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HYBRID SIMULATION IN CONSTRUCTION

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ABSTRACT

Hybrid Simulation (HS) is the application of multiple simulation techniques, for example, Discrete-event, Agent-based and System Dynamics, in the context of a single simulation study. HS is a growing area of research; numerous papers have delved into conceptualizations, frameworks, and case studies applied to specific application domains. The focus of our paper is on the construction domain. Through a systematic methodology for literature assessment, it presents a synthesis of the existing literature, providing insights on the choice of simulation technique, the context of its application, and the level of implementation, among others. Through an in-depth review of 36 relevant papers published over the past two decades, we contribute to a comprehensive understanding of the current state-of-the-art in HS as applied to Construction. The results of our investigation underscore the immense potential of HS in construction, with broad applicability spanning diverse areas such as structural analysis and building performance evaluation.

1 INTRODUCTION

The construction industry is a multifaceted field that encompasses a broad spectrum of activities ranging from building and maintaining structures and infrastructures to manufacturing raw materials, tools, and machines. In recent years, the industry has experienced rapid urbanization and expansion of construction projects, making it one of the fastest-growing industries worldwide (Rhodes 2019). As construction projects become increasingly large and complex, managing them becomes more challenging. Moreover, construction activities are inherently risky and uncertain; thus, effective management in this industry should be grounded in evidence-based practices that can address complex issues. However, research has shown that the construction industry struggles with the limitations of existing tools and techniques in managing the complexities of construction operations. As Barbosa et al. (2017) reports, productivity growth in the construction industry has only increased by 1% over the past two decades. This highlights the urgent need for innovative tools and solutions that can help improve construction projects' efficiency and effectiveness, overcome these challenges, and realize their full potential for growth.

Modeling & Simulation (M&S) comprises a set of decision support tools that have significantly benefited the industry. It has enabled the development of dynamic models, which, through experimentation and evaluation of competing construction strategies, provide insights into dealing with complex and

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uncertain conditions inherent in the construction industry. M&S is also used in the context of scheduling of construction projects, production of construction tools and technologies, assessing the environmental impact of construction projects, and the construction supply chain (e.g. König et al. 2012; Ahn et al. 2010).

The increasing complexity and inter-relationships in real-world systems mean that it is not often possible for one simulation technique to fully represent the system of interest. Recent advances in the functionality afforded by simulation packages, e.g., having one simulation executive for ABS, DES and SD, together with the exponential increase in computational capabilities, have meant that researchers and practitioners are increasingly combining multiple M&S methods to develop hybrid solutions. In the paper titled *"Combined discrete event continuous systems simulation"*, David Fahrland raised the following question: *"Why limit the modelling to either discrete event or continuous when evolving situations requiring more interdisciplinary solutions?"* (Fahrland 1970). He argued that a combined approach would provide a more complete set of methodologies for addressing the problems better and developing models closer to the real systems. A hybrid approach is not a new concept in operational research. According to Mustafee et al. (2015), hybrid simulation (HS) is the deployment of joint simulation techniques in an integrative way, where both approaches harmoniously improve each other's capabilities and reduce limitations by sharing information. Thus, HS endeavours to derive synergy through the application of multiple methods. The application of HS in industry is well established, and there is general acceptance of the use of continuous modeling techniques (i.e., SD) for high-level and strategic problems (long-term planning) and the use of discrete modeling techniques (i.e., DES) for operational-level problems.

Many studies, such as Lattila et al. (2010) and Mustafee and Powell (2018), argued that discrete-continuous HS could assist decision-makers in evaluating the impact of micro-level on macro-level decisions and vice versa. It is noted that some researchers, e.g., Venkateswaran and Son (2005) and Oleghe and Salonitis (2019), used the hybrid approach for evaluating the strategic planning before real-world implementation, while some researchers use HS to evaluate the domino effects decisions from a wholistic perspective, e.g., Rodrigues et al. (2020) and Rabelo et al. (2007).

