. Another area of improvement is the verification and validation of simulation models. Modern visualisation techniques such as 3D animation and VR/AR can be utilised to facilitate model verification and validation [13].

5.3.3 Strengthen the relationship between academia and industry

It is vital to establish a strong relationship between simulation researchers and construction practitioners to leverage acceptance of computer simulation as a decision-support tool in the industry. An example of the few successful partnership cases reported in the literature is provided by AbouRizk [2]. This partnership was achieved by the collaboration since 1994 between the Natural Science and Engineering Research Council of Canada (NSERC) Industrial Research Chair (IRC), a consortium of construction companies, and the University of Alberta. Several applications were deployed through this partnership including earthmoving, tunnelling, construction claims, fabrication shops, and site layout. The success of this partnership was built on several factors such as (1) useful input from industry into the research program, (2) flexible and powerful simulation tools, (3) tangible results in reasonable timeframes, (4) long-term relationship and trust with industry, and (5) sufficient funding for the research program.

5.3.4 Integrating simulation modelling into construction engineering curricula

It can be concluded that the two barriers related to construction practitioners (IP1 and IP2) are linked to lack of simulation education in construction engineering curricula. Even though simulation has been identified as one of the top research areas in construction between 1985 and 2002 [97], it received less interest in construction education compared to other engineering departments such as mechanical and industrial engineering. Integration can provide future engineers with sufficient knowledge of simulation and increase their ability to create valid and useful models for real-world construction problems.

6 Conclusion

Despite being at the centre of attention of construction scholars, computer simulation has not received the same wide recognition from the construction industry. This paper investigated the barriers to computer simulation adoption in the construction industry. Previous research presented 6 main challenges based on focus-group of simulation experts [14,17]. In this study, we aimed at complementing previous research by addressing the gap from a different perspective. Therefore, a systematic procedure was followed to investigate a wider community to provide a deeper understanding of the problem of lack of simulation adoption in the industry. Accordingly, 14 barriers were identified and four main directions were proposed that can be taken to overcome the barriers which are: (1) Reducing the skill, effort, and time required to build simulation models; (2) Improving the quality of computer simulation studies; (3) Strengthening the relationship between academia and industry; and (4) Integrating simulation modelling into construction engineering curricula.

Even though construction systems have unique characteristics compared to other simulation domains, the practice of simulation modelling should not be significantly different [4]. Therefore, a closer examination of the efforts in overcoming the barriers in other simulation domains can provide specific insights to contribute to the recommended four directions. One aspect of simulation that has received little attention in construction simulation research is conceptual modelling, which is the simulation study phase concerned with model description and system abstraction. Even though the need for a meaningful specification of the system was repeatedly reported in construction simulation research [1,2,4,17,26,53,84], only a few attempts were made to incorporate the conceptual modelling phase in construction simulation solutions such as in [73]; [89]; and [91]. Therefore, future work will investigate the role of conceptual modelling in overcoming the barriers of simulation adoption in the construction industry as identified in this paper.

It is plausible that some limitations may have affected the findings of this paper. First, with the increasing number of studies in the area of construction simulation and the different taxonomies used in this field, some papers that have reported barriers may have been missed in the search results. However, a dedicated effort was made by two of the authors of this paper to ensure that we covered most of the available literature on the topic. Second, the definition and categorisation of barriers may have been influenced by the researchers' bias. Therefore, a validation of the content analysis was carried out by one of the co-authors to ensure the accuracy of the findings by cross-checking the identified barriers with the selected literature. Finally, the findings of this study may not reflect the viewpoints of all industry practitioners, who use simulation modelling as a decision-support tool in construction, as they do not necessarily publish the outcomes of their simulation studies in academic literature. The last limitation can trigger future research on investigating the reasons for lack of simulation adoption in construction from an industrial perspective.

