A STRATEGIC FRAMEWORK FOR INTEGRATING ROBOTIC TECHNOLOGY IN SRI LANKAN HIGH-RISE CONSTRUCTION: INSIGHTS FROM A DELPHI STUDY ON ENABLERS AND BARRIERS

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Abstract: This study explores the adaptability of robotic technology in precast high-rise construction in Sri Lanka, aiming to identify the enablers and barriers. Further by addressing the challenges associated with the adoption of robotics, this study provides valuable insights into the future of construction automation and its potential to enhance efficiency, safety, and quality in the precast high-rise sector. Furthermore, the study examines the technical feasibility of robotic technology in the construction industry in Sri Lanka. The study involved two rounds of sixteen (16) semi-structured interviews with experts selected through heterogeneous purposive sampling adapting interpretive approach. The data was analysed using manual content analysis. MSVisio data visualisation tool was used to present the findings. This study found that the integration of robotic technology in precast high-rise construction has the potential to enhance efficiency, quality, and safety significantly. The study revealed that while the adoption of robotics in construction can result in reduced labour costs and increased productivity, challenges such as high initial investment costs, limited technical expertise, and resistance to change from workers need to be addressed. This study offers a unique contribution to the field of construction by exploring the integration of robotic technology in precast high-rise construction, an area that remains under-researched, especially in developing countries like Sri Lanka. The study adds value by addressing the gap in understanding the real-world challenges and benefits of robotics adoption in construction projects.

Keywords: *Building Construction Projects, Precast high-rise construction, Robotics, Sri Lanka*

1. Introduction

High-rise buildings present unique challenges, including intricate logistics, heightened safety concerns, and the need for effective construction strategies that ensure high craftsmanship and timely completion (Tracy et al., 2025). These challenges are compounded by the vertical movement of materials and personnel within confined spaces. As Elliott and Jolly (2013) emphasised, the efficiency of construction methods is crucial for the success of high-rise projects, particularly in managing safety, construction quality, schedules, and logistics. Precast construction is particularly advantageous for high-rise buildings because it leverages repetitive and modular elements, which streamline construction activities and reduce overall project timelines (Chew, 2017). The structural performance of precast systems in high-rise buildings is critical, offering excellent load-bearing capabilities, enhanced earthquake resistance, and precise interconnections that protect structures from dynamic loads and environmental influences (Gan et al., 2019). Additionally, precast construction aligns with sustainable building practices by reducing waste, optimising energy use, and managing resources more effectively, thereby contributing to the sustainability of high-rise projects (Lachimpadi et al., 2012). Furthermore, recent advancements in technology further enhance the suitability of precast systems for high-rise construction (Naganathan et al., 2021).

Robotics technology in precast high-rise construction is recognised for enhancing efficiency, precision, and safety during various construction phases (Chea et al., 2020). Reichenbach and Kromoser (2021) highlighted by automating tasks such as formwork, reinforcement placement, and concreting, robotics reduces project durations while improving overall construction quality and precision. Similarly, robotics ensures the production of high-quality, error-free precast components, contributing to superior construction outcomes (Cai et al., 2018). Furthermore, robotics allows for the creation of more sophisticated and complex precast designs, surpassing traditional methods (Gharbia et al.,2019). Chea et al. (2020) stated that robots significantly increase productivity by reducing reliance on manual labour, particularly in assembling and erecting precast elements. Elsheikh et al. (2021) underlined the safety benefits, noting that robots minimise the need for workers to perform dangerous tasks, thus enhancing safety on high-rise construction sites. Additionally, robotics aids in tracking activities and quality control, allowing for timely problem identification and resolution (Cai et al., 2018). Precast construction is particularly well suited for robotics adoption because its modular, repetitive components and factory-controlled production environment align naturally with automation (Chea et al., 2020). These characteristics allow robots to perform standardised, repeatable tasks efficiently, maintain high precision, and produce complex geometries consistently, making precast systems ideal for robotic integration rather than merely beneficial for structural or timeline considerations. Despite these advantages, challenges such as high initial costs, the need for specialised technical skills, and integration with existing construction processes remain significant barriers to widespread adoption (Mahbub, 2008; Reichenbach & Kromoser, 2021). The adoption of robotics in precast high-rise construction offers developing countries a pathway to align

