Hybrid simulation in construction: Trends and design framework

Xuming Zhu[1] and Jinchi Han[1]

[1]Department of the Built Environment, National University of Singapore, Singapore
E0688540@u.nus.edu, hanjinchi@bucea.edu.cn

Abstract

Due to construction work's complexity and uncertainty, single simulation methods such as system dynamics (SD), discrete-event simulation (DES), and agent-based modelling (ABM) face significant limitations when applied independently. Hybrid simulation offers a promising solution, yet lacks both a comprehensive review and a structured framework for construction applications. This paper addresses these gaps by providing a thorough review identifying trends and improvement areas, and presenting a detailed framework integrating SD, DES, and ABM tailored to the construction industry. The study also identifies future research directions, including case studies to validate the framework's effectiveness and demonstrate its practical application in real-world construction projects.

Keywords

Hybrid simulation; Construction; System dynamics; Discrete-event simulation; Agent-based modelling; Framework

1 Introduction

In the construction industry, simulation has become an essential tool for planning, analyzing, and optimizing complex projects [1]. The dynamic nature of construction sites, with its multiple variables such as time, cost, labor, materials, and site-specific constraints, makes it challenging to manage efficiently using traditional analytical methods. Simulations provide a means to model construction processes, forecast outcomes, and assess the impact of various strategies across different scenarios. They aid in improving safety, productivity, and quality by providing a virtual platform to test and optimize construction operations prior to real-world implementation [2].

Three fundamental simulation approaches, namely system dynamics (SD), discrete-event simulation (DES), and agent-based modelling (ABM), are widely employed in construction [3]. SD focuses on capturing the behavior of complex systems over time by modelling the interrelationships among components, often through causal loop diagrams and stock-flow models. DES, in contrast, models systems as sequences of discrete events that alter the system state, such as the initiation or completion of tasks, the allocation or release of resources, or the arrival of materials and equipment on site. ABM models systems through autonomous agents whose state-dependent actions and interactions determine both individual behavior and the emergent evolution of the system. In this context, it is important to recognize that SD, DES, and ABM are simulation paradigms, conceptual approaches that define how a system is abstracted and represented at a logical level, and are fundamentally distinct from physics-based simulation platforms that replicate physical-world behaviors within three-dimensional virtual environments. For instance, NVIDIA Isaac Sim provides a GPU-accelerated environment for simulating robotic kinematics, rigid-body dynamics, and sensor responses such as LiDAR and camera feeds, primarily for the purpose of testing and training AI-driven robotic systems [4]. Similarly, Unity, originally developed as a game engine, has been increasingly adopted for robotics and industrial simulation due to its real-time physics engine and photorealistic rendering capabilities, enabling applications such as digital twin development and robot navigation testing [5]. While these platforms offer valuable capabilities for replicating physical interactions at the individual object or equipment level, they do not address how to conceptualize and structure the broader system-level processes and interdependencies that characterize construction projects. This study focuses on the paradigm level, as the integration of these conceptual approaches remains a more pressing methodological challenge in construction simulation compared to the selection of specific implementation platforms. While these methods contribute valuable insights, no single approach can fully capture the multifaceted complexity of real-world construction projects. Reliance on a single method either narrows the scope of analysis or produces oversimplified representations, thereby limiting both validity and practical applicability [3].

To overcome these limitations, an integration framework is essential to coordinate simulation paradigms, prevent incompatible sub-models, and enable cross-project replication [3]. However, current frameworks for hybrid simulation remain fragmented, hindered by inconsistent terminology and a tendency to operate at high levels of abstraction [6], [7], treating each method as a unified whole. This oversimplification fails to reflect the reality of hybrid modelling, where numerous combinations of interaction are possible, creating significant challenges for model development. Consequently, these frameworks offer limited practical guidance for researchers attempting to construct models, as they lack the details needed to handle the complexity of hybrid modelling.

