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Risk Management in Modular Construction and Offsite Manufacturing: Challenges, Opportunities, Trends and Technological Solutions

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Abstract: This study systematically reviewed 87 peer-reviewed publications from 2002 to 2024 to explore the challenges and opportunities in modular construction and offsite manufacturing, with a specific focus on risk management. Using six-step thematic analysis framework by Braun and Clarke, this review identified three critical barriers to the adoption of advanced technologies: (1) logistical complexities in transportation and site coordination, (2) stakeholder fragmentation leading to communication breakdowns and (3) regulatory inconsistencies that hinder scalability. To address these challenges, the study highlighted three transformative digital solutions: (1) digital twins for real-time monitoring and scenario planning, (2) the Internet of Things for enhanced coordination and data transparency and (3) artificial intelligence for predictive analytics and decision support. The findings revealed that offsite manufacturing and modular construction offer significant benefits in terms of sustainability, cost savings and time efficiency. However, achieving full-scale adoption requires harmonised regulatory frameworks, targeted training initiatives to address skill gaps and policies that support digital technology integration. The study concludes with a call for coordinated action among policymakers, industry stakeholders and educators to facilitate technology-driven transformation in modular construction and maximise its contribution to sustainable and resilient infrastructure development.

Keywords: Modular construction, Offsite manufacturing, Risk management, Digital technologies, Systematic literature review

INTRODUCTION

The construction industry is undergoing a transformation driven by the growing demand for more efficient, sustainable and innovative construction methods. In this context, modular construction and offsite manufacturing have emerged as a pivotal approach, leveraging controlled environments to achieve better quality, minimising waste, controlling budgets and expediting project timelines (Pervez et al., 2022; Khan et al., 2023). Modular construction and offsite manufacturing address critical global challenges, including urbanisation pressures, housing shortages and sustainability requirements (Wuni, Shen and Hwang, 2020; Lee and Lee, 2021; Wang et al., 2024). However,

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their implementation faces substantial challenges, such as complex risk management, logistical inefficiencies and regulatory barriers (Zhou et al., 2023; Ortega, Mesa and Alarcón, 2023; Ali and Kineber, 2023).

The recent development has been enabled by the implementation of digital technologies that include digital twins, building information modelling (BIM), Internet of Things (IoT) and artificial intelligence (AI), among others, which enhance risk management with a real-time information monitoring and predictive capability for analyses in dynamic decision-making environment (Okudan, Budayan and Dikmen, 2021; Tatari, 2023). Digital twins are capable of facilitating the simulation in construction processes, hence improving safety and operational efficiency (Tatari, 2023; Rodríguez-Espíndola et al., 2022). Meanwhile, AI provides robust frameworks for identifying and mitigating cost and safety risks, bolstering project planning and execution (Liu et al., 2022; Torres et al., 2024).

However, even with technological development, modular construction and offsite manufacturing face contradictions that of modular ones. Also, the lack of qualified professionals or reluctance to the adoption of novelty acts as a barrier to successful development (Wuni, Shen and Hwang, 2020; Ali and Kineber, 2023). These, of course, could be alleviated through policy and stakeholder education to achieve harmony among a variety of parties involved and capacity building to build capacities in those missing them (Ortega, Mesa and Alarcón, 2023; Aladayleh and Aladaileh, 2024). Other examples of worker-centred innovations include parametric design frameworks and BIM-based safety tools, which have further demonstrated their potential to improve workplace safety and efficiency (Zaalouk and Han, 2021; Chatzimichailidou and Ma, 2022).

Existing studies also show how geography influences sociocultural and logistical barriers. For instance, prior case studies conclude the various barriers between Egypt and Chile. This, therefore, presents a well-framed approach of interventions that involve fragmented workflows, enhance stakeholder communication and use advanced analytics in the pursuit of more optimal planning and scheduling. According to Ali and Kineber (2023) and Hussein, Eltoukhy and Darko (2021), the need, therefore, as stressed by each, is basically for adaptation, which will ensure the full potential inherent in the concept of modular construction is maximised across contexts.

modular construction and offsite manufacturing are a game-changing solution for solving world construction challenges, but regulatory misalignment, skill gaps and sociocultural resistance first need to be overcome through policy reforms, capacity-building and regional strategies. Continuous integration of technologies such as digital twins, BIM and AI has remained vital for driving its global adoption and achieving sustainable, efficient and safe construction practices.

The present study aimed to fill the knowledge gap based on improved understanding through comprehensive, interrelated risk assessment and emerging technologies for the management of risk in modular construction and offsite manufacturing, such as through digital twins and state-of-the-art simulation models. The findings can have implications for practical application by industry professionals, legislators and researchers interested in the sustainable and efficient use of modular construction and offsite manufacturing methods. This study sought to provide a roadmap for the future direction and trends that will guarantee the successful implementation and increased adoption of modular construction and offsite manufacturing techniques globally.