Over the last decade, studies on the application of HS in construction are increasingly being reported in the literature. A few literature reviews have also been published. Leite et al. (2016) conducted a review to identify the grand challenges in M&S for the construction industry to assist the academic and industry communities in establishing a future research agenda. Abdelmagid et al. (2020) conducted a systematic review to complement the findings reported by Leite et al. (2016) to address a wider community of interests. Fernando et al. (2003) reviewed simulation applications for varying demands related to a specific form of construction, namely, tunnelling. There are also some reviews in the literature that have specifically focused on one M&S method. For example, Khodabandehlu and Park (2021) conducted a systematic literature review on ABS applications, while Xu and Zou (2021) examined SD applications within the construction domain. However, our review of the literature suggests a lack of a systematic review of the application of HS in the construction industry. Hence, the purpose of this review is to fill these gaps and categorize and synthesize academic literature on the use of HS in construction problems (a) over a number of unrelated publishing outlets, (b) with a broader scope of simulation techniques and (c) in a variety of construction applications. This would, in turn, help ascertain the current state-of-the-art in HS and M&S for construction.

The remainder of the paper is structured as follows. The next section provides an overview of the M&S methods selected for this study and discusses the application of M&S in the construction industry. Section three presents the literature review methodology and discusses eight variables for literature synthesis. In Section 4, a preliminary synthesis of the literature is presented, accompanied by a discussion of significant findings. Section 7 is the concluding section and summarizes the research contribution, and provides pointers for future work.

2 SIMULATION IN THE CONSTRUCTION INDUSTRY

The three commonly used M&S techniques in Operations Research/Management Science are DES, ABS and SD. These conventional M&S approaches are widely used in the construction industry, mainly as stand-alone methods. For example, DES was used to evaluate the expected improvement of project performance due to the reduction of waste in residential building projects (Heravi et al. 2019). Another example is the use of DES to investigate the integration of DES and value stream mapping (VSM) to enhance the productivity of road surfacing operations by achieving high production rates and minimum road closure times (Aziz et al. 2017). SD was used to evaluate construction projects' cost and time performance and their variation when affected by changes in internal factors and the surrounding environment and how these may impact project performance (Jing et al. 2019). Another example of the use of SD, in conjunction with analytics models (interpretative structural modeling or ISM), was to simulate the relationships between stakeholders and payments delays and their combined impact on project progress (Xie et al. 2019). SD was used with VSM and Discrete Optimization (DO) for optimizing energy consumption in modular construction (Xie et al. 2018). Examples of ABS include the work by Jabri and Zayed (2017), who developed an ABS model consisting of smart adaptive agents to simulate earthmoving projects to capture equipment units with varied specifications performing within the same task. ABS is also used as an experimental tool for evaluating the emergent nature of production in construction with a particular focus on capturing trade crew behaviours (Ben-Alon and Sacks 2017).

As per the literature, the construction industry has benefited from the use of conventional simulation, including better estimation of performance (DES), the ability to capture emergent issues (ABS) and dealing with feedback and impacts of various components (SD). Further, it is recognized that the M&S techniques have been used in conjunction with existing methods, such as VSM and ISM. Several articles stated the importance of combining simulation techniques. Some stated the need to mitigate for apparent weaknesses of individual techniques by combining them with other methods, i.e., HS. HS is mainly about developing a simulation model based on two or more different simulation approaches. HS is originally sought due to the rising complexity of business systems (including the construction sector). Problems associated with multiple levels of details and complex variables interactions are more common now than ever. In such case, HS aims to tackle this complexity and has been widely reported to do so (e.g. Bowers et al. 2013; Fakhimi et al. 2013; Hwang et al. 2016).