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with global sustainability practices by enhancing efficiency, reducing waste, and improving construction quality (Regona et al., 2024; Cai et al., 2018). Despite this potential, Sri Lanka's integration of robotic technology remains limited. Gunawardena et al. (2016) identified a lack of research and practical implementation strategies as key barriers, a situation compounded by insufficient studies on effective integration methods (Pan & Pan, 2016). Recent investigations have begun to address this gap: Gamlath et al. (2020) highlighted the underutilisation of robotics in Sri Lanka, noting a significant gap between current applications and international best practices. Jayasena et al. (2023) reported that local adoption remains largely restricted to basic mechanised operations such as automated batching, material handling, and simple lifting with advanced applications, including robotic assembly, 3D concrete printing, and automated quality inspection, still rare. These findings indicate that the Sri Lankan construction industry is in the early stages of technological maturity, despite the clear potential benefits demonstrated globally.

In contrast, countries such as Japan, Singapore, and South Korea have successfully integrated robotics into high-rise and large-scale construction projects, achieving measurable improvements in productivity and labour efficiency. For instance, Singapore's public housing sector plans to scale up robotics and automation explicitly to boost site productivity (Housing & Development Board, 2024). These outcomes illustrate the transformative potential of robotics when supported by targeted research, skilled labour development, and policy incentives. Sri Lanka's research gap, however, extends beyond the lack of studies; it also includes the absence of practical frameworks, pilot projects, and data-driven evaluations demonstrating measurable productivity and sustainability outcomes. Initial investigations by Perera and Lenora (2023) have begun to explore the viability of robotics in the local context, emphasising the need for advanced applications to elevate industry standards. Addressing these research and implementation gaps is critical to enable Sri Lanka to participate in the global transition toward more efficient, safe, and sustainable high-rise construction practices.

This study bridges this gap by investigating the enablers and barriers to integrating robotic technology in precast high-rise construction processes in Sri Lanka. This study aims to devise an implementation framework that outlines the integration of robotic technology into precast high-rise construction in the local context. The study will investigate the enablers of integrating robotic technology in the precast high-rise construction processes , assess the barriers to integrating robotic technology in the precast high-rise construction processes, examine the technical feasibility of introducing robotic technology into precast high-rise construction and propose effective strategies that can be employed to seamlessly integrate the robotic technology in the precast high-rise construction processes in the local context.

2. Literature Review

2.1 ROBOTICS IN CONSTRUCTION

Construction Robotics is considered a ground-breaking innovation in the construction industry, capturing the attention of academics, business leaders, and government entities (Lynch and Park, 2017). Cai et al. (2018) highlighted the range of construction robotics, from hand-operated mechanical systems to remote-controlled, semi-automated, and fully autonomous robots. As construction robots advance, it is expected to resolve critical issues related to labour shortages, worker safety, and health by replacing humans in physically demanding and dangerous tasks (Yahya, Lee Hui, et al., 2019). Gharbia et al. (2019) suggested that while the widespread use of robots in construction is not yet fully realised, conditions will improve significantly as resources and support are funnelled into advancing robotics technology. When robots can perform complex on-site tasks, the focus for the next generation will shift towards operating and managing these machines, potentially completing projects on time and within budget (Hack & Lauer, 2014).

2.2 ROBOTICS IN PRECAST HIGH-RISE CONSTRUCTION

High-rise construction presents a distinct set of challenges that differentiate it from low or mid-rise projects. Vertical material transport, repetitive assembly of structural components, safety risks associated with working at height, and complex logistics make high-rise construction inherently demanding (Hack & Lauer, 2014; Lu et al., 2021). These factors create a strong case for automation, as robotic technologies can efficiently address tasks that are repetitive, dangerous, or logistically constrained.