Research Objectives and Study Contribution

This study aimed to examine the current state of risk management in modular construction and offsite manufacturing by reviewing 87 peer-reviewed publications published between 2002 and 2024. Through a systematic literature review and thematic analysis using Braun and Clarke's (2006) framework, the research aimed to: (1) identify and categorise the key challenges hindering the adoption of advanced technologies in modular construction, (2) explore digital solutions, such as digital twins, IoT and AI, that support better risk forecasting and management and (3) highlight implications for policy development, workforce training and technology integration to support broader adoption. The study would contribute to both academic knowledge and industry practice by offering a structured synthesis of barriers and enablers, providing a roadmap for future research and actionable insights for stakeholders aiming to improve the efficiency, safety and scalability of modular construction.

METHODOLOGY

Research Design

This study adopted a qualitative research design grounded in a systematic literature review and thematic analysis to explore risk management challenges and technological solutions in modular construction and offsite manufacturing. Thematic analysis was conducted following Braun and Clarke's (2006) six-phase framework, chosen for its flexibility and rigor in identifying patterns and drawing insights across diverse studies. The methodology followed a structured process of article identification, screening, inclusion, coding and synthesis.

Data Sources and Search Strategy

The data collection process was conducted through a comprehensive and systematic search strategy using Scopus and ISI Web of Science, two leading academic databases known for the rich repositories of high-quality, peer-reviewed literature, to ensure the methodological robustness and academic rigor of the review.

The search strategy was developed using Boolean operators and keyword combinations. Figure 1 displays the main search string used.

```
("modular construction" OR "off-site manufacturing" OR "prefabricated construction")
AND ("risk management" OR "uncertainty" OR "digital twin" OR "IoT" OR "artificial intelligence")
AND ("construction industry")
```

Figure 1. Main search string

Search terms were refined iteratively and adapted to the syntax of each database. Articles were filtered to include only those written in English and published in peer-reviewed journals or conferences.

Time Frame Justification

The review selected publications spanning from 2002 to 2024. The starting point reflected the early academic emergence of modular and offsite construction as formal areas of research, while the end point captured the most recent developments, including the integration of Industry 4.0 technologies such as digital twins, AI and IoT. This 22-year period provided a comprehensive view of evolving trends, challenges and solutions in the field.

Inclusion and Exclusion Criteria

The strict inclusion and exclusion criteria were followed to ensure a reliable and focused dataset. Inclusion criteria included the selection of English language peer-reviewed articles that fall within the specified timeframe (i.e., 2002 to 2024) and those that were directly related to either modular construction, offsite manufacturing and risk management. These involved exclusions based on studies not in the English language, duplicates, non-peer-reviewed literature, studies irrelevant to the topic, lack of empirical data or clear methodologies within the studies, publications outside of the predefined period and availability in full text. This ensured that the selected papers were strictly methodologically sound, relevant and of high quality.

Study Selection Process

A total of 451 records were initially retrieved. After removing duplicates, titles and abstracts were screened, followed by full-text reviews based on the inclusion criteria. The selection process is illustrated in Figure 2, adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, 2020) guidelines.

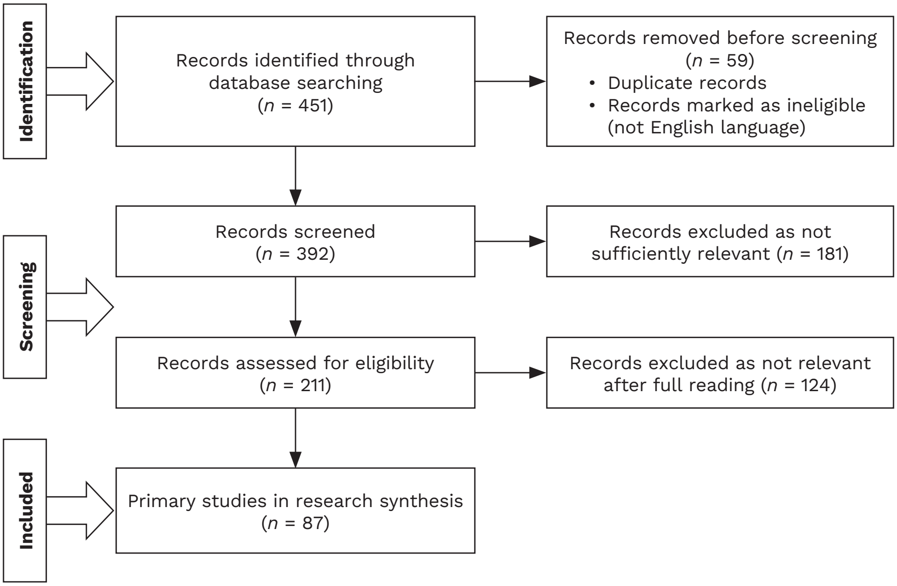

Figure 2. PRISMA flow chart for systematic literature review included searches of databases and registers only

Keyword Analysis

After study inclusion, keyword frequency analysis was conducted to identify dominant themes and emerging trends. Keywords were extracted from article metadata (title, abstract and author-assigned keywords) using a text-mining tool. Frequently occurring terms were grouped thematically to guide the coding process during thematic analysis. Figure 3 presents the most frequent keywords, providing a snapshot of research emphasis within the reviewed literature. The network visualisation analysis underlines how technology, risk management strategies and sustainability objectives all combine in an interdisciplinary way to further develop project performance, resilience and risk mitigation in modular construction and offsite manufacturing environments.

