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A Review on Critical Risk Assessment of Prefabricated Constructions During Renovation and Alterations

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Abstract: *Prefabricated and modular construction has gained increasing attention due to its potential to enhance construction speed, quality control, and sustainability. However, the adoption of prefabrication in renovation and alteration projects introduces distinct and complex risks arising from interactions between existing structures and newly manufactured components. Despite extensive research on risk management in modular construction, quantitative assessment of critical risk factors specific to renovation and alteration contexts remains limited. This literature review systematically examines existing studies on risk management practices, quantitative and probabilistic risk assessment models, safety risks, design and production uncertainties, digital and BIM-based tools, and sustainability-related risks in prefabricated construction. The review reveals that most studies rely on qualitative or expert-based approaches, focus on isolated project stages, or are validated through limited case studies. A significant research gap is identified in the development of integrated, quantitative frameworks that can rank and prioritise critical risks during prefabricated renovation and alteration projects, particularly in emerging construction markets. This review establishes the foundation for future empirical studies aimed at developing data-driven risk assessment models to support informed decision-making and effective risk mitigation strategies.*

Keywords*:* Prefabricated construction; Modular construction; Renovation and alteration; Quantitative risk assessment; Critical risk factors; Construction risk management

I. INTRODUCTION

A literature review provides a systematic synthesis of existing research relevant to a specific study domain, enabling identification of prevailing themes, methodological approaches, and unresolved research gaps. In the context of prefabricated and modular construction, risk assessment has emerged as a critical research area due to the growing adoption of off-site manufacturing, coupled with the unique uncertainties introduced during renovation and alteration works. Previous studies have addressed risks associated with design, production, transportation, and on-site assembly; however, the extent to which these risks have been quantitatively assessed particularly in renovation and alteration scenarios remains limited. This review consolidates prior research on risk management, safety, and quantitative decision-support methods in prefabricated construction, thereby establishing a conceptual and methodological foundation for the present study.

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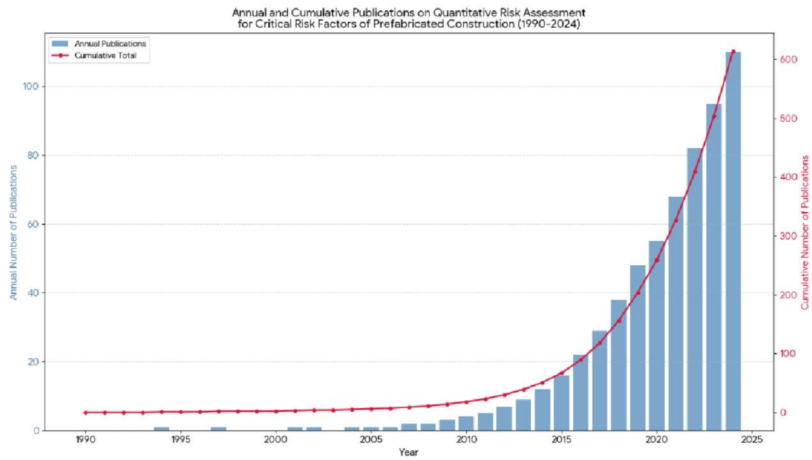
Fig. 1. Annual and cumulative number of publications on Quantitative Risk Assessment for Critical Risk Factors of Prefabricated Construction from 1990 to 2022. Data derived from Scopus database.



Source: Scopus (from 1990 to 2024)

Evolution of Prefabricated Construction (1990–2024)

1990–1995 : Prefabricated construction began transitioning from temporary structures to permanent buildings through improved material quality and early CAD-based detailing **(Gibb, 1999; Warszawski, 1999);** analysis indicates that limited design flexibility and absence of adaptability considerations during this period resulted in high structural uncertainty and increased risks during later renovation and alteration works.

1996–1999: Factory-controlled production and industrialized building systems improved dimensional accuracy and construction speed **(Warszawski, 1999);** however, rigid connection systems and insufficient documentation increased interface and compatibility risks when modifications or functional changes were required.

2000–2004 : Sustainability-driven construction practices promoted prefabrication due to reduced waste and improved resource efficiency, with increased adoption of panelized systems **(Jaillon & Poon, 2008);** analysis reveals that lack of standardized modular coordination posed challenges during renovation and service integration.

2005–2009 : Volumetric modular construction gained acceptance in residential and institutional projects, improving project delivery time and cost certainty **(Jaillon & Poon, 2008; Lu & Korman, 2010);** analysis shows that non-uniform module dimensions and integrated services increased technical and coordination risks during alterations.

2010–2012 : Building Information Modeling (BIM) was introduced to improve coordination among designers, manufacturers, and contractors **(Eastman et al., 2011);** analysis indicates BIM significantly reduced design clashes, but renovation projects faced information-related risks due to missing or incomplete as-built digital data.