Although numerous studies have reviewed single simulation methods in construction, research on hybrid simulation in construction remains limited. The few existing studies [2], [8], [9] primarily summarize frameworks developed in other industries rather than proposing approaches tailored to the construction-specific characteristics: temporary nature, site-specific constraints, high uncertainty, and diverse activities requiring different simulation approaches. Moreover, no comprehensive review systematically maps hybrid simulation applications, development trends, and thematic focus in construction, limiting researchers' ability to track field evolution and identify future directions. Therefore, this study aims to address these gaps by providing a comprehensive review and a holistic framework for implementing hybrid simulation approaches in the construction domain.

The remainder of this paper is organized as follows: Section 2 describes the literature collection; Section 3 conducts a bibliometric analysis; Section 4 proposes a framework for hybrid simulation in construction; conclusion and future work are provided in Section 5.

2 Literature collection

This study adopts a comprehensive approach to search and collect literature, guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [10] (Figure 1). To collect papers on hybrid simulation in construction, databases including “Scopus”, “Web of Science”, and “Google Scholar” were used to search for the papers from 2000-2024. Three search term sets (hybrid simulation-related, method-related, and construction-related) are shown in Table 1. Four method combinations were used: “SD AND DES”, “SD AND (ABM OR ABS)”, “DES AND (ABM OR ABS)”, and “SD AND DES AND (ABM OR ABS)”, where agent-based simulation (ABS) is an ABM variation. Terms from the first and third sets were paired with each method combination, covering all possible combinations (such as “Hybrid simulation” AND “SD AND DES” AND “Construction"). Papers underwent two-stage screening: initial review of titles, abstracts, and metadata, followed by full-text examination. This method maximizes inclusion of relevant papers, with automation tools removing duplicates and ineligible studies.

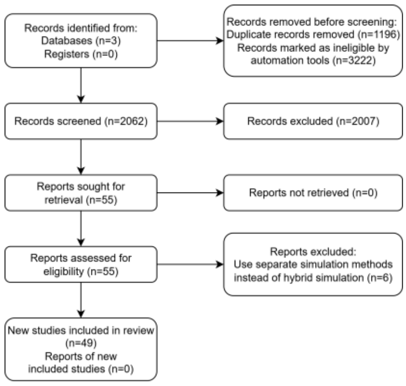

Figure 1. PRISMA flow diagram

The next step involved a manual screening process to exclude irrelevant papers, followed by retrieval of the remaining studies for a more detailed eligibility assessment. Finally, a total of 49 papers were selected (listed in Table 2) for the analysis.

Table 1 Search terms used to collect papers

Hybrid simulation-related search terms	Specific method-related search terms	Construction-related search terms
Hybrid simulation	System dynamics/SD	Construction
Mixed simulation	Discrete event simulation/DES	Civil engineering
Multi-method simulation	Agent-based modelling/ABM	Building
Integrated simulation	Agent-based simulation/ABS	Infrastructure
		Project management

Table 2 Database of papers included

Review & framework	[11] [12] [1] [3] [2]		
Stage	**SD-DES**	**SD-ABM**	**DES-ABM**
Pre-constr.	[13] [14]	[15]	-
Constr.	[8] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31]	[32] [33] [34] [35] [36] [37]	[32] [38] [39] [40] [41] [42] [43]
Post-constr.	[44]	-	[45] [46] [47]
Cross-stage	[48] [49]	[50] [51] [52]	[53] [54]

3 Bibliometric analysis

As identified in Section 1, no comprehensive review has systematically mapped hybrid simulation applications, development trends, and thematic focus in construction. To address this gap, this section presents a bibliometric analysis of the collected literature.

3.1 Bibliometric analysis on publications

This bibliometric analysis examines the publication trends from 2007 to 2024. Figure 2 illustrates the yearly distribution of publications, highlighting a peak in 2018 with a total of 9 publications. A polynomial-fitted dashed trend line represents the overall trajectory, indicating a gradual increase in publications leading up to 2018, followed by fluctuations in subsequent years. Notably, during the five-year period from 2015 to 2019, nearly half of the total publications (24 out of 49) were produced, underscoring a concentrated period of research activity.