Since the last decade, researchers have proposed HS framework for various fields. For example, Helal et al. (2007) proposed the integration of SD with multiple discrete models. They argued that the approach would increase the efficiency and reuse of discrete models. In addition, this research also identified studies that used discrete-continuous HS to simulate long-term and short responses simultaneously in a complex system (e.g. Chahal et al. 2013) also proposed an SD-DES hybrid simulation framework for studying complex systems in healthcare. Fakhimi et al. (2016) proposed a hybrid framework for sustainability analysis that included DES and a qualitative format of system dynamics (Qualitative System Dynamics/QSD) for analyzing sustainability.

The potential benefits of using HS in the construction industry are obvious. This is particularly the case given the complex nature of the industry where engineering factors interact with physical factors, and both are closely interlinked with economic factors and project constraints. Adding to the complexity are the socio-cultural factors associated with the multiplicity of stakeholders and the eventual human use. All these factors together necessitate the use of HS to capture the relevant dimensions for each of these factors. However, and despite the clear need, the use of HS in the construction industry has continued to be sporadic and more pragmaticthan systematic. A recent review of the overall applications of HS shows that only 9% of the applications are in construction (Brailsford et al. 2019). Given the widespread use of simulation in this industry, such low levels of utilization of HS make it imperative to conduct further investigations in this field.

3 LITERATURE REVIEW METHODOLOGY

Our methodological review of the literature consisted of three phases. **In Phase 1** (*initial search results*), we used the *Web of Science* (WOS) database to search for articles related to HS in construction. We used a set of agreed-upon keyword combinations, for example, *hybrid simulation* AND *construction*; (*agent* OR *multi-agent* OR *ABS*) AND (*DES* OR *discrete*) AND *simulation* AND *construction*. We conducted the searches in 2023, covering the period 1900–March 2023. Further, we included only peer reviewed journal and conference papers indexed under the *Operations Research and Management Science* category of WOS. A total of 126 papers were retrieved in Phase 1. **In Phase 2** (*abstract screening stage*), the co-authors read 126 abstracts and independently determined whether a paper could be included in the dataset for the final review. We excluded articles where the model described was not HS and/or not related to construction. Although the aim was to make the review as systematic as possible, some degree of subjectivity in selecting papers and applying inclusion/exclusion criteria was inevitable. We tried to minimize this by retaining papers where a reviewer was undecided to avoid mistakenly excluding relevant articles. A total of 41 papers were selected at the end of Phase 2. **In Phase 3** (*full-text reading*), the papers were downloaded using journal databases and Google Scholar. In some cases, all three reviewers engaged in full-text reading before finalizing a paper's suitability for the review. The process of referencing checking (backward citation searching) was not conducted as part of this systematic review. Following Phase 3, a total of 36 papers were selected as the underlying dataset for the review (refer to Table 1).

Table 1: List of papers considered in the literature review (Note: papers are prefixed with a numbering scheme for subsequent analysis).

[1] Araya, F. 2022. "Integration of discrete event simulation with other modeling techniques to simulate construction engineering and management: an overview". *Revista de la construcción*, 21(2), 338-353.

[2] Ding, Z., Wen, X., Cao, X., and H. Yuan. 2022. "A GIS and hybrid simulation aided environmental impact assessment of city-scale demolition waste management". *Sustainable Cities and Society*, 86, 104108.

[3] Ding, Z., Cao, X., Shi, M., Tam, V. W., and I. C. S. Illankoon. 2021. "New hybrid simulation model for urban construction waste management: an empirical study". In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, vol. 174, no. 6, pp. 275-288. Thomas Telford Ltd.

[4] Taghaddos, H., Heydari, M. H., and A. Asgari. 2021. "A hybrid simulation approach for site layout planning in construction projects". *Construction Innovation*, 21(3), 417-440.

[5] Raoufi, M., and A. R. Fayek. 2021. "Hybrid fuzzy Monte Carlo agent-based modeling of workforce motivation and performance in construction". *Construction Innovation*, 21(3), 398-416.

[6] Hwang, S., Ahn, S., and S. Lee. 2021. "Agent-embedded system dynamics (aeSD) modeling approach for analyzing worker policies: a research case on construction worker absenteeism". *Construction Innovation*, 21(3), 379-397.