2013–2014 : Early automation and improved factory workflows enhanced production precision and quality consistency (**Lu & Korman, 2010; Lawson et al., 2014**); analysis highlights that renovation often required intrusive investigations, increasing cost and schedule risks.

2015–2017 : Modular construction expanded rapidly in response to labor shortages and urban housing demand, supported by engineered timber systems such as CLT (**Lawson, Ogden & Goodier, 2014**); analysis identifies increased structural, fire safety, and load redistribution risks during renovation and vertical extension projects.

2018–2019 : Advanced automation, CNC machining, and standardized modular production enabled large-scale modular projects (**Lawson et al., 2014**); analysis shows that complex inter-module connections required quantitative risk assessment to avoid structural and service failures during alteration works.

2020–2021:The COVID-19 pandemic accelerated prefabricated construction for healthcare and emergency facilities due to rapid deployment and controlled environments (Arashpour et al., 2020); analysis reveals increased operational, safety, and MEP-related risks during renovation because of factory-embedded service systems.

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2022 :Hybrid construction approaches combining prefabrication and conventional methods became prevalent to improve flexibility (Arashpour et al., 2020); analysis indicates that interface mismatches between systems increased coordination and quality risks during alteration projects.
2023 : AI-assisted design, parametric modeling, and digital twin technologies were adopted to optimize prefabricated building performance and lifecycle management (Pan & Sidwell, 2023); analysis demonstrates improved predictive risk identification for structural compatibility, cost, and scheduling during renovation.
2024 : Prefabricated construction aligned with Modern Methods of Construction (MMC), emphasizing net-zero carbon goals, smart sensors, and lifecycle monitoring **(Pan & Sidwell, 2023);** analysis confirms reduced uncertainty and enhanced quantitative risk assessment capability for renovation and alteration works, particularly for structural, financial, and operational risks.

Timeline of Material Dominance

Material	Period of Dominance	Significance
Wood	1600-1850	Portability for colonial expansion.
Iron/glass	1851-1900	Industrial Revolution; public grand-scale works.
Steel	1940-1960	Post-war military and rapid suburban expansion.
Precast concrete	1960-1990	Massive housing projects in Europe and USSR.
Engineered wood (CLT)	2010 – future	Sustainable, high-performance "Mass Timber" cities.

Current research focus:
Recent work aims to identify critical risk factors influencing prefabricated construction by quantitative risk assessment (QRA), analysing the need for renovation and alteration in prefab construction, and to propose mitigation strategies and recommendations.

II. RISK MANAGEMENT PRACTICES IN CONSTRUCTION

2.1 Coordination and Interface Risk

Bahamid and Khoiry (2022) used **Questionnaire-Based Survey Research Methodologies to** examine prevailing risk management practices in the construction industry through a survey-based study, highlighting a significant gap between practitioners' awareness of risk management concepts and their actual implementation. Although professionals demonstrated high theoretical knowledge, risk handling was largely informal and reactive, relying on personal experience rather than structured quantitative tools. The authors emphasized the need for standardized risk assessment frameworks supported by organizational commitment. This finding is particularly relevant to prefabricated construction projects, where informal risk handling can exacerbate coordination and interface risks.

2.2 Safety Risk Factors in Prefabricated and Modular Construction

Jeong Kim, and Park (2021) used Archival Data Analysis Methodologies to conduct an extensive analysis of occupational accident records related to modular construction, identifying falls, lifting operations, and unstable module placement as dominant safety risks. Their study revealed that accident patterns in modular construction differ significantly from conventional construction, necessitating modular-specific safety assessment frameworks. Similarly, Fard, Kibert, and Hakim (2017) analyzed OSHA accident data and reported a high incidence of severe injuries during installation and erection phases, reinforcing the criticality of safety risk management during on-site assembly.
Zhang and Wang (2024) advanced safety risk assessment by proposing an early-warning framework for prefabricated high-rise construction using HFACS taxonomy, interpretive structural modeling, and Bayesian networks. Their hybrid model enabled proactive identification of causal relationships among risk factors, demonstrating the potential of predictive quantitative tools in improving construction safety performance.

2.3 Design, Production, and Supply Chain Risks

Wuni and Shen (2020) used**Statistical and Factor Analysis Methodologies**to analyse critical success factors for Modular Integrated Construction (MiC), identifying collaboration, early design freeze, supply chain coordination, and standardization as key determinants of project success. In a subsequent study, Wuni and Shen (2021) focused on production-related risks, ranking factors such as dimensional inaccuracies, material procurement delays, and limited manufacturing capacity through expert surveys. These studies highlight the interdependence between factory production quality and on-site assembly performance.