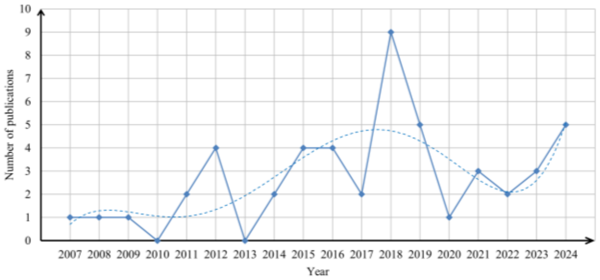

Figure 2. Yearly number of publications

A comprehensive analysis of keywords is conducted. Of 210 unique keywords, 40 appear more than once, signifying recurring research topics. The ten most frequent keywords are: SD, DES, hybrid simulation, simulation, ABM, ABS, construction management, productivity, construction industry, and construction.

3.2 Bibliometric analysis on journals

Bibliometric analysis of journals identifies key publication venues, tracks influential studies, and reveals field impact and productivity. An analysis of 49 selected papers shows that they are distributed across 30 journals or conferences, with only 9 journals featuring more than one publication. "Automation in Construction" leads in publication count, followed by "Construction Innovation" and "Journal of Construction Engineering and Management". 9 journals collectively account for 57.1% (28 out of 49) of total publications.

3.3 Bibliometric analysis on authors

Bibliometric analysis on authors documents contributions. Among the 49 selected papers, 131 authors were identified, of whom 24 published more than one paper. There are 6 distinct research clusters and 5 overall research groups, as some clusters exhibit strong interconnections. The largest group comprises 8 authors with 9 papers, where SangHyun Lee and Simaan AbouRizk occupy key positions. The second largest group consists of 5 authors with 4 papers, centered on Farnad Nasirzadeh. The third largest includes 4 authors with 6 publications, centered on Tarek Zayed.

4 Framework for hybrid simulation

As identified in Section 1, existing hybrid simulation frameworks lack consideration of construction-specific characteristics. To address this gap, this section presents an integrated framework (Figure 3) that serves as a practical decision-support tool for hybrid simulation in construction. The hybrid simulation design framework consists of four phases that guide researchers and industry practitioners systematically from problem definition to implementation.

4.1 Problem definition

The framework's initial phase develops comprehensive understanding of the construction problem, like other hybrid simulation frameworks [55], helping researchers articulate problems with modelling precision and determine whether complexity warrants a hybrid approach. Precise problem definition requires four elements: a problem statement identifying concrete issues and consequences; primary performance focus (productivity, quality, or safety); construction context (temporal and spatial); and scope boundaries balancing comprehensiveness with feasibility. Researchers then analyze characteristics along three dimensions: continuous (feedback loops, flows, accumulations), discrete (events, queuing, sequential operations), and behavioral (autonomous decision-making), each suggesting different modelling requirements. This characterization determines whether hybrid simulation is necessary: single methods suffice when problems align with one dimension, while hybrid approaches are essential when problems span multiple dimensions. If hybrid simulation is needed, proceed to Phase 2 for method selection; otherwise, exit for single methods.

4.2 Model selection

To guide method selection, we systematically analyzed 49 reviewed papers to identify patterns in hybrid simulation applications. Papers were classified by construction phase (pre-construction, construction, post-construction, cross-stage) and hybrid approach. While some papers incorporated all three methods (SD, DES, ABM), they typically applied them in paired