[7] Moharrami, S., Taghaddos, M., RazaviAlavi, S., and S. AbouRizk. 2021. "A hybrid simulation approach for microtunneling construction planning". *Construction Innovation*, 21, no. 3 (2021): 363-378.

[8] Hussein, M., Karam, A., Eltoukhy, A. E., Darko, A., and T. Zayed, T. 2023. "Optimized multimodal logistics planning of modular integrated construction using hybrid multi-agent and metamodeling". *Automation in Construction*, 145, 104637.

[9] Scales, J. 2020. "A design science research approach to closing the gap between the research and practice of project scheduling". *Systems Research and Behavioral Science*, 37(5), 804-812.

[10] Luo, L., Zhang, L., Zheng, X., and G. Wu. 2022. "A hybrid approach for investigating impacts of leadership dynamics on project performance". *Engineering, Construction and Architectural Management*, 29(5), 1965-1990.

[11] Hussein, M., Darko, A., Eltoukhy, A. E., and T. Zayed, T. 2022. "Sustainable logistics planning in modular integrated construction using multimethod simulation and Taguchi approach". *Journal of Construction Engineering and Management*, 148(6), 04022022.

[12] Chen, H., Chen, B., Zhang, L., and H. X. Li. 2021. "Vulnerability modeling, assessment, and improvement in urban metro systems: A probabilistic system dynamics approach". *Sustainable Cities and Society*, 75, 103329.

[13] Dorrah, D. H., M. Marzouk. 2021. "Integrated multi-objective optimization and agent-based building occupancy modeling for space layout planning". *Journal of Building Engineering*, 34, 101902.

[14] Li, Q., Zhang, L., Zhang, L., and S. Jha. 2021. "Exploring multi-level motivations towards green design practices: A system dynamics approach". *Sustainable Cities and Society*, 64, 102490.

[15] Li, X., Wu, C., Wu, P., Xiang, L., Shen, G. Q., Vick, S., and C. Z. Li. 2019. SWP-enabled constraints modeling for on-site assembly process of prefabrication housing production. *Journal of Cleaner Production*, 239, 117991.

[16] Xiang, S., Arashpour, M., and R. Wakefield. 2019. “A simulation model for investigation of operation of elevator’s up-peak”. *Journal of Simulation*, 14(3), pp.229-238.
[17] Bokor, O., Florez, L., Osborne, A., and B.J. Gledson. 2019. “Overview of construction simulation approaches to model construction processes”. *Organization, technology & management in construction: an international journal*, 11(1), 1853-1861.
[18] Wu, C., Chen, C., Jiang, R., Wu, P., Xu, B., and J. Wang. 2019. “Understanding laborers’ behavioral diversities in multinational construction projects using integrated simulation approach”. *Engineering, Construction and Architectural Management*, 26(9), 2120-2146.
[19] Xu, X., Wang, J., Li, C. Z., Huang, W., and N. Xia. 2018. “Schedule risk analysis of infrastructure projects: A hybrid dynamic approach”. *Automation in Construction*, 95, 20-34.
[20] Li, C. Z., Hong, J., Fan, C., Xu, X., and G. Q. Shen. 2018. “Schedule delay analysis of prefabricated housing production: A hybrid dynamic approach”. *Journal of cleaner production*, 195, 1533-1545.
[21] Ding, Z., Gong, W., Li, S., and Z. Wu. 2018. “System dynamics versus agent-based modeling: A review of complexity simulation in construction waste management”. *Sustainability*, 10(7), 2484.
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[24] Nasirzadeh, F., Khanzadi, M., and M. Mir. 2018. “A hybrid simulation framework for modelling construction projects using agent-based modelling and system dynamics: an application to model construction workers' safety behavior”. *International Journal of Construction Management*, 18(2), 132-143.
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[26] Paez-Perez, D., and M. Sanchez-Silva. 2016. “A dynamic principal-agent framework for modeling the performance of infrastructure”. *European Journal of Operational Research*, 254(2), 576-594.
[27] AbouRizk, S., Hague, S., Ekyalimpa, R., and S. Newstead. 2016. “Simphony: A next generation simulation modelling environment for the construction domain”. *Journal of Simulation*, 10(3), 207-215.
[28] Hwang, S., Park, M., Lee, H. S., and S. Lee. 2016. “Hybrid simulation framework for immediate facility restoration planning after a catastrophic disaster”. *Journal of Construction Engineering and Management*, 142(8), 04016026.
[29] RazaviAlavi, S., and S. AbouRizk. 2015. “A hybrid simulation approach for quantitatively analyzing the impact of facility size on construction projects”. *Automation in Construction*, 60, 39-48.
[30] Jo, H., Lee, H., Suh, Y., Kim, J., and Y. Park. 2015. “A dynamic feasibility analysis of public investment projects: An integrated approach using system dynamics and agent-based modeling”. *International Journal of Project Management*, 33(8), 1863-1876.
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3.1 Variables for Analysis