Precast construction is particularly suitable for high-rise buildings because it enables factory-controlled production, which ensures high precision, uniform quality, and consistency in structural components (Schneiderman, 2012; Fernández-Ordóñez et al., 2018). The modular and repetitive nature of precast elements allows for rapid on-site assembly, minimizing labour requirements and reducing construction timelines (Chew, 2017; Elliott & Jolly, 2013). This modularity also permits design flexibility, enabling adaptation to various building requirements while maintaining efficiency and quality (Gan et al., 2019). Recent technological advancements have further strengthened the applicability of precast construction in high-rise projects, particularly in meeting the high demands for structural performance, safety, and construction efficiency (Naganathan et al., 2021; Lu et al., 2021).

Integrating robotics into precast high-rise construction further enhances these benefits by automating fabrication, assembly, transportation, and installation processes (Cai et al., 2018; Chea et al., 2020). Robot-assisted additive manufacturing improves the accuracy, speed, and consistency of precast component production (Urhal et al., 2019). Robotics also enables the creation of complex concrete geometries that are difficult or inefficient to achieve manually (Heikkilä et al., 2015). In addition, robotic installation reduces on-site labour requirements, improves construction quality, and enhances safety by minimizing human exposure to high-risk tasks (Akhnoukh & Elia, 2023; Wei et al., 2022).

By addressing the specific demands of high-rise construction including repetition, vertical logistics, safety, and quality, robotics in combination with precast modularity represents a transformative approach. This integration not only improves construction efficiency and precision but also provides a pathway for the modernization and sustainability of high-rise projects, particularly in developing countries where labour shortages, skill constraints, and safety challenges are prevalent.

2.3 ENABLERS AND BARRIERS WHEN APPLYING ROBOTICS TO THE CONSTRUCTION SECTOR

There are several enablers and barriers associated with the application of robotic technology in precast high-rise construction. Figure 1 demonstrates those factors associated with the application of robotic technology in precast high-rise construction. The enablers and barriers influencing the adoption of robotics in construction can be categorized as enablers and barriers. Enablers include characteristics such as high repetitiveness and modularity of tasks, which promote robotization by standardizing processes. Key considerations like cost-effectiveness and technological feasibility further support adoption. However, significant barriers such as high initial investment costs and technical challenges hinder progress. On the positive side, robotics offers compelling driving forces, including improved productivity, enhanced quality, and safety benefits. Conversely, challenges such as union resistance and legal complexities act as restraining forces.

2.4 STRATEGIES TO ADOPT ROBOTICS FOR PRE-CAST HIGH-RISE CONSTRUCTION

According to Leng et al. (2023), the adoption of robotics within the construction industry remains limited. This reluctance to fully embrace automation contrasts with the growing call for modern technologies highlighted by Oke et al. (2017), who emphasised the necessity of adopting robotics and automation to meet the industry's increasing demands and improve overall performance. Castro-Lacouture et al. (2007) further elaborated on the potential advantages that robotics can offer construction firms, noting significant improvements in productivity, safety, and quality when robots are utilised for simple and complex tasks. Strategies that can be implemented to adopt robotics technology in precast high-rise construction are demonstrated in Figure 1. According to Figure 1, the adoption of robotics in precast high-rise construction requires a strategic approach that addresses user needs, financial concerns, and infrastructure investment, while fostering collaboration, pilot projects, and workforce development to ensure successful implementation and long-term benefits.

2.5 TECHNICAL FEASIBILITY OF THE USE OF ROBOTICS FOR PRE-CAST HIGH-RISE CONSTRUCTION

The technical feasibility of using robotics in precast high-rise construction depends on the alignment of robotic capabilities with the specific demands of the construction industry, particularly in precision and repetition, integration with advanced tools, improved safety and speed and production scalability (Seward and Zied, 2023). Various studies demonstrate that precast construction's structured and modular nature makes it a suitable domain for robotics adoption.