7 References

[1] A.H. Behzadan, C.C. Menassa, A. Predhan, Enabling real time simulation of architecture, engineering, construction, and facility management (AEC/FM) systems: a review of formalism, model architecture, and data representation, Journal of Information Technology in Construction 20 (2015) 1-23, https://www.itcon.org/paper/2015/1, Accessed date: 4 October 2019.

[2] S. AbouRizk, Role of Simulation in Construction Engineering and Management, Journal of Construction Engineering and Management 136 (10) (2010) 1140-1153, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000220.

[3] S. Robinson, Simulation : The Practice of Model Development and Use, 2nd edition.. Palgrave Macmillan, Basingstoke, 2014, ISBN: 9781137328038.

[4] J.C. Martinez, Methodology for Conducting Discrete-Event Simulation Studies in Construction Engineering and Management, Journal of Construction Engineering and Management 136 (1) (2010) 3-16, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000087.

[5] S. AbouRizk, D. Halpin, Y. Mohamed, U. Hermann, Research in Modeling and Simulation for Improving Construction Engineering Operations, Journal of Construction Engineering and Management 137 (10) (2011) 843-852, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000288.

[6] D.W. Halpin, An investigation of the use of simulation networks for modeling construction operations, Ph.D. Thesis, University of Illinois at Urbana-Champaign, 1973, Available at: https://ci.nii.ac.jp/naid/10024820941/, Accessed date: 4 October 2019.

[7] J.C. Martinez, Stroboscope: State and resource based simulation of construction processes, Ph.D. Thesis, University of Michigan, 1996, Available at: http://www.ioannou.org/publications/umthesis, Accessed date: 4 October 2019.

[8] D. Hajjar, S. AbouRizk, Simphony: an environment for building special purpose construction simulation tools, Proceedings of the Winter Simulation Conference, IEEE, Phoenix, Arizona, USA, 1999, pp. 998-1006, https://doi.org/10.1109/WSC.1999.816811.

[9] S.M. AbouRizk, S. Hague, An overview of the COSYE environment for construction simulation, Proceedings of the Winter Simulation Conference, IEEE, Austin, TX, USA, USA, 2009, pp. 2624-2634, https://doi.org/10.1109/WSC.2009.5429307.

[10] W. Jeong, S. Chang, J.W. Son, J.S. Yi, BIM-integrated construction operation simulation for just-in-time production management, Sustainability (Switzerland) 8 (11) (2016), https://doi.org/10.3390/su8111106.

[11] S.H. Lee, F. Peña-Mora, M. Park, Dynamic planning and control methodology for strategic and operational construction project management, Automation in Construction 15 (1) (2006) 84-97, http://dx.doi.org/10.1016/j.autcon.2005.02.008.

[12] R. Akhavian, A.H. Behzadan, Evaluation of queuing systems for knowledge-based simulation of construction processes, Automation in Construction 47 (2014) 37-49, http://dx.doi.org/10.1016/j.autcon.2014.07.007.

[13] R. Kamat Vineet, C. Martinez Julio, M. Fischer, M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Research in Visualization Techniques for Field Construction, Journal of Construction Engineering and Management 137 (10) (2011) 853-862, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000262.

[14] F. Leite, Y. Cho, A. Behzadan, S. Lee, S. Choe, Y. Fang, R. Akhavian, S. Hwang, Visualization, Information Modeling, and Simulation: Grand Challenges in the Construction Industry, Journal of Computing in Civil Engineering 30 (6) (2016) 04016035, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000604.

[15] M.A. Abdelmegid, V.A. González, A.M. Naraghi, M.O. Sullivan, C.G. Walker, M. Poshdar, Towards a conceptual modeling framework for construction simulation, Proceedings of the Winter Simulation Conference, IEEE, Las Vegas, NV, USA, 2017, pp. 2372-2383, https://doi.org/10.1109/WSC.2017.8247967.