Following the literature search, we identified several variables for the final analysis. Six of these variables are included in the Winter Simulation Conference paper (the journal version is a work in progress). Identifying these variables was organic and often meant that co-authors would read and discuss an article several times. Table 2 lists the variables and includes a short description.

Table 2: Description of the variables for literature synthesis.

Variables for Literature Synthesis	Description
Type of study	Classification of the HS papers as Types A-C (Adopted from Brailsford et al. 2019): • Papers on conceptual framework accompanied by an application (Type A) • Articles that are purely application-based or case studies (Type B) • Theoretical, conceptual, or methodological papers (Type C).
Thematic area of research	Thematic groups of research based on the department names of authors' primary affiliation.
Type of hybridization and information flows	• The type of hybridization (*Integration*, *Enriching*, *Sequential and interaction)* • The form of information flow between the sub-models of an HS (*uni-directional*, *bi-directional* and *mixed*)
Software	Software used in the implementation of HS (e.g., commercial-off-the-shelf software, bespoke software or programming language).
Model development, validation & verification (V&V)	Aspects related to the development of HS, V&V.
Level of maturity and real-world implementation	This variable reflects the reasons for hybridization (e.g., academic curiosity, problem requirements), the level of maturity and real world-implementation.

4 FINDINGS

The 36 publications in our review dataset covered the period 2006-2023. There were only five articles between 2006 and 2015. From 2015, the publication trend showed an upward trajectory, with three articles published in 2015 and 2016, seven in 2018, four in 2019, and 14 articles between 2020 and March 2023. A surprising finding was that almost all the publications were journal publications (34). There remaining two papers were conference papers. This is contrary to the findings of a recent review in HS (Brailsford et al. 2019), which found that more than half the articles were published in conferences (76 out of a total of 139 papers). In reference to the timeline of publications, the findings from the same study *(ibid.)* demonstrated the expected trend of an increasing number of papers being published in conferences at the start of the timeline, and, and as the discipline matures, there are more publications reported in journal outlets. However, the publication trend reported in our dataset does not follow this trend. This suggests that HS in the construction industry has built upon methodological advancement in the use of mixing methods from the wider simulation literature. For example, Brailsford et al. (2009) report the first HS publication in the year 2000.

Analysis of the journal publication outlets also reveals that the sources of dissemination of this research can be classified into three categories: first, journals that had an application-specific focus on Construction Engineering and allied journals; second, those that focused more generally on Operations Research (OR) and M&S; third, journals related to sustainability. In the first category, a total of 23 papers (64%) were published in journals such as *Automation in Construction*, *Construction Innovation*, *International Journal of Project Management*, *Engineering Construction and Architectural Management*, *Tunnelling and Underground Space Technology*. *European Journal of Operational Research*, *International Journal of*

Production Economics, *Systems Research and Behavioral Science* and the *Journal of Simulation* formed the second category with five papers (14%). The third category, comprised of seven papers (20%) published in the *Journal of Cleaner Production*, *Sustainable Cities* and *Society and Sustainability*, reflecting the rising importance of sustainable construction approaches and the use of computer experimentation. Journals that accounted for the most publications were the *Journal of Construction Engineering and Management* (four papers), *Automation in Construction* (four papers) and the *Journal of Cleaner Production* and *Construction Innovation* (each with three papers).