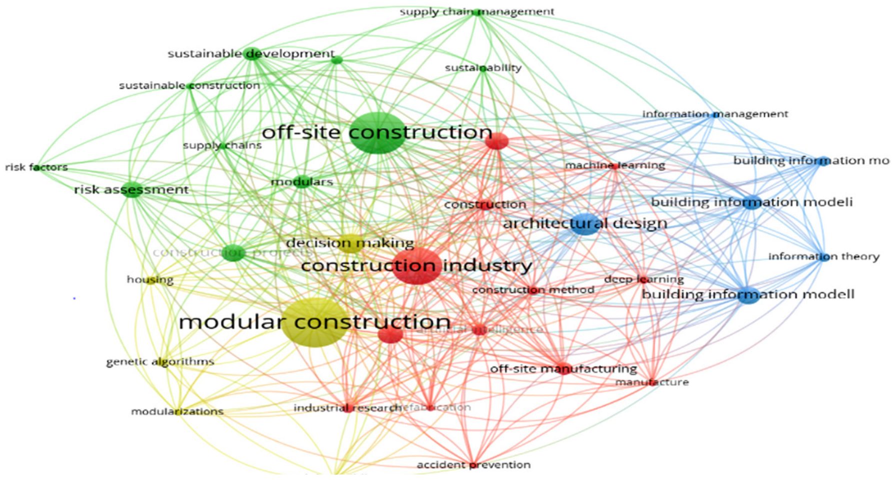

Figure 3. Interconnections between risk management, emerging technologies and modular construction: A network visualisation

Quality Assessment

Each selected study was evaluated in terms of journal impact, methodological rigour and relevance to the review's research questions to ensure credibility and validity. A careful selection was made to choose only high-impact journal articles and conference proceedings, thus ensuring the reliability of the findings. Studies scoring low on methodological rigor or lacking relevance were excluded. This ensured that the final dataset of 87 articles reflected a high standard of scholarly integrity.

RESULTS AND ANALYSIS

This section presents the key findings from the thematic analysis of 87 peer-reviewed publications. Four main themes were identified: (1) persistent challenges in modular construction and offsite manufacturing, (2) emerging opportunities, (3) current trends and (4) technological responses to risk management.

Challenges in Modular Construction and Offsite Manufacturing

Between 2002 and 2024, there was significant attention on offsite manufacturing and modular construction as potential game changers in the construction industry. However, their full-scale implementation and wider diffusion were greatly hampered by several challenges. The most important barriers to wider adoption were the logistical complexities of the transport and onsite assembly of the prefabricated modules (Vithanage et al., 2022;

Liu et al., 2022). Poor infrastructure for large component transportation, especially in urban and developing areas, created more delays and increased costs. According to Picard, Blanchet and Bégin-Drole (2024), coordination in the transport schedule with readiness on site was the key to continuing these inefficiencies.

The second barrier was stakeholder fragmentation. The fragmentation prevented collaboration among contractors, suppliers and regulatory authorities. It then led to delay, misalignment and ineffective execution in modular projects (Lee et al., 2023; Zhou and Huang, 2023). Advanced technologies such as BIM and digital twins can allow for effective coordination of stakeholders and enable seamless decision-making processes. However, existing collaboration barriers relevant to the consideration of innovative solutions had to be overcome to proceed with implementation (Ghalenoei et al., 2024).

modular construction and offsite manufacturing faced regulatory barriers. For example, different building codes and non-standardised specifications require customisation, reducing scalability and discouraging investment in modular construction technologies (Wuni, Shen and Mahmud, 2022; Sing et al., 2023). There is a need for harmonised policies and frameworks that can resolve such inconsistencies and allow for uniform uptake. As a matter of fact, such changes will be critical in nurturing industry growth and luring international investments into modular practices (Rathnasinghe et al., 2024).

The knowledge gap in the techniques of modular construction persisted and acted as a significant barrier to innovation (Zhong, Zhang and Fang, 2022; Ouda and Haggag, 2024). Besides, there was an acute shortage of professional human resources with developed skills in digital tools, modular methods and risk management, which is identified by Kazeem et al. (2024) as being more critical in regions dependent on conventional methods of construction. This calls for the development of focused training programmes and knowledge-sharing platforms that will help improve the skill base and capacity within the industry as a whole. The development of holistic strategies to respond to these challenges will be crucial in realising full value from modular construction and offsite manufacturing.