[16] G. Lucko, P.C. Benjamin, K. Swaminathan, M.G. Madden, Comparison of manual and automated simulation generation approaches and their use for construction applications, Proceedings of the Winter Simulation Conference, IEEE, Baltimore, MD, USA, 2010, pp. 3132-3144, https://doi.org/10.1109/WSC.2010.5679006.

[17] S. Lee, A. Behzadan, A. Kandil, Y. Mohamed, Grand Challenges in Simulation for the Architecture, Engineering, Construction, and Facility Management Industries, Computing in Civil Engineering, American Society of Civil Engineers, 2013, pp. 773-785, https://doi.org/10.1061/9780784413029.097.

[18] Q. Shi, X. Ding, J. Zuo, G. Zillante, Mobile Internet based construction supply chain management: A critical review, Automation in Construction 72 (2016) 143-154, https://doi.org/10.1016/j.autcon.2016.08.020.

[19] M. Borrego, M.J. Foster, J.E. Froyd, Systematic Literature Reviews in Engineering Education and Other Developing Interdisciplinary Fields, Journal of Engineering Education 103 (1) (2014) 45-76, https://doi.org/10.1002/jee.20038.

[20] M. Jahangirian, A. Naseer, L. Stergioulas, T. Young, T. Eldabi, S. Brailsford, B. Patel, P. Harper, Simulation in health-care: lessons from other sectors, Operational Research 12 (1) (2012) 45-55, https://doi.org/10.1007/s12351-010-0089-8.

[21] A. Panas, J. Pantouvakis, Evaluating research methodology in construction productivity studies, The Built & Human Environment Review 3 (1) (2010) 63-85, https://bit.ly/31Lv8Im, Accessed date: 4 October 2019.

[22] S. Jalali, C. Wohlin, Systematic literature studies: database searches vs. backward snowballing, Proceedings of the ACM-IEEE international symposium on Empirical software engineering and measurement, Lund, Sweden, 2012, pp. 29-38, https://doi.org/10.1145/2372251.2372257.

[23] R. Labban, S. AbouRizk, Z. Haddad, A. Elsersy, A discrete event simulation model of asphalt paving operations, Proceedings of the Winter Simulation Conference, IEEE, Washington, DC, USA, 2013, pp. 3215-3224, https://doi.org/10.1109/WSC.2013.6721687.

[24] R.R. Labban, A Methodology for the Automated Creation of Construction Simulation Models, Ph.D. Thesis, University of Alberta, 2015, Available at: https://era.library.ualberta.ca/items/c97cbc2b-db3c-4adb-9a67-01d62132bc7e, Accessed date: 4 October 2019.

[25] S. Robinson, Conceptual modelling for simulation: Progress and grand challenges, Journal of Simulation (2019), https://doi.org/10.1080/17477778.2019.1604466.

[26] M. Al-Hussein, M. Athar Niaz, H. Yu, H. Kim, Integrating 3D visualization and simulation for tower crane operations on construction sites, Automation in Construction 15 (5) (2006) 554-562, https://doi.org/10.1016/j.autcon.2005.07.007.

[27] S. AbouRizk, Y. Mohamed, Simphony - an integrated environment for construction simulation, Proceedings of the Winter Simulation Conference, Vol. 2, IEEE, Orlando, FL, USA, 2000, pp. 1907-1914, https://doi.org/10.1109/WSC.2000.899185.

[28] V.R. Kamat, VITASCOPE: Extensible and scalable 3D visualization of simulated construction operations, Ph.D. Thesis, Virginia Tech, 2003, Available at: https://vtechworks.lib.vt.edu/handle/10919/26846, Accessed date: 4 October 2019.

[29] V.R. Kamat, J.C. Martinez, Validating Complex Construction Simulation Models Using 3D Visualization, Systems Analysis Modelling Simulation 43 (4) (2003) 455-467, https://doi.org/10.1080/02329290290028507.