In the remainder of this section, we discuss the findings from the analysis of the six variables reported in Table 2. As mentioned earlier, the conference paper presents work-in-progress and only reports a sub-set of the findings. Our analysis frequently references the literature review paper titled *"Hybrid Simulation Modelling in Operational Research: A State-of-the-art Review"*, published in the *European Journal of Operational Research* in 2019 (Brailsford et al. 2019). The reason for this is two-fold. First, the paper is widely acknowledged as an authoritative review on HS (as on May 2023, it has received close to 300 citations; Google Scholar). Second, two co-authors of this paper are also co-authors of the aforementioned paper. Thus, it was interesting to compare and reflect on the trajectory of HS literature since 2019.

4.1 Type of Study

We employed the categorization framework proposed by Brailsford et al. (2019) to classify the HS studies into three distinct types based on the simulation methods used. Our analysis revealed that out of the 36 papers surveyed, 21 belonged to the *Type A* category, presenting a conceptual framework accompanied by an application. There were 12 *Type B* papers that were purely application-based or case studies. Finally, *Type C* included three papers that were theoretical, conceptual, or methodological in nature. Considering the papers classified as either Type A or Type B (33 papers in total), it could be argued that researchers and practitioners working in the construction industry have shown a keen interest in using HS to tackle real-world problems.

Several *Type A* papers adopted a combination of SD and DES techniques to address the inherent dichotomy between operational and strategic models. Specifically, papers such as [4], [7], [9], [28], and [31]-[36] employed SD to capture long-term feedback processes, while DES was utilized to represent short-term operational performance (refer to Table 1 for the mapping of the literature numbering scheme with the reference). 19 out of 21 *Type* A papers claim that the reason for using HS was the nature of the problem; one paper claimed that HS was used due to practical/operational considerations, whilst another paper claimed 'academic curiosity' as the primary motivation.

Our analysis of *Type B* papers revealed that 11 articles used real data in their HS model; illustrative data was the source for one study. Most of the *Type B* papers adopted a combination of SD and DES (e.g., [15], [19], [20]). Two out of the total of 12 papers also adopted a combination of ABS-SD-DES ([1] and [2]). All *Type B* papers claimed that the main reason they used HS was due to the nature of the problem and only one paper [16] claimed that it was due to academic curiosity.

Only three papers were classified as *Type C* papers. Two were literature reviews [1] and [21], whilst one paper [34] investigated the meaningful level of change (MLC) concept to prevent the simulation time-advancing issues for SD-DES hybrid models used for construction systems.

Overall, the most popular combination of modeling methods, regardless of paper type, was *SD and DES*. However, recent years have seen a growth in models with ABS elements. This could be explained in terms of the increasing prevalence of Agent-based modeling and the need for models that incorporate intelligent and/or emotional decision-making entities. Our findings suggest that 42% of studies used *SD and DES*, 20% used *SD and ABS*, 11% used *ABS and DES*, and the remainder of the studies (27%) used either *DES and ABS and SD, DES and Monte Carlo Simulation*, *DES and Continuous Simulation (Not SD)* or *SD and Monte Carlo Simulation*.