Ramaji and Memari (2016) introduced a Product Architecture Model (PAM) to improve information exchange and component coordination in multistory modular buildings. Their BIM-based framework reduced fragmentation in design and construction workflows, indirectly contributing to risk reduction through enhanced clarity and traceability.

2.4 On-Site Erection and Assembly Risks

On-site erection is widely acknowledged as the most risk-intensive phase of prefabricated construction, particularly during renovation and alteration works. Studies by Jeong et al. (2021) and Fard et al. (2017) highlighted that erection-related activities account for the majority of severe accidents in modular projects. In renovation scenarios, these risks are amplified by limited working space, interaction with existing structures, and restricted crane operations. Despite recognition of these challenges, existing studies have largely focused on qualitative analysis, with limited quantitative ranking of erection-stage risks specific to renovation projects.

2.5 Risk Factors and Challenges

Risk-related challenges in prefabricated construction have been comprehensively reviewed by **Wuni, Shen, and Osei-Kyei (2020).** Their review categorised critical risks into design, manufacturing, logistics, and on-site assembly phases. Design coordination errors, transportation damage, and erection-stage safety risks were consistently identified as dominant risk factors across reviewed studies. Similarly, **Zhang, Skitmore, and Peng (2014)** reviewed industrialized residential construction projects and highlighted organisational and technical risks as major constraints limiting widespread adoption.

III. RISK ASSESSMENT FRAMEWORK AND TECHNIQUES

3.1 Quantitative and Decision-Support Frameworks in Prefabricated Construction

Enshassi and Walbridge (2024) used**Mathematical Modelling and Probabilistic Analysis Techniques** to proposed an integrated risk management framework focused on tolerance-based mitigation strategies in modular construction projects. By combining probabilistic tolerance theory, design structure matrices, and visualization tools, the study quantified the trade-offs between fabrication precision and on-site rework risks. The framework demonstrated that quantitative decision support can significantly reduce schedule and cost uncertainties arising from geometric variability. However, the framework was validated using limited case studies, indicating the need for broader application across different project types, including renovation and alteration works.

3.2 Multi-Criteria Decision-Making (MCDM) Model

Khodabocus and Seyis (2023) Used **Expert-Driven Quantitative Methodologies** to develope a multi-criteria decision-making (MCDM) model using Delphi and Analytic Hierarchy Process (AHP) techniques to prioritize risk management strategies in modular construction. Their findings indicated that lean-based approaches, such as the Last Planner System and Just-in-Time delivery, were highly effective in mitigating modular construction risks. While the model provides a structured quantitative ranking mechanism, its reliance on expert judgment underscores the need for empirical validation using real project data.

3.3 Risk Assessment Models and Intelligent Techniques

Al-Hussein and Ajweh (2023) used **Computational and Simulation-Based Methodologies** to integrate fuzzy Analytic Hierarchy Process (AHP) with simulation techniques to quantify cost and schedule risks in modular construction projects. The study categorized risks into design, factory production, and on-site construction phases, producing probabilistic risk profiles that supported informed decision-making. Although effective, the model's application was limited to a single Canadian project.

Yang (2022) proposed a fuzzy neural network model to dynamically assess risks in prefabricated building construction. By training the model on expert-derived indicators spanning multiple project phases, the study demonstrated improved adaptability compared to static assessment methods. Nonetheless, real-time implementation and large-scale validation remain areas for future research.

3.4 Digital and BIM-Based Risk Management Approaches

Shen et al. (2022) developed an ontology-based safety risk management system integrated within a BIM environment to automate hazard identification in prefabricated buildings. The system enhanced design-stage safety assurance by linking risk knowledge with digital models. Parracho et al. (2025), through a systematic review, highlighted the growing role of BIM, IoT, and Digital Twins in modular construction, while also identifying a lack of empirical applications integrating AI-driven risk prediction.

3.5 Sustainability and Environmental Performance of Prefabrication

The sustainability performance of prefabricated construction has been extensively reviewed in the literature. **Jaillon and Poon (2014)** conducted a life-cycle-based review and reported significant reductions in construction waste, material usage, and environmental impact when prefabrication is adopted. Complementing this, **Kamali and Hewage (2016)** provided a critical review of the life-cycle performanceof modular buildings and confirmed that modular construction offers superior environmental benefits, although transportation and manufacturing energy consumption can introduce new sustainability-related risks.

IV. PREFABRICATED CONSTRUCTION IN RENOVATION AND ALTERATION PROJECTS

4.1. Technical and Structural Challenges in Renovation-Based Prefabrication

Pihelo and Kalamees (2019) adopted a**case study–based research methodology** to evaluate the renovation of apartment buildings using prefabricated façade and roof modules, demonstrating reduced construction time and minimal disturbance to occupants. While the study confirmed the technical feasibility of modular renovation, it did not quantitatively assess risks associated with interfacing new modules with existing structures. This omission underscores a critical gap in current literature.