[30] J. Fente, C. Schexnayder, K. Knutson, Defining a probability distribution function for construction simulation, Journal of Construction Engineering and Management 126 (3) (2000) 234-241, https://doi.org/10.1061/(ASCE)0733-9364(2000)126:3(234).

[31] R. Akhavian, A.H. Behzadan, Knowledge-based simulation modeling of construction fleet operations using multimodal-process data mining, Journal of Construction Engineering and Management 139 (11) (2013), https://doi.org/10.1061/(ASCE)CO.1943-7862.0000775.

[32] Y. Mohamed, S. AbouRizk, Framework for Building Intelligent Simulation Models of Construction Operations, Journal of Computing in Civil Engineering 19 (3) (2005) 277-291, https://doi.org/10.1061/(ASCE)0887-3801(2005)19:3(277).

[33] K.A. Neuendorf, The content analysis guidebook, Sage Publications, Thousand Oaks, Calif., 2002, ISBN: 0761919775.

[34] A.H. Hilal, S.S. Alabri, Using NVivo for data analysis in qualitative research, International interdisciplinary journal of education (2) (2013) 181-186, http://www.iijoe.org/v2/IIJOE_06_02_02_2013.pdf, Accessed date: 4 October 2019.

[35] W. Lu, H. Yuan, A framework for understanding waste management studies in construction, Waste Management 31 (6) (2011) 1252-1260, https://doi.org/10.1016/j.wasman.2011.01.018.

[36] D. Hajjar, Y. Mohamed, S. AbouRizk, Creating Special Purpose Simulation Tools with Simphony, Construction Congress VI, 2000, pp. 87-96, https://doi.org/10.1061/40475(278)11.

[37] V.R. Kamat, J.C. Martinez, 3D visualization of simulated construction operations, Proceedings of the Winter Simulation Conference, IEEE, Orlando, FL, USA, 2000, pp. 1933-1937, https://doi.org/10.1109/WSC.2000.899189.

[38] G. Kannan, L. Schmitz, C. Larsen, Industry perspective on the role of equipment-based earthmoving simulation, Proceedings of the Winter Simulation Conference, Vol. 2, IEEE, Orlando, FL, USA, 2000, pp. 1945-1952, https://doi.org/10.1109/WSC.2000.899191.

[39] J.J. Shi, Activity Based Construction (ABC) Simulation Modeling vs. Critical Path Method (CPM), Construction Congress VI, 2000, pp. 131-139, https://doi.org/10.1061/40475(278)16.

[40] V.R. Kamat, J.C. Martinez, Enabling smooth and scalable dynamic 3D visualization of discrete-event construction simulations, Proceedings of the Winter Simulation Conference, Vol. 2, IEEE, Arlington, VA, USA, 2001, pp. 1528-1533, https://doi.org/10.1109/WSC.2001.977481.

[41] J. Kim, D.W. Halpin, D.M. Abraham, Interactive Simulation System, Fifth International Conference on Information Visualisation 2001, pp. 361-366, https://doi.org/10.1109/IV.2001.942083.

[42] Z. Hong, J.J. Shi, C.M. Tam, Visual modeling and simulation for construction operations, Automation in Construction 11 (1) (2002) 47-57, https://doi.org/10.1016/S0926-5805(01)00049-8.

[43] H. Zhang, J.J. Shi, C.M. Tam, Iconic animation for activity-based construction simulation, Journal of Computing in Civil Engineering 16 (3) (2002) 157-164, https://doi.org/10.1061/(ASCE)0887-3801(2002)16:3(157).

[44] S. Fernando, K.C. Er, Y. Mohamed, S. AbouRizk, J. Ruwanpura, A Review of Simulation Applications for Varying Demands in Tunneling, Construction Research Congress, 2003, pp. 1-10, https://doi.org/10.1061/40671(2003)35.

[45] D.W. Halpin, H. Jen, J. Kim, A construction process simulation Web service, Proceedings of the Winter Simulation Conference, Vol. 2, IEEE, New Orleans, LA, USA, 2003, pp. 1503-1509 vol.1502, https://doi.org/10.1109/WSC.2003.1261595.