Robotic systems excel in performing repetitive and precise tasks, which are prevalent in precast high-rise construction (Cai et al., 2018). Processes such as cutting, welding, concreting, and assembly can be optimised using robotic technology. Heikkilä et al. (2015) emphasised that robotics ensures consistent quality in manufacturing processes, a critical factor for high-rise buildings where structural integrity and precision are paramount. The compatibility of robotics with advanced digital tools like Building Information Modeling (BIM) enhances its technical feasibility. BIM provides precise digital representations of precast components, which can be directly integrated into robotic programming for fabrication and assembly (Marzouk and Tayeh, 2021). According to Tang et al. (2022), robotics combined with BIM streamlines workflows by allowing seamless coordination between design, manufacturing, and on-site construction, reducing errors and rework. As prefabrication occurs in controlled environments, robotics can be scaled to meet high production demands without compromising quality (Yahya, Lee Hui, et al., 2019). According to Bao et al. (2023), robotic fabrication of precast modules significantly improves production rates while maintaining uniformity, a key advantage for high-rise projects requiring mass production of identical units.

2.6 WHY IS IT IMPORTANT TO INTEGRATE ROBOTIC TECHNOLOGY IN THE PRECAST HIGH-RISE CONSTRUCTION PROCESSES

The integration of robotics in precast high-rise construction offers significant advantages, including enhanced efficiency, safety, and precision, which contribute to better overall project outcomes (Gharbia et al., 2019). This trend aligns with the broader push for automation and technological advancements in the construction industry, aimed at addressing persistent challenges such as labour shortages, improving productivity, and enhancing safety measures (Cai et al., 2018). Robotics improves construction precision, reduces material waste, enhances working conditions, and supports sustainable construction practices (Moselhi & Hason, 2011). Furthermore, automation provides opportunities to establish new industry benchmarks for efficiency, safety, and sustainability in high-rise projects (Shi et al., 2023). Figure 1 summarizes the purposes of using robotics for precast high-rise construction.

While global research demonstrates these benefits, the application of robotics in Sri Lanka remains limited. Existing models of enablers and barriers, developed in other contexts, may not fully account for the unique economic, regulatory, and cultural factors influencing the local construction sector. Challenges such as limited technical expertise, high initial investment, labour dynamics, and regulatory constraints require context-specific investigation (Gunawardena et al., 2016; Gamlath et al., 2020). Therefore, bridging this gap is essential: it allows identification of locally relevant strategies and practical frameworks for effective robotics integration in Sri Lankan precast high-rise construction, rather than relying solely on generic global models.