Table 1. Challenges in modular construction and offsite manufacturing

Challenge	Description	Subthemes	Codes	Source
Logistical complexities	Delays in module transportation and onsite assembly due to poor coordination and infrastructure.	1. Transportation delays 2. Onsite readiness gaps 3. Insufficient infrastructure	1. Poor scheduling coordination 2. Limited transport options 3. Inefficient site planning	Thurairajah et al. (2023); Vithanage et al. (2022); Liu et al. (2022)
Stakeholder fragmentation	Lack of collaboration among contractors, suppliers and regulatory authorities disrupting project execution.	1. Weak communication 2. Supply chain misalignment 3. Ineffective decision-making	1. Inconsistent goals 2. Poor use of collaborative technologies 3. Fragmented workflows	Lee et al. (2023); Zhou and Huang (2023); Assaad et al. (2022)
Regulatory barriers	Variations in building codes and absence of clear standards hinder scalability and investments.	1. Inconsistent codes 2. Lack of modular-specific standards 3. Policy uncertainty	1. Delays in approvals 2. Extensive customisation 3. Inadequate regulatory frameworks	Nesarnobari et al. (2024); Sing et al. (2023); Wuni, Shen and Mahmud (2022)
Knowledge gaps	Limited research and practical expertise in using advanced risk management strategies (e.g., digital twins and BIM) particularly in developing regions.	1. Lack of training programmes 2. Limited technical expertise 3. Resistance to innovation	1. Shortage of skilled professionals 2. Gaps in research 3. Reluctance to adopt new methods	Zhang et al. (2024); Shahzad et al. (2023); Ghalehnoei et al. (2022)

Table 1 presents an elaborate scheme for the analysis of challenges concerning modular construction and offsite manufacturing. The challenges were grouped into four major themes: (1) "Logistical complexities", (2) "Stakeholder fragmentation", (3) "Regulatory barriers" and (4) "Knowledge gaps". Further, each challenge was discussed on subthemes that highlighted different aspects of the same but larger issue, including delays in transportation or weak communication. This required sophisticated coding to facilitate thematic analysis, pinpointing actionable concerns related to persistent trends such as inadequate schedule coordination or deficient regulatory frameworks. The resultant detailed structure could provide a nuanced understanding of interrelated challenges found in modular construction and offsite manufacturing, with relevant academic sources validating these findings.

Opportunities in Modular Construction and Offsite Manufacturing

modular construction and offsite manufacturing offered opportunities to shift the paradigm in the construction industry. This included sustainability, whereby these methods drastically reduced construction waste and energy use. Prefabrication-controlled manufacturing process reduces material losses and ensures energy efficiency, hence responding to the global challenges in sustainability facing the world today (Wuni, Shen and Mahmud, 2022; Ouda and Haggag, 2024). The integration of recyclable materials and green technologies further enhances environmental benefits, providing innovative solutions for eco-friendly construction practices (Ali and Kineber, 2023; Shahzad et al., 2024). Another key advantage was time efficiency. Modular construction allows for parallel workflows between offsite fabrication and onsite preparation, thus shortening project timelines considerably (Tatari, 2023; McDermott et al., 2024). Technologies such as BIM allow for enhanced accuracy in scheduling and coordination that avoid delays and optimise resources. Better contingency planning with advanced simulation tools also contributes to assuring smooth operations and timely project delivery (Hussein, Eltoukhy and Darko, 2021; Ginigaddara et al., 2025).

Also, the modular method of construction was complemented by long-term cost benefits. Large initial investments may be necessary, but such efficiency pertaining to bulk material procurement, factory-controlled environments and reduced waste accrues huge financial advantages. Economic viability, therefore, makes modular methods extremely feasible in large infrastructure and housing projects. Indeed, Zhang et al. (2024) and Zabala-Vargas, Jaimes-Quintanilla and Jimenez-Barrera (2023) have documented that better labour optimisation in controlled environments reinforces cost efficiency, thus making it financially viable (Wrigley et al., 2024). Improved quality and at higher levels were ensured. Quality outputs could be produced through precision and consistency, as ensured by production within a factory and human mistakes that are limited to a few or none at all. This technology, together with digital twins-enabled real-time quality assurance, helps in ascertaining whether such components could eventually meet such set standards, long before these reach the assembling phase (Zhong, Zhang and Fang, 2022; Ouda and Haggag, 2024). These hence hint at increased possibility on the part of modular construction in ensuring qualities superior to the traditional methodologies for the construction of infrastructures.

Finally, scalability and adaptability made modular construction very important in terms of solving urbanisation problems and housing shortages. With increasing investments in digital infrastructure and prefabrication technologies around the world, the sector is bound to grow rapidly. The scalability of the methods involved in modular construction means that they can be applied in various contexts, thus making them a very strong solution for the changing demands in construction (Liu et al., 2022; Ginigaddara et al., 2025). These opportunities reflect the transformative potential that modular construction has in driving innovation, sustainability and efficiency within the global construction industry.

Table 2 gives the thematic analysis of the opportunities regarding modular construction and offsite manufacturing. The opportunities were grouped into five broad categories: (1) “Sustainability”, (2) “Gains relating to time”, (3) “Cost savings”, (4) “Improved quality” and (5) “Global market growth”.