[46] K.J. Kim, G.E. Gibson Jr, Interactive simulation modeling for heavy construction operations, Automation in Construction 12 (1) (2003) 97-109, http://dx.doi.org/10.1016/S0926-5805(02)00048-1.

[47] M. Lu, W.H. Chan, Modeling concurrent operational interruptions in construction activities with simplified discrete event simulation approach (SDESA), Proceedings of the Winter Simulation Conference, Vol. 2, IEEE, Washington, DC,USA, 2004, pp. 1260-1267, https://doi.org/10.1109/WSC.2004.1371458.

[48] H. Zhang, H. Li, C.M. Tam, Fuzzy discrete-event simulation for modeling uncertain activity duration, Engineering, Construction and Architectural Management 11 (6) (2004) 426-437, https://doi.org/10.1108/09699980410570184.

[49] M. Lu, Adapted process-interaction modeling paradigm for construction simulation, Proceedings of the ASCE International Conference on Computing in Civil Engineering, Cancun, Mexico, 2005, pp. 1405-1414, https://doi.org/10.1061/40794(179)133.

[50] C. Schexnayder, K. Knutson, J. Fente, Describing a beta probability distribution function for construction simulation, Journal of Construction Engineering and Management 131 (2) (2005) 221-229, https://doi.org/10.1061/(ASCE)0733-9364(2005)131:2(221).

[51] E.K. Zaneldin, AOA-based modelling and simulation of construction operations, International Journal of Simulation Modelling 4 (4) (2005) 184-195, https://doi.org/10.2507/IJSIMM04(4)3.050.

[52] Y. Mohamed, S.M. AbouRizk, A hybrid approach for developing special purpose simulation tools, Canadian Journal of Civil Engineering 33 (12) (2006) 1505-1515, https://doi.org/10.1139/L06-073.

[53] M. Lu, W.-H. Chan, J.-P. Zhang, M. Cao, Generic Process Mapping and Simulation Methodology for Integrating Site Layout and Operations Planning in Construction, Journal of Computing in Civil Engineering 21 (6) (2007) 453-462, https://doi.org/10.1061/(ASCE)0887-3801(2007)21:6(453).

[54] M. Lu, L.-C. Wong, Comparison of two simulation methodologies in modeling construction systems: Manufacturing-oriented PROMODEL vs. construction-oriented SDESA, Automation in Construction 16 (1) (2007) 86-95, http://dx.doi.org/10.1016/j.autcon.2005.12.001.

[55] S. Palaniappan, A. Sawhney, H.H. Bashford, K.D. Walsh, Special purpose simulation template for workflow analysis in construction, Proceedings of the Winter Simulation Conference, IEEE, Washington, DC, USA, 2007, pp. 2090-2098, https://doi.org/10.1109/WSC.2007.4419841.

[56] J.Y. Ruwanpura, S.T. Ariaratnam, Simulation modeling techniques for underground infrastructure construction processes, Tunnelling and Underground Space Technology 22 (5–6) (2007) 553-567, http://dx.doi.org/10.1016/j.tust.2007.05.001.

[57] H. Guo, Rethinking construction project management using the VP-based manufacturing management model, Ph.D. Thesis, Hong Kong Polytechnic University (Hong Kong), 2008, Available at: http://hdl.handle.net/10397/2793 Accessed date: 4 October 2019.

[58] G. Lucko, P.C. Benjamin, M.G. Madden, Harnessing the power of simulation in the project management / decision support aspects of the construction industry, Proceedings of the Winter Simulation Conference, IEEE, Miami, FL, USA, 2008, pp. 2479-2487, https://doi.org/10.1109/WSC.2008.4736357.