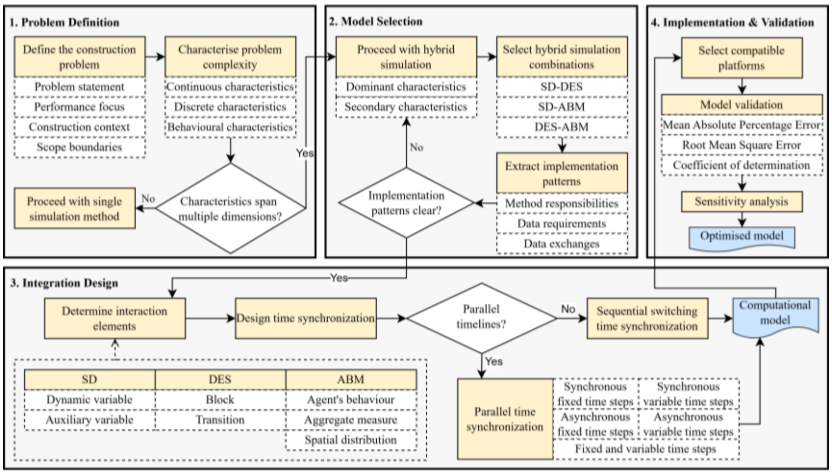

Figure 3. Framework for hybrid simulation design

combinations rather than fully integrated systems. Consequently, we focused on three hybrid subcategories: SD-DES, SD-ABM, and DES-ABM. This systematic classification, calculated from Table 2, revealed clear patterns in how researchers have matched hybrid approaches to specific construction challenges. Construction phase dominates with 30 studies (61%), while pre-construction (3 studies) and post-construction (4 studies) remain underexplored. Cross-stage applications represent 7 studies (14%), addressing strategic planning spanning multiple phases. SD-DES combinations lead with 22 studies, reflecting alignment between system-level dynamics and operational processes. DES-ABM follows with 12 studies addressing process modelling and agent behavior, while SD-ABM accounts for 10 studies focusing on system-wide factors interacting with individual behaviors.

Researchers evaluate hybrid simulation methods based on Phase 1 problem analysis. The dominant characteristic determines the primary method, whilst secondary characteristics guide complementary method selection. Once methods are selected, researchers verify that method responsibilities are clearly defined, required data exists for both methods, and sufficient implementation guidance is available. Meeting these criteria produces a conceptual model for Phase 3 integration design. Gaps require refinement or reconsideration of earlier framework steps.

4.3 Integration design

Phase 3 addresses how the selected methods will exchange information and coordinate their execution. This paper references the hybrid SD-ABM model presented by Nguyen et al. [55]. For each method (SD, DES, and ABM), key elements are identified and summarized, acting as interaction points between different methods. For SD, the key elements are dynamic variables (stocks and flows that accumulate or change over time through feedback) and auxiliary variables (intermediaries that establish relationships without accumulating). In DES, the primary elements are blocks, whose characteristics can influence and be influenced by other methods, and transitions, which are either deterministic (leading to a single block) or stochastic (providing probabilistic pathways to multiple blocks). For ABM, the essential elements include individual agent behavior (rules and decisions guiding actions), aggregate measures (collective outcomes from agent interactions), and spatial distribution (agent positioning and movement within space).

After designing the information exchange elements, the next step is synchronization of time advancement. The summarized categories are presented. The first category is sequential switching, where dynamic switching occurs along a single timeline. In this case, only one method is active at a time, and a new method can only begin once the previous one has ended. For other hybrid simulation models, the timelines are always parallel. In synchronous fixed time steps category, the interchanges of information happen at the same time with equal time intervals. While in synchronous variable time steps category, the data exchanges occur simultaneously but at varying intervals. Asynchronous fixed time steps and asynchronous variable time steps follow a similar pattern to synchronous ones, but in an asynchronous way. Finally, the data exchange can combine both fixed and variable time steps, meaning that whenever a model is updated, it immediately sends information to the other model. Phase 3 results in a computational model ready for implementation.

4.4 Implementation & validation

Phase 4 transforms this design into an executable simulation through systematic implementation and validation. Implementation begins with choosing between single platforms supporting all methods (simplified integration) or multiple specialized platforms (greater flexibility but complex bridging) [3]. Development follows an incremental approach: build method components independently, verify individual functionality, then implement integration mechanisms. Hybrid model validation addresses three levels. Component validation tests each method against benchmarks [36]. Interface validation ensures data exchanges maintain integrity through transformations and synchronization [44]. Integrated validation examines overall model behavior against historical construction data, revealing emergent properties from method interactions [40].

Accuracy metrics include mean absolute percentage error (MAPE) and root mean square deviation (RMSE), and R-squared for overall fit [17]. Acceptable thresholds depend on application. Sensitivity analysis systematically varies key parameters to identify critical inputs and assess model stability [51]. Well-constructed models demonstrate logical sensitivity to critical parameters while maintaining robustness against reasonable variations in less certain inputs. A final optimized model is obtained once it passes both the accuracy and sensitivity tests.