Each category was described by subthemes and codes to explain the implications and benefits of adopting modular methods in practice. For example, sustainability highlighted waste reduction and energy efficiency, and time efficiency highlighted parallel workflows and advanced scheduling tools. Cost savings were achieved through the financial benefits of bulk procurement and resource optimisation, while improved quality control related to precision in factory-based production and global market expansion pertains to the scalability and rising demand for modular solutions addressing urbanisation and housing challenges. This structured approach provides a holistic framework for understanding how modular construction meets the needs of the industry in driving innovation

Table 2. Thematic analysis of opportunities in modular construction and offsite manufacturing

Opportunity	Description	Subthemes	Codes	Source
Sustainability	Reduction in construction waste and energy use through controlled processes and recyclable materials.	1. Reduction of waste 2. Energy efficiency 3. Use of green technologies	1. Minimising material losses 2. Energy-saving manufacturing 3. Recyclable materials	Wuni, Shen and Mahmud (2022); Ali and Kineber (2023)
Time Efficiency	Faster project completion through simultaneous offsite fabrication and onsite preparation.	1. Parallel workflows 2. Enhanced scheduling 3. Real-time resource allocation	1. BIM-based scheduling 2. Simulation models 3. Contingency planning	Tatari (2023); Hussein, Eltoukhy and Darko (2021)
Cost Savings	Long-term cost reductions via bulk purchasing, reduced labour and waste minimisation.	1. Bulk procurement 2. Labour optimisation 3. Efficiency-driven cost savings	1. Reduced rework costs 2. Factory-controlled processes 3. Optimised resource use	Zabala-Vargas, Jaimes-Quintanilla and Jimenez-Barrera (2023); Shahzad et al. (2023)
Enhanced Quality Control	Controlled environments ensure precision, reduce errors and improve quality.	1. Factory-controlled production 2. Digital monitoring 3. Defect prevention	1. Real-time quality assurance 2. Digital twins 3. Improved material usage	Zhong, Zhang and Fang (2022); Assaad et al. (2022)
Global Market Growth	Increasing demand for scalable and sustainable solutions to address urbanisation and housing shortages.	1. Rising urban demands 2. Investment in prefabrication 3. Digital infrastructure growth	1. Scalable solutions 2. Infrastructure investments 3. Growing modular market demand	Liu et al. (2022)

Trends in Modular Construction and Offsite Manufacturing

A series of transformational trends was identified in modular construction and offsite manufacturing towards the environment and the development of the sector using improved methods, along with strong technological advancement. Some other main trends were related to the increasing levels of digital integration. Most firms already had worked in this particular arena by implementing BIM-digital twins. These tools provide smooth project planning, real-time monitoring and predictive analytics, thus ensuring effective collaboration and efficiency at every stage of the construction project at hand, found in the works of Liu et al. (2022), Cheng et al. (2023) and AlZarooni and Rashid (2024).

Another concerning trend was the development of prefinished prefabricated volumetric construction. The trend increasingly received boosts in urban areas because it reduced the period of construction in such instances with improved cost-effectiveness. PPVC focuses on modularity at scale in making improvements that enable quicker project delivery but maintain quality standards. The integration of PPVC into urban planning programmes reduces the challenges of space constraints and sustainability demands. Wood and other materials in use should not be toxic, hence be friendly towards the environment (Zabala-Vargas, Jaimes-Quintanilla and Jimenez-Barrera, 2023; Liu, Hwang and Lim, 2023; Doan et al., 2024).

Automation and robotics further transformed modular construction by enhancing precision in manufacturing and reducing dependency on manual labour. Advanced robotic systems, together with machine learning algorithms, optimise the production and assembly of prefabricated components, improving accuracy and reducing material waste significantly (Tatari, 2023; Pan et al., 2022; Ginigaddara et al., 2024). These systems also play a critical role in safety management, especially analysis of lifting operations during the assembling of prefabricated buildings (Liu et al., 2022; Wrigley et al., 2024). Furthermore, the increasing focus on resilience and sustainability in modular design addressed the growing need for disaster-resistant structures. Indeed, innovative materials and structural techniques were being adopted in modular construction to enhance the durability and adaptability of buildings, especially in regions prone to environmental hazards. This trend will ensure structural integrity and align with global sustainability goals (Tatari, 2023; Peiris et al., 2023; Raza, Besklubova and Zhong, 2024). The development of international standards and policies would be better aligned and scaled in the modular construction methods. Harmonised guidelines and regulatory frameworks promote cross-border collaborations, reduce uncertainty and attract investments in prefabrication technologies. Efforts towards harmonisation create the right environment to help the diffusion of modular construction as a mainstream solution for infrastructure and housing needs (Hasan and Lu, 2022; Cheng et al., 2023; Zhang et al., 2024).

The main findings are summarised in Table 3, organising the leading works related to modular construction and offsite manufacturing according to methodological approach and theme. The themes were:

1. The digital integration supported by digital twins and AI methods that enable near real-time sensing and decision support (Tatari, 2023).
2. The use of IoT and cloud-based systems to enhance communication and centralise information (Li et al., 2022).
3. Monte Carlo analysis simulation to identify and manage risks (He, Zhang and Li, 2021).