[59] F.K. Schramm, G.L. Silveira, H. Paez, H. Mesa, C.T.V. Formoso, D. Echeverry, Using discrete-event simulation to support decision-makers in production system design and operations, Proceedings of IGLC16: Annual Conference of the International Group for

Lean Construction, Manchester, UK, 2008, pp. 131-141, http://iglc.net/Papers/Details/609, Accessed date: 4 October 2019.

[60] N. Dawood, S. Castro, Automating road construction planning with a specific-domain simulation system, Electronic Journal of Information Technology in Construction 14 (2009) 556-573, http://www.itcon.org/2009/36, Accessed date: 4 October 2019.

[61] G. Lucko, K. Swaminathan, P.C. Benjamin, M.G. Madden, Rapid deployment of simulation models for building construction applications, Proceedings of the Winter Simulation Conference, IEEE, Austin, TX, USA, 2009, pp. 2733-2744, https://doi.org/10.1109/WSC.2009.5429255.

[62] S. AbouRizk, Y. Mohamed, H. Taghaddos, F. Saba, S. Hague, Developing complex distributed simulation for industrial plant construction using high level architecture, Proceedings of the Winter Simulation Conference, IEEE, Baltimore, MD, USA, 2010, pp. 3177-3188, https://doi.org/10.1109/WSC.2010.5679010.

[63] A. ElNimr, Y. Mohammed, A Simulation Driven Visualization Framework for Construction Operations: Development and Application, Construction Research Congress, American Society of Civil Engineers, 2010, pp. 257-266, https://doi.org/10.1061/41109(373)26.

[64] Y. Zhang, E. Moghani, S.M. AbouRizk, S. Fernando, 3D cad modeling and visualization of the tunnel construction process in a distributed simulation environment, Proceedings of the Winter Simulation Conference, IEEE, Baltimore, MD, USA, 2010, pp. 3189-3200, https://doi.org/10.1109/WSC.2010.5679011.

[65] O. Al-Tabbaa, R. Rustom, General framework for designing multi-use simulation modules for estimating project durations, Construction Innovation 11 (3) (2011) 321-337, https://doi.org/10.1108/14714171111149034.

[66] A. ElNimr, Y. Mohamed, Loosely coupled visualization of industrial construction simulation using a gaming engine, Proceedings of the Winter Simulation Conference, IEEE, Phoenix, AZ, USA, 2011, pp. 3577-3587, https://doi.org/10.1109/WSC.2011.6148052.

[67] A.A. ElNimr, Y. Mohamed, Application of gaming engines in simulation driven visualization of construction operations, Electronic Journal of Information Technology in Construction 16 (2011) 23-38, http://www.itcon.org/2011/3, Accessed date: 4 October 2019.

[68] A. Marx, M. König, Preparation of Constraints for Construction Simulation, Computing in Civil Engineering, 2011, pp. 462-439, https://doi.org/10.1061/41182(416)57.

[69] R. Scherer, A. Ismail, Process-based simulation library for construction project planning, Proceedings of the Winter Simulation Conference, IEEE, Phoenix, AZ, USA, 2011, pp. 3488-3499, https://doi.org/10.1109/WSC.2011.6148044.

[70] H. Xie, Improving Dynamic Project Control in Tunnel Construction, Ph.D. Thesis, University of Alberta 2011, Available at: https://era.library.ualberta.ca/items/9570335a-b5e6-4b63-92ce-7a837ab015a4, Accessed date: 4 October 2019.

[71] H. Xie, S. Fernando, S. AbouRizk, Integrating realtime project progress input into a construction simulation model, Proceedings of the Winter Simulation Conference, IEEE, Phoenix, AZ, USA, 2011, pp. 3443-3454, https://doi.org/10.1109/WSC.2011.6148040.

[72] V. Puri, Incorporation of continuous activities into activity cycle diagram based discrete event simulation for construction operations, Ph.D. Thesis, Purdue University, 2012, Available at: https://docs.lib.purdue.edu/dissertations/AAI3545359/, Accessed date: 4 October 2019.