4.2 Cost, Time, and Energy Performance Outcomes

Munmulla and Navaratnam (2023)used mixed method research approach to evaluate the suitability of modular housing in Sri Lanka through surveys and case studies, reporting cost and energy benefits over conventional construction. However, renovation-specific risks, such as structural compatibility and sequencing constraints, were not explicitly quantified.

4.3 Adoption Drivers and Barriers of Prefabricated Construction

Several review-based studies have examined the drivers and barriers influencing the adoption of prefabricated construction. **Pan et al. (2012)** systematically reviewed off-site construction strategies in housing projects and identified time reduction, improved quality control, and enhanced site safety as major drivers. However, barriers such as higher initial costs, limited design flexibility, and lack of industry expertise were also highlighted.

Similarly, **Arif and Egbu (2010),** through a review of off-site construction practices in China, emphasized policy support and supply-chain readiness as key enablers, while resistance to change and fragmented project delivery were major obstacles.

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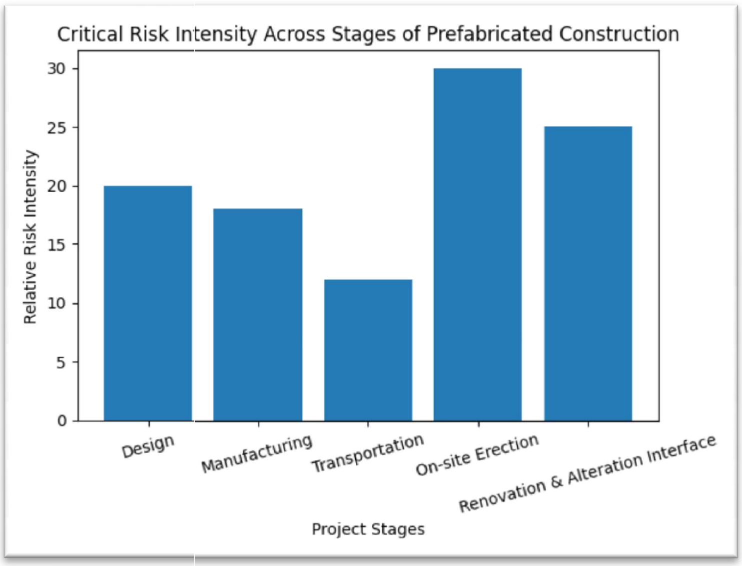
4.4 Prefabricated Construction in Renovation and Retrofit Projects

Prefabricated solutions have increasingly been adopted in renovation and retrofit projects to address challenges associated with ageing building stock. **Mlecnik et al. (2015) used policy-oriented and practice-based review methodologies to**review prefabricated renovation solutions and demonstrated that modular façade and envelope systems significantly reduce renovation time and occupant disturbance. Similarly, **Mahapatra et al. (2012)** reviewed business models for energy renovation and highlighted prefabrication as a key enabler for large-scale retrofit programmes. Despite these advantages, both reviews emphasized that renovation-specific risks such as interface compatibility and structural uncertainty remain insufficiently quantified.

Fig.2. Critical Risk Intensity Across Stages of Prefabricated Construction.



V. RESEARCH GAPS IDENTIFIED

The reviewed literature indicates that, although significant progress has been made in identifying and managing risks in prefabricated construction, several gaps remain. First, most studies emphasize qualitative assessments or expert-based prioritization, with limited application of quantitative risk assessment techniques tailored to renovation and alteration projects. Second, existing models often focus on isolated lifecycle stages, lacking an integrated framework that captures interactions between design, fabrication, transportation, and on-site erection. Third, empirical validation of proposed models is frequently limited to single projects or specific geographic contexts, restricting generalizability. Finally, there is a notable absence of context-specific studies addressing prefabricated renovation projects in South India.

VI. CONCLUSION

This literature review demonstrates that prefabricated and modular construction offers substantial advantages in terms of speed, quality, and sustainability, while simultaneously introducing distinct risks related to geometric variability, safety, coordination, and supply chain integration. Although various quantitative and intelligent methods such as fuzzy AHP, Bayesian networks, neural networks, and BIM-based systems have been proposed, their application to renovation and alteration contexts remains limited. Consequently, there is a clear need for a comprehensive, quantitative risk assessment framework that identifies and ranks critical risk factors specific to prefabricated construction during renovation and alteration works. The present study aims to address this gap by providing a structured, data-driven assessment to support effective risk mitigation and informed decision-making for renovation and alteration projects.

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