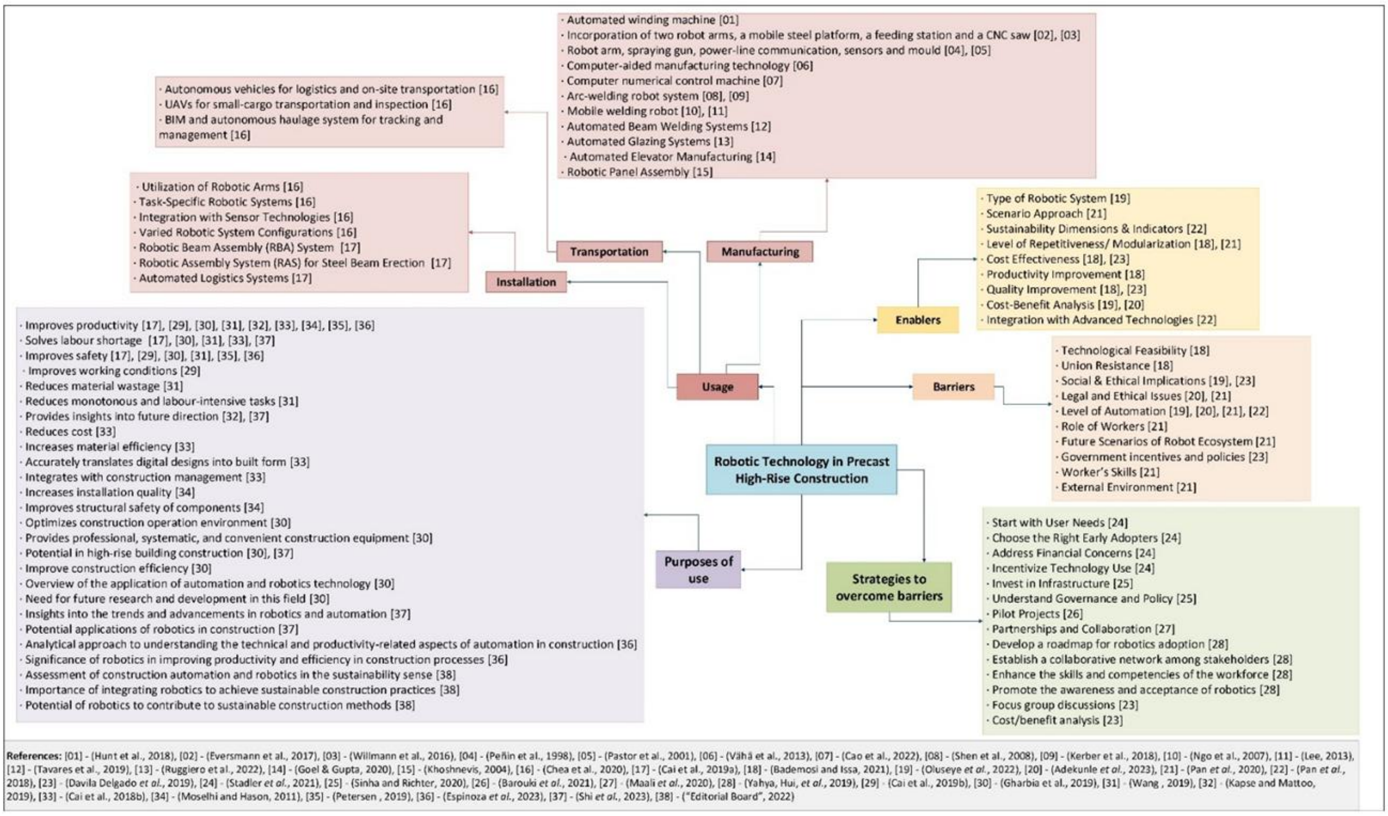

Figure 1, Summary of literature findings

3. Methodology

The research philosophy serves as the lens through which a researcher interprets reality, generates knowledge, and utilizes theory to support the methodology (Mauthner, 2020). The choice of research philosophy depends on the nature of knowledge the researcher aims to obtain through the study (Gannon et al., 2022). In management research, among the four primary philosophies, interpretive approach emphasizes understanding human differences as social actors, distinguishing research involving people from that involving non-human objects (Saunders et al., 2019). As the initial step in this study, a literature review was conducted to explore the adaptability of robotic technology in precast high-rise construction, focusing on both global and Sri Lankan contexts. Given the limited research on this topic in Sri Lanka, it is crucial to capture the diverse perspectives of experts within the Sri Lankan construction sector. Aligning with Ludlow's (2016) argument that technological choices seek to balance social, environmental, and financial goals, an interpretivist approach enables a nuanced understanding of how stakeholders perceive and prioritize these values in the Sri Lankan context. This perspective assumes reality is socially constructed (ontology) and that knowledge is derived from individuals' perspectives (epistemology), while acknowledging the researcher's contribution to shaping insights (axiology) (Saunders et al., 2019).
Methodological choices generally encompass three main approaches: qualitative, quantitative, and mixed methods (Abdelhakim & Badr, 2021). A qualitative approach was adopted to capture the complex and context-specific nature of integrating robotics into precast high-rise construction. Qualitative research allows rich insights from industry experts and is particularly suitable for exploring the meaning, implications, and interrelationships of local factors (Chih-Pei & Chang, 2017; Abdelhakim & Badr, 2021).