4.5 Case study of construction equipment repair yard inventory management

To demonstrate the practical applicability of the proposed framework, a hybrid simulation case study involving repair yard inventory management for vibroflotation equipment (hereafter referred to as vibros) in foundation construction is mapped onto the four phases, as illustrated in Figure 4.

In Phase 1, the problem concerns managing spare parts inventory for a fleet of vibros, each comprising interdependent components. Component failures cause equipment downtime and costly emergency procurement, with productivity and cost efficiency as the primary performance focus. The problem spans all three dimensions: continuous dynamics in inventory stock and flows; discrete events in the vibro operational process; and behavioral characteristics from individual vibros and their components, each with unique degradation patterns and interdependencies. A hybrid simulation approach is therefore warranted.

In Phase 2, the DES component serves as the main operational workflow, modelling vibro assignment, spare parts demand prediction, normal ordering, and monitoring. During monitoring, preventive maintenance leads the vibro directly to the repair yard, while corrective maintenance first evaluates whether emergency ordering is necessary. ABM represents individual vibros (Vibro 1 to Vibro n) as agents with status parameters (working, under maintenance, or idle), and each component within a vibro is also modelled as an agent. A component correlation matrix captures part interdependencies and feeds into the DES demand prediction module. SD models the ordering strategy through a stock-flow structure (orders into inventory, demands as outflow), governed by parameters including supplier reliability, safety stock, order quantity, lead time, emergency order quantity, and consumption quantity. Optimization objectives include fill rate, turnover ratio, service level, and cost metrics (normal ordering, emergency ordering, holding, and penalty costs).

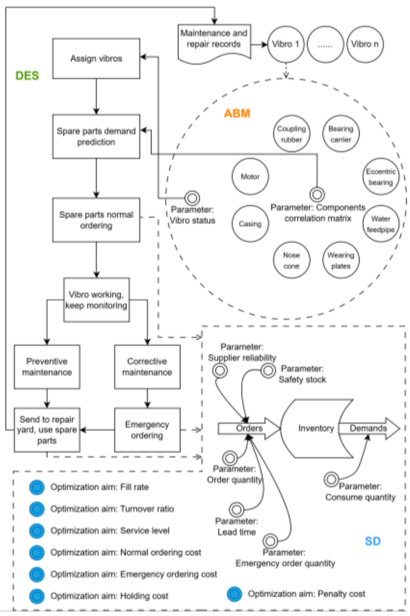

Figure 4. Hybrid simulation implementation of construction equipment repair yard inventory management

In Phase 3, the interaction points are defined as follows: ABM transmits component correlation matrices and vibro status to the DES demand prediction module; DES updates the SD model through ordering events (order inflow) and repair completion (consumption outflow); and SD inventory levels and safety stock status influence whether normal or emergency ordering is activated in DES. Historical maintenance and repair records initialize the ABM agents, and a feedback mechanism from the DES "Send to repair yard" block updates these records, enabling dynamic calibration as the simulation progresses. The DES component operates on an event-driven basis while SD advances continuously, with information exchanged at each relevant state change.

In Phase 4, the model will be built in Python as a single-platform approach to simplify integration across the three methods. Development follows an incremental strategy, building and verifying each component independently before implementing integration mechanisms. Validation will address three levels: component, interface, and integrated, with accuracy assessed using metrics such as MAPE, RMSE, and R-squared against historical construction data. Sensitivity analysis will vary key parameters to identify critical inputs and assess model stability. The validation of this case study is currently ongoing, as data collection from the repair yard is still in progress.

5 Conclusion and future work

This study addresses critical gaps in construction hybrid simulation research: the absence of comprehensive reviews and lack of frameworks guiding SD, DES, and ABM integration. Following PRISMA guidelines, bibliometric analysis of 49 papers revealed declining research from 2019-2021, reversing upward from 2022, with publications spanning interdisciplinary venues and forming 6 distinct authorship clusters.

The developed four-phase framework revealed that SD-DES combinations dominate current research, with focus concentrated on active construction phases. The framework's modular structure enables continuous adaptation as technologies emerge. An illustrative case study on repair yard inventory management for vibroflotation equipment has been presented to demonstrate the framework's applicability, and future work will focus on completing its validation as field data collection progresses, further demonstrating practical value in real-world construction applications.

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