Other important features included the prominence of sustainability and resilience, with both displaying the work of AI regarding fostering better energy efficiency and waste reduction, as well as resilience against building disasters. In short, current research supports efficiency and sustainability in the technological innovations evident in modular construction (Khan et al., 2023).

Table 3. Summary of methodologies and thematic focus on modular construction and offsite manufacturing research

Source	Trends Key Findings	Methodology	Thematic Focus
Liu et al. (2022)	Faster region-based convolutional neural network demonstrated higher accuracy than single shot detector in modular object detection; Performance affected by surrounding objects and image background.	Quantitative	Deep learning algorithms in modular detection
Zabala-Vargas, Jaimes-Quintanilla and Jimenez-Barrera (2023)	Emerging technologies like AI, big data and IoT significantly impact project management in the AEC industry; Identified trends in cost, quality and risk management.	Qualitative	Role of emerging technologies in AEC management
Hasan and Lu (2022)	Variance analysis in regression models for labour cost estimation; Introduced error propagation theory to improve precision of multi linear regression models for prefabricated components.	Quantitative	Labour cost estimation in modular construction
Tatari (2023)	Bayesian networks effectively assess cost risks for prefabricated construction in developing countries; Machinery and technology identified as critical risk factors.	Quantitative	Cost risk analysis for modular construction

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Table 3. *Continued*

Source	Trends Key Findings	Methodology	Thematic Focus
Li et al. (2022)	Blockchain-enabled IoT-BIM platforms enhance supply chain transparency and reduce costs; Developed service-oriented architecture for modular construction projects.	Qualitative	Supply chain management in modular construction
Peiris et al. (2023)	Metaheuristic algorithms like particle swarm optimisation and ant colony optimisation show potential for optimising modular construction scheduling; Identified research gaps in intelligent production scheduling.	Mixed methods	Scheduling optimisation in modular construction
Cheng et al. (2023)	Digital twins and BIM facilitate integration in offsite construction; Identified trends and research directions for digital technology in modular projects.	Qualitative	Digital integration in modular construction
Liu et al. (2022)	Digital twins-based risk control frameworks reduce safety risks during prefabricated building hoisting; Bayesian Networks used for decision analysis.	Quantitative	Safety risk management in prefabricated hoisting
Pan et al. (2022)	AI and robotics enhance modular construction precision and efficiency; Proposed interdisciplinary approaches to improve project outcomes.	Qualitative	AI and robotics in modular construction
Kazeem, Olawumi and Osunsanmi (2023)	AI and machine learning improve construction efficiency, sustainability and planning; Identified future research trends in sustainable community development.	Qualitative	AI in sustainable modular construction

Technological Solutions for Risk Management

Technological solutions pushed the modular construction and offsite manufacturing industry towards improved risk management due to its naturally complex and uncertain nature. Predictive analytics, mainly using Bayesian Networks and AI, has proven effective in forecasting risks and supporting decisions about them. The tools enable stakeholders to find potential cost overruns and safety concerns, thus enabling proactive intervention. Of these, Bayesian Networks provide a probabilistic framework for the interdependencies of risk factors that gives a very valuable view in the mitigation of cascading effects (Tatari, 2023; Liu et al., 2022). Similarly, AI makes use of big datasets to find out patterns and trends, which again makes it indispensable while dealing with the intricacies of modular construction projects (Zabala-Vargas, Jaimes-Quintanilla and Jimenez-Barrera, 2023; Rodríguez-Espíndola et al., 2022; Rafi-Ul-Shan et al., 2024). In particular, digital twins technology emerged as an enabling tool that allows real-time monitoring and simulation of modular construction processes. Digital twins technology is a digital reproduction of physical structure and workflows (Liu et al., 2022; Cheng et al., 2023). It enables analysis of scenarios by stakeholders, optimise operations and proactively acts on risks before escalating. For instance, digital twins integration into the assembling of prefabricated buildings improves dynamic safety monitoring and hazard control with reduced delays; therefore, an overall successful project delivery could be guaranteed (Li et al., 2022; He, Zhang and Li, 2021; Wang et al., 2024). In such a context, a digital twins system with IoT sensors enables information and knowledge sharing transparently among users in its life cycle with a holistic framework for risk management (Peiris et al., 2023; Okudan, Budayan and Dikmen, 2021; Odimarha, Ayodeji and Abaku, 2024).