The Delphi method, combined with semi-structured interviews, was selected because it is particularly effective for emerging topics requiring expert consensus (Brady & O'Connor, 2014). While a three-round Delphi is typical, single, and two round Delphi studies have also been completed (Ameyaw et al., 2016). This study involved two rounds of the Delphi process, as two rounds are necessary to reach a solid conclusion (Xia & Chan, 2012). Among studies that specified a consensus threshold, the median value was 75% (range: 50–97%) (Diamond, 2014). Following this precedent, the present study adopted a 75% agreement rate to identify factors considered statistically significant and most critical to the research objectives. Feedback was collected at the start of each round to refine responses and ensure accuracy. An interpretivist approach was used to prioritise expert insights and contextual understanding, allowing qualitative feedback to inform the coding process. Themes were selected based on frequency of occurrence and validation by participants, ensuring relevance and consistency in the final framework. A value-driven approach underpins the research, aligning with its interpretivist stance. The study is guided by values such as enhancing safety, improving national construction productivity, and supporting sustainable high-rise construction. These values shaped the research design, including the selection of aims, the choice of semi-structured interviews, and the criteria for selecting 16 highly experienced experts. Sampling used heterogeneous purposive techniques to ensure participants could provide detailed and contextually relevant insights (Ernawati et al., 2022; Klar & Leeper, 2019). This approach not only enhances the depth of findings but also offers flexibility in generalizing results despite a relatively small sample size, while minimizing sample randomness (Sharma, 2017). The selection process involved filtering respondents based on both mandatory and additional qualifications specified in Table 1. To ensure the richness of data (Ames et al., 2019), the chosen sample consisted of individuals with a minimum of 10 years in the construction industry, 5 years of experience in robotic technologies, and 5 years in precast high-rise construction. Additionally, they needed at least three (03) qualifications, such as a bachelor's degree in the built environment, post-graduate qualifications in the built environment/Information Technology, professional qualifications in the built environment, or a having indexed publications relating to robotic technology.

Data collection involved semi-structured interviews to allow flexibility and adapt to the expertise of the respondents. The interviews, lasting 60–80 minutes each, were conducted both online and face-to-face, considering practical constraints. Feedback was incorporated between rounds to refine the findings. Manual content analysis, was employed to identify patterns and themes in the qualitative data, ensuring both depth and focus (Ridder, 2014; Connelly, 2016).

Table 1, Details of Delphi rounds and profile of Delphi experts

Delphi Round	Focus of the Round	Delphi Round Phase	Objective of Phase
Round I	Robotic technology in the precast high-rise construction processes	R1/P1	Identify the enablers and barriers of integrating robotic technology in the precast high-rise construction processes
		R1/P2	Identify the technical feasibility of introducing robotic technology into precast high-rise construction processes
		R1/P3	Identify effective strategies that can be employed to seamlessly integrate the robotic technology in the precast high-rise construction processes
Round II	Robotic technology in the precast high-rise construction processes in Sri Lanka	R2/P1	Investigate the enablers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka
		R2/P2	Assess the barriers to integrating robotic technology in the precast high-rise construction processes in Sri Lanka
		R2/P3	Examine the technical feasibility of introducing robotic technology into precast high-rise construction in Sri Lanka
		R2/P4	Propose effective strategies that can be employed to seamlessly integrate the robotic technology in the precast high-rise construction processes in Sri Lanka