4.2 Thematic Area of Research

We collected information on author affiliation, including capturing data on authors' home departments. This exercise aimed to ascertain the breadth of research activity in HS by identifying thematic groups from department names. For example, "Department of Building, Civil, and Environmental Engineering" was classified under three themes, namely, *Civil Engineering*, *Building/Construction Engineering* and *Environmental Engineering*, whereas the "College of Civil Engineering" has only one theme - *Civil Engineering*. This analysis enabled us to investigate the thematic breadth of research activity. From a total of 30 unique departments based on author affiliations, we identified a total of 17 themes. This unique count included two instances where specific department information could not be ascertained and was consequently ignored ("Ruhr University Bochum" and "US Air Force"). We adopted a qualitative approach to merge themes, for example, *Industrial Engineering* (three instances) and *Systems Engineering* (one instance) were merged into *Industrial and Systems Engineering* (four instances). Note that the instances reported in parenthesis refer to the number of authors. In our analysis, one author could be classified under multiple overarching themes, and which is based on the name of the department.

This exercise also allowed us to group the resulting 17 themes (subsequently referred to as sub-themes) into the following three overarching categories - *Engineering*, *Management* and *Sustainability* (Table 3). The sub-theme *Environmental Engineering* is an example of inter-disciplinary research and is classified under both *Engineering* and *Sustainability* main themes. Finally, the sub-theme *Real Estate/Property* was classified under the *Management* main theme. This was based on the department name (e.g.,"Faculty of Construction Management and Real Estate", "Department of Construction Management and Real Estate").

Our analysis shows that *Engineering* is the most prominent theme as it not only has the largest number of sub-themes (9) but also in terms of the number of contributing authors (93 instances). The theme associated with *Sustainability* is next; it has 26 authors grouped under five sub-themes. *Management* has 17 contributing authors grouped under three sub-themes.

Table 3: Thematic assessment of research area based on authors' affiliation. The instances reported in parenthesis refer to the number of authors.

Engineering	Civil Engineering (38)	Environmental Engineering (13)	Building/Construction Engineering (7)
	Architecture/Architectural Engineering (16)	Construction Engineering (5)	Industrial and Systems Engineering (4)
	Design and Built Environment (3)	Electronics and Telecommunication Engineering (4)	Engineering (3)
Sustainability	Environmental Engineering (13)	Construction Management (9)	Mining and Geology (1)
	Sustainable Infrastructure (2)	Transportation (1)	
Management	Real Estate/Property (10)	Management (5)	Project Management (2)

4.3 Type of Hybridization and Information Flows

We employed the categorization framework proposed by the aforementioned review to identify the type of hybridization employed in the articles. *Integration* – a method which seamlessly combines submodels, making it impossible to distinguish where one ends and the other begins – is by far the most popular method of hybridization and used in 23 out of 36 papers (e.g., [19], [20], [28]). It is, however, noticeable that, even within a single modeling environment like *AnyLogic*, there is still a clear delineation between the DES, SD, and ABS components. *Enriching* (one dominant method, with limited use of another method) and *Sequential* were jointly placed as the second most popular hybridization types, each accounting for five papers (e.g., [33], [34], [36] for *Enriching* (two or more distinct single-method models that are executed sequentially (but only once), so that the output of one becomes the input to another); [28], [30], [32] for

Sequential). One paper used the *Interaction* type, which involves running two or more separate single-paradigm submodels multiple times.

In terms of information flows between models, our review found that 25 papers employed *bi-directional information flows* (e.g., [28], [29], [30], [31]), indicating that the models were intrinsically connected. Three papers used *uni-directional flows* (e.g., [34]), where one model provided information to another model one-way. Finally, five papers used *mixed flows*, where both uni and bi-directional flows existed (e.g., [20], [21]).

4.4 Software

This section presents our findings on the software and programming languages used in the construction industry to support HS. Notably, only 29 out of 36 papers acknowledged the software or programming language. Our findings show that *AnyLogic* is the most widely used tool for building HS models; 17 papers reported the use of the software (e.g., [2], [3], [5], [6]). *Simphony* (ABS) is the second most popular software with four instances reported (e.g., [4], [7]). Additionally, we found that *Vensim* (SD) was the most commonly used software when combining SD with a method other than DES or ABS such as MCS; four instances were reported, e.g., [12], [14]. *ExtendSim*, *Matlab*, and *Stroboscope* were also among the packages used in the HS for construction studies.