IoT in modular construction played a transformational role, especially in strengthening communication and coordination. The IoT-enabled systems enable timely data sharing among the modular components, equipment and stakeholders. This reduces delays and enhances operational efficiency (Peiris et al., 2023; Okudan, Budayan and Dikmen, 2021; Odimarha, Ayodeji and Abaku, 2024). Safety was also enhanced through IoT technology by automating hazard detection and providing real-time alerts, hence limiting human error. Cloud-based platforms help in centralising project data complementary to IoT applications and enable all stakeholders to access information with ease. This would aid in bringing a better amount of transparency and collaboration, a key element involved in large modular construction projects (Liu et al., 2022; Torres et al., 2024). Advanced simulation tools involving Monte Carlo simulations and fault tree analysis became meaningful for the assessment of risks. These tools make it possible to have some quantification on likely risks; this allows the project manager to compare scenarios with each other, elaborating appropriate measures that will give full assurance from possible incidents of occurrence. In this connection, Tatari (2023) and Zhong, Zhang and Fang (2022) outlined that Monte Carlo simulation provides a probabilistic review of complex modular operations, while fault tree analysis visually maps out critical failure points that should have interventions. These technologies have improved risk management practices that enhance sustainability, resilience and further development in modular construction methods (Temel and Durst, 2021; Durst, Hinteregger and Zieba, 2024; Zhang et al., 2024).

Major methodological approaches adopted in researching technological advances in risk management for modular construction are summarised in Table 4. Quantitative approaches using probability models and simulation for the assessment and enhancement of predictive decision-making, while qualitative research explored aspects of organisational and integration issues of technologies such as IoT. A mixed-methods approach combines the quantitative and qualitative approaches to conduct an integrated analysis of technological impacts along with stakeholder dynamics. The approach addressed key themes of digital integration by facilitating digital tools like digital twins and AI-based real-time monitoring or even risk forecasting (Tatari, 2023), incorporating IoT and cloud systems to improve transparency in communication (Li et al., 2022), creating specific mitigation planning of risks through simulation tool(s) such as the Monte Carlo (He, Zhang and Li, 2021) and empowering sustainability perspectives via waste reduction and/or energy efficiency powered through AI (Khan et al., 2023). These findings pinpoint the place of advanced technologies in modular construction to improve safety and efficiency.

Table 4. Methodological approaches in technological solutions for risk management in modular construction

Source	Study Focus	Methodology	Major Findings
Rodríguez-Espíndola et al. (2022)	Adoption of emergent technologies for risk management in digital manufacturing	Mixed methods	Identified the role of emergent technologies in enhancing risk management and reducing operational delays.
Tatari (2023)	Bayesian network applications for cost risk management in prefabricated construction	Quantitative	Demonstrated that Bayesian networks effectively address interdependencies between cost risk factors.
Liu et al. (2022)	Digital twins technology for real-time monitoring and risk control in prefabricated building assembly	Quantitative	Highlighted the benefits of digital twins in improving safety, minimising delays and optimising resource allocation.
Zabala-Vargas, Jaimes-Quintanilla and Jimenez-Barrera (2023)	Big data and AI in project management for the architecture, engineering and construction industry	Mixed methods	Emphasised the role of AI in predicting project outcomes and addressing risk in modular construction.
Cheng et al. (2023)	IoT-enabled systems for modular construction risk management	Qualitative	Discussed the integration of IoT with other technologies to enhance real-time communication and risk control.
Peiris et al. (2023)	Simulation tools for evaluating operational risks in modular construction	Quantitative	Monte Carlo simulations and fault tree analysis provide robust quantitative risk assessments.

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Table 4. *Continued*

Source	Study Focus	Methodology	Major Findings
Temel and Durst (2021)	Knowledge of risk prevention strategies for technological innovations in small businesses	Qualitative	Provided strategies for risk prevention using targeted knowledge management frameworks.
He, Zhang and Li (2021)	IT solutions for managing risks during the COVID-19 pandemic	Qualitative	Discussed how information technology systems address uncertainties and improve risk management in complex scenarios.
Zhong, Zhang and Fang (2022)	Cloud-based risk assessment models for safety in prefabricated construction	Quantitative	Demonstrated the effectiveness of cloud-based systems for reducing risk uncertainties in lifting operations.
Okudan, Budayan and Dikmen (2021)	Case-based reasoning tools for construction project risk management	Mixed methods	Showcased how knowledge-based systems improve decision-making and mitigate risks in modular construction.

DISCUSSION

The results of this study underscored the transformative potential of modular construction and offsite manufacturing, particularly when empowered by advanced digital technologies such as digital twins, AI, IoT and simulation tools. Compared to previous systematic reviews that largely emphasised technical, logistical and human resource barriers in modular construction (e.g., Wuni, Shen and Hwang, 2020; Khodabocus and Seyis, 2024b), this review advanced the discourse by integrating a comprehensive review of digital risk management tools that enable predictive, real-time decision-making frameworks. While past frameworks have acknowledged these tools, few have synthesised them into a cohesive roadmap for mitigating interrelated risks on scale.

A clear advancement of this review was the identification of how these digital innovations address core risk dimensions, namely, logistical uncertainty, stakeholder fragmentation, regulatory inconsistencies and knowledge deficits by applying real-time data monitoring, probabilistic risk modelling (e.g., Bayesian Networks) and system-wide integration via IoT and cloud platforms. The convergence of these tools enhances forecasting accuracy, resource optimisation and contingency planning, positioning modular construction as a scalable, resilient strategy, especially in the context of rapid urbanisation and resource scarcity. Moreover, this review situated the findings within the broader goals of Sustainable Development Goals (SDGs), particularly SDG 9: Build Resilient Infrastructure, Promote Inclusive and Sustainable Industrialisation, and Foster Innovation. The identified benefits, such as sustainability via waste minimisation, increased project speed and cost control and reduced environmental impact through energy-efficient modular production demonstrate modular construction's strategic role in advancing green, technology-enabled infrastructure solutions. Furthermore, AI- and digital twins-powered quality assurance mechanisms align with SDG 11 (Sustainable Cities and Communities) by promoting safer, more liveable built environments.