[73] F. Saba, A Semantic-Driven Framework for Facilitating Reusability and Interoperability of Construction Simulation Modeling, Ph.D. Thesis, University of Alberta 2012, Available at: https://era.library.ualberta.ca/items/124ed522-d960-433b-8d2c-83a2724cc7b6, Accessed date: 4 October 2019.

[74] J. Siadat, J.Y. Ruwanpura, K. Siyadat, Engineering design estimation using SimFC, Emerging M and S Applications in Industry and Academia Symposium, 2012, pp. 99-105, https://dl.acm.org/citation.cfm?id=2338798, Accessed date: 4 October 2019.

[75] R. Akhavian, A.H. Behzadan, Automated knowledge discovery and data-driven simulation model generation of construction operations, Proceedings of the Winter Simulation Conference, IEEE, Washington, DC, USA, 2013, pp. 3030-3041, https://doi.org/10.1109/WSC.2013.6721670.

[76] M. Al-Bataineh, S. AbouRizk, H. Parkis, Using Simulation to Plan Tunnel Construction, Journal of Construction Engineering and Management 139 (5) (2013) 564-571, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000626.

[77] H. Alzraiee, T. Zayed, O. Moselhi, Assessment of construction operations productivity rate as computed by simulation models, Proceedings of the Winter Simulations Conference, IEEE, Washington, DC, USA, 2013, pp. 3225-3236, https://doi.org/10.1109/WSC.2013.6721688.

[78] D. Morley, M. Lu, S. AbouRizk, Utilizing simulation derived quantitative formulas for accurate excavator hauler fleet selection, Proceedings of the Winter Simulations Conference, IEEE, Washington, DC, USA, 2013, pp. 3018-3029, https://doi.org/10.1109/WSC.2013.6721669.

[79] J.-P. Pantouvakis, A. Panas, Computer simulation and analysis framework for floating caisson construction operations, Automation in Construction 36 (2013) 196-207, http://dx.doi.org/10.1016/j.autcon.2013.04.003.

[80] J. Siadat, J.Y. Ruwanpura, Effective simulation of earth moving projects, Proceedings of the Winter Simulations Conference, IEEE, Washington, DC, USA, 2013, pp. 3282-3293, https://doi.org/10.1109/WSC.2013.6721693.

[81] J. Louis, P. Dunston, J. Martinez, Simulating and Visualizing Construction Operations using Robot Simulators and Discrete Event Simulation, Computing in Civil and Building Engineering, 2014, pp. 355-363, https://doi.org/10.1061/9780784413616.045.

[82] W. Lu, T. Olofsson, Building information modeling and discrete event simulation: Towards an integrated framework, Automation in Construction 44 (2014) 73-83, https://doi.org/10.1016/j.autcon.2014.04.001.

[83] D. Morley, M. Lu, S. AbouRizk, Identification of invariant average weighted haul distance to simplify earthmoving simulation modeling in planning site grading operations, Journal of Construction Engineering and Management 140 (12) (2014) 04014057, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000907.

[84] J. Zhu, A. Mostafavi, Integrated simulation approach for assessment of performance in construction projects: A system-of-systems framework, Proceedings of the Winter Simulation Conference, IEEE, Savanah, GA, USA, 2014, pp. 3284-3295, https://doi.org/10.1109/WSC.2014.7020163.

[85] I. Flood, Modeling construction processes: A structured graphical approach compared to construction simulation, Congress on Computing in Civil Engineering, Vol. 2015-January, 2015, pp. 491-498, https://doi.org/10.1061/9780784479247.061.

[86] K. Szczesny, M. König, Reactive scheduling based on actual logistics data by applying simulation-based optimization, Visualization in Engineering 3 (1) (2015) 10, https://doi.org/10.1186/s40327-015-0020-8.