4.5 Model Development, Validation & Verification (V&V)

This section presents our preliminary findings on model development, validation and verification processes related to HS in construction studies. This review shows no significant differences in our domain compared to HS studies in other disciplines. Most lifecycle steps, such as conceptual modeling, tools and integration methods, are similar. Compared to the study by Brailsford et al. (2019), there is some improvement in the level of integrated automation, 48% in the former study versus 59% reported in this review. It could be argued that automated integration is a vital aspect of HS. Papers such as [23], [26], [37] presented forms of integrated automation between different packages other than *AnyLogic*.

It was noted in the same review that V&V processes for HS models are often not adequately reported. They found that although individual sub-models were verified and validated using existing standard approaches in some cases, the overarching hybrid model was not, and no additional steps were taken to verify the links between submodels. However, our review suggests that the level of V&V is higher in construction than in other industries. Validation remains one of the most challenging steps in developing simulation models, particularly in HS models. Our review shows a significant rise in the process model validation. What is unclear from this study is whether this is linked to an overall improvement of the validation process in HS or is it linked to the construction industry. Of the 36 papers we reviewed, 17 (47%) reported verifying their models, compared to only 25% reported previously for all industries. Similarly, 19 papers (53%) reported validating their modules, compared to the 26% reported for all industries.

Finally, our findings show that 22 out of 36 papers reviewed in the construction domain (61%) used real-world data in their HS studies (in comparison with only 30% reported earlier). Despite these promising findings, it is evident that the implementation of HS studies in the construction industry is limited, and further work is needed to translate research to practice.

4.6 Level of Maturity and Implementation

An interesting outcome in this review is that 86% of studies are based on real-world problems. This is a significant departure from the review conducted formerly by Brailsford et al. (2019), which reported that only 50% of studies had the underlying motivation of real-world problem-solving. Arguably, this evidences the maturity of HS in construction and its move from pure theoretical aspiration to its use as a real-world problem-solving tool.

The findings of this review are mostly consistent with the former review, which report that real problems and real-world data usually drive the HS models; yet, the level of implementation of the results of a simulation study is often not reported. It is perhaps a false premise to assume that experimental results from a successful research-based model should be fully implemented in practice. In our review, approx. 86% of papers were motivated by real-world problems; thus, it may be reasonable to conclude that the value of modeling extends to a better understanding of the problem situation and offers insights. For example, [19], [31], [32], [35] all demonstrate the value of HS in construction projects without necessarily the need for the full implementation of the results of the simulation study.

5 CONCLUSION AND FUTURE WORK

The paper presents a literature review of hybrid simulation (HS) in the construction industry. Towards this, we retrieved 36 papers using a methodological approach. Several variables were identified for the purposes of literature synthesis, with a sub-set reported in this paper (as a work-in-progress). These include variables that report on the different combinations of the hybrid methods employed (e.g., *SD and DES*, *ABS and DES*); HS model integration processes (e.g., *Enriching*, *Integration*, *Interaction*); variables related to model development, implementation, validation and verification; variables on information flows (e.g., *uni-directional* and *bi-directional flows*). The findings of this study show that HS is a promising approach in the construction domain and could be applied to various aspects of construction, including structural analysis and building performance evaluation.

Our review has identified several avenues for future research. One area that requires more attention is the development of HS models for the analysis and design of complex building systems. These models should be able to capture the nonlinear and time-varying behaviors of construction materials and systems. Another area for future research is the integration of HS with other advanced technologies, such as virtual reality and augmented reality (AR/VR). This integration can provide a more immersive and interactive environment for construction professionals to simulate and evaluate different construction scenarios. Yet another avenue of future research is the development of standardized guidelines, protocols and frameworks for developing HS specific to the construction industry. These guidelines cover different aspects of HS, including conceptual modeling and model implementation.

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