Despite these innovations, persistent risks remain. The study affirmed that risk in modular construction is not just technological or operational, it is also institutional. Misaligned policies, lack of capacity-building programmes and inconsistent regulatory codes in many developing countries continue to deter investment and widespread adoption. A risk governance framework should thus be multidimensional, combining technical solutions with policy reforms, cross-sectoral collaborations and scalable training models. Aligning with recent work by Khodabocus and Seyis (2024a), the development of multi-criteria decision-making models for risk prioritisation could support targeted interventions across various project phases. To support full-scale implementation, a conceptual framework integrating technological enablers (digital twins, AI and IoT), policy mechanisms (harmonised regulations and sustainability incentives) and human capacity development (training and upskilling) is proposed. This multi-tiered framework directly responds to the complexity of risk across planning, design, logistics and operations, offering a practical approach for public and private sector actors seeking to align construction innovation with sustainable development imperatives.

Recommendations and Future Agenda

The current review identified two innovative methods for making construction more efficient, sustainable and scalable, namely: modular construction and offsite manufacturing. However, there were several obstacles to further diffusion: logistical problems, misaligned regulatory frameworks and skill gaps. The recommendations for surmounting identified barriers to fully realising the potential associated with modular construction included integrating advanced digital technologies, improving regulatory frameworks and collaborating among stakeholders to reinvent the global diffusion construction processes.

The recommendations focus on a multidimensional approach s existing constraints while opening new avenues for innovative practices and sustainable outcomes. New advanced tools, including digital twins, IoT and AI, are proposed to be integrated for real-time monitoring and risk management. Standardising the regulatory framework and improving the logistic infrastructure shall help reduce friction, thereby enabling scaling. The table also shows that promoting sustainability through using green materials and energy-efficient designs is imperative. Capacity-building programmes involving training and collaboration platforms are highly desired to address the knowledge gap and provide relevant skills to the workforce. Further, research and development in automation and robotics will offer a sound basis for future developments. This comprehensive table is a roadmap, offering actionable insights and strategies to elevate modular construction and offsite manufacturing in various contexts. These are summarised systematically in Table 5 and connected with actionable outcomes for better modular approach uptakes.

Table 5. Strategic recommendations and future agenda for advancing modular construction and offsite manufacturing

Recommendation	Details	Expected Outcome
Adopt digital technologies	1. Invest in tools like digital twins, IoT and AI. 2. Financial incentives and pilot programmes can encourage integration.	Enhanced real-time monitoring, risk management and project collaboration.
Standardise regulations	Develop harmonised building codes and policies to minimise customisation and promote scalability.	Improved regulatory clarity, increased investments and streamlined processes.
Enhance skills and knowledge	1. Implement training programmes on modular techniques, digital tools and risk management. 2. Facilitate knowledge sharing via industry platforms.	Increased workforce capability and reduced resistance to innovative methods.
Foster collaboration	Use BIM tools to enhance stakeholder coordination and reduce project fragmentation.	Improved decision-making, streamlined workflows and more substantial stakeholder alignment.
Strengthening logistics and infrastructure	Upgrade transportation networks and develop modular-friendly solutions for efficient delivery and assembly.	Reduced logistical delays and cost savings.
Promote sustainability	1. Use sustainable materials, improve energy efficiency and design disaster-resilient structures. 2. Provide incentives like green certifications.	Alignment with global sustainability goals and reduced environmental impact.
Encourage research and development	Support advancements in automation, robotics and scheduling through academic and industrial partnerships.	Innovation in modular processes and enhanced project efficiency.

CONCLUSION

This review revealed that modular construction and offsite manufacturing, when supported by digital technologies such as digital twins, AI and IoT, could revolutionise the construction industry by enhancing efficiency, reducing risks and promoting sustainable practices. The integration of predictive analytics, simulation tools and real-time data systems enables proactive risk management and supports safer, more efficient project execution. Nonetheless, challenges include fragmented stakeholder engagement, misaligned regulatory frameworks and skill shortages. Addressing these will require a coordinated effort combining policy reform, digital infrastructure investment and inclusive capacity-building programmes. In particular, the study highlights the importance of harmonising building codes, fostering stakeholder collaboration and expanding training in emerging construction technologies. Importantly, the findings contribute to global development efforts, aligning with SDG 9 by fostering resilient infrastructure and innovation and SDG 11 by supporting sustainable and inclusive urban development. Policy makers, industry leaders and academic researchers should leverage these insights to shape future regulations and investment strategies that maximise the impact of modular technologies in delivering smart, sustainable infrastructure – particularly in the developing world.

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