[87] A. ElNimr, M. Fagiar, Y. Mohamed, Two-way integration of 3D visualization and discrete event simulation for modeling mobile crane movement under dynamically changing site layout, Automation in Construction 68 (2016) 235-248, http://dx.doi.org/10.1016/j.autcon.2016.05.013.

[88] J. Larsson, W. Lu, J. Krantz, T. Olofsson, Discrete Event Simulation Analysis of Product and Process Platforms: A Bridge Construction Case Study, Journal of Construction Engineering and Management 142 (4) (2016), https://doi.org/10.1061/(ASCE)CO.1943-7862.0001093.

[89] M. Poshdar, V. González, M. O'Sullivan, M. Shahbazpour, C. Walker, H. Golzarpoor, The Role of Conceptual Modeling in Lean Construction Simulation, Proceedings of IGLC24: Annual Conference of the International Group for Lean Construction, Boston, USA, 2016, http://iglc.net/Papers/Details/1349, Accessed date: 4 October 2019.

[90] R.C. Thompson, G. Lucko, Y. Su, Reconsidering an Appropriate Probability Distribution Function for Construction Simulations, Construction Research Congress, 2016, pp. 2522-2531, https://doi.org/10.1061/9780784479827.251.

[91] H. Golzarpoor, V.A. González, M. O'Sullivan, M. Shahbazpour, C.G. Walker, M. Poshdar, A non-queue-based paradigm in Discrete-Event-Simulation modelling for construction operations, Simulation Modelling Practice and Theory 77 (2017) 49-67, https://doi.org/10.1016/j.simpat.2017.05.004.

[92] A. Ismail, Y. Srewil, R.J. Scherer, Integrated and collaborative process-based simulation framework for construction project planning, International Journal of Simulation and Process Modelling 12 (1) (2017) 42-53, https://doi.org/10.1504/IJSPM.2017.082789.

[93] P. Shrestha, A.H. Behzadan, An evolutionary method to refine imperfect sensor data for construction simulation, Proceedings of the Winter Simulation Conference, IEEE, Las Vegas, NV, USA, 2017, pp. 2460-2471, https://doi.org/10.1109/WSC.2017.8247975.

[94] N. Zeng, M. Dichtl, M. König, A scenario-based simulation framework of on- and off-site construction logistics, Proceedings of the Winter Simulation Conference, IEEE, Las Vegas, NV, USA, 2017, pp. 2348-2359, https://doi.org/10.1109/WSC.2017.8247965.

[95] P. Shrestha, A.H. Behzadan, Chaos Theory-Inspired Evolutionary Method to Refine Imperfect Sensor Data for Data-Driven Construction Simulation, Journal of Construction Engineering and Management 144 (3) (2018), https://doi.org/10.1061/(ASCE)CO.1943-7862.0001441.

[96] L. Koskela, An exploration towards a production theory and its application to construction Ph.D. Thesis, Helsinki University of Technology, 2000, Available at: https://aaltodoc.aalto.fi/bitstream/handle/123456789/2150/isbn951385566x.pdf?sequence=1, Accessed date: 17 November 2019.

[97] O. Abudayyeh, A. Dibert-DeYoung, E. Jaselskis, Analysis of trends in construction research: 1985–2002, Journal of Construction Engineering and Management 130 (3) (2004) 433-439, https://doi.org/10.1061/(ASCE)0733-9364(2004)130:3(433).

[98] J.J. Shi, Activity-based construction (ABC) modeling and simulation method, Journal of Construction Engineering and Management 125 (5) (1999) 354-360, https://doi.org/10.1061/(ASCE)0733-9364(1999)125:5(354).

[99] L. Koskela, G. Howell, E. Pikas, B. Dave, If CPM is so bad, why have we been using it so long?, Proceedings of IGLC22: Annual Conference of the International Group for Lean Construction, Oslo, Norway, 2014, pp. 27-37, Available at: http://eprints.hud.ac.uk/id/eprint/22989/, Accessed date: 04 October 2019.