Code	Designation	Years of Experience							Participation in Delphi rounds	
		Compulsory Qualification			Additional Qualifications (Expert must satisfy at least two qualifications)				R1	R2
		Experiences in construction industry > 10 years	Experiences in robotic technology > 5 years	Experiences in precast high-rise construction > 5 years	Bachelor's degree in built environment	Post-graduate qualifications in the built environment/Information Technology	Professional qualifications in the built environment	Having indexed publications relating to robotic technology		
IE1	Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓	✓	✓
IE2	Project Manager	✓	✓	✓	✓	✓	✓	-	✓	✓
IE3	MEP Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
IE4	Civil Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
IE5	Contract Manager	✓	✓	✓	✓	✓	✓	-	✓	✓
IE6	Construction Manager	✓	✓	✓	✓	✓	✓	-	✓	✓
IE7	Project Manager	✓	✓	✓	✓	✓	✓	-	✓	✓
IE8	Chief Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
IE9	Quantity Surveyor	✓	✓	✓	✓	✓	✓	-	✓	✓
IE10	Civil Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
IE11	Project Manager	✓	✓	✓	✓	✓	✓	-	✓	✓
IE12	Site Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
IE13	Chief Engineer	✓	✓	✓	✓	✓	✓	✓	✓	✓
IE14	Site Manager	✓	✓	✓	✓	-	✓	✓	✓	✓

IE15	Chief Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
IE16	Structural Engineer	✓	✓	✓	✓	✓	✓	-	✓	✓
	Total								**16**	**16**

4. Findings and analysis

The study's findings are presented under four (04) sub-sections: enablers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka, barriers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka, technical feasibility of introducing robotic technology into precast high-rise construction in Sri Lanka and effective strategies that can be employed to seamlessly integrate the robotic technology in the precast high-rise construction processes in Sri Lanka.

4.1 ENABLERS IDENTIFIED IN THE LOCAL CONTEXT

This section presents the findings from Round I Phase 01, and Round II Phase 01 of the study. Initially, a literature review identified nine (09) enablers associated with the application of robotic technology in precast high-rise construction, as illustrated in Figure 1. During the expert interviews conducted in Round I, Phase 01, the experts were asked to identify enablers associated with the application of robotic technology in precast high-rise construction. Experts agreed to all nine (09) enablers identified through literature and a further eleven (11) enablers were identified as enablers to the integration of robotic technology in precast high-rise construction. As a result, a total of twenty (20) enablers were identified as enablers to the local context by the conclusion of Round I Phase 01. Feedback gathered at the start of Round I Phase 01 involved summarizing the literature findings and providing participants with clear definitions and explanations of each enabler to ensure a shared understanding.

In Round II Phase 01, experts were asked to identify enablers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka. In there, two (02) enablers were omitted due to insufficient responses from experts, not meeting the 75% response cut-off. Following Delphi Round II Phase 01, eighteen (18) significant enablers were identified as enablers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka, as demonstrated in the 'bold' text in Table 2.

Table 2, Enablers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka

Enablers	Findings from the Literature	Round I Findings	Round II Findings (Agreement more than 75%)
Type of Robotic System	✓	✓	✓
Sustainability dimensions & indicators	✓	✓	✓
Level of Repetitiveness/ Modularization	✓	✓	✓
Cost-effectiveness	✓	✓	✓
Productivity improvement	✓	✓	✓
Quality improvement	✓	✓	✓
Integration with Advanced Technologies	✓	✓	✓
Scenario approach	✓	✓	
Cost-benefit analysis	✓	✓	
International collaboration		✓	✓
Education and Training		✓	✓
Improved Regulations and Standards		✓	✓
Government incentives		✓	✓
Awareness of Long-term Benefits		✓	✓
Improved safety		✓	✓
Higher efficiency		✓	✓
New job opportunities		✓	✓
Research and Development		✓	✓
Public-private partnerships		✓	✓
Industry-academia partnerships		✓	✓

According to IE10, by integrating robotics, construction processes achieve increased productivity, reduced costs, enhanced time efficiency, and advanced technical precision, distinguishing them from traditional methods. Furthermore, IE2 emphasized several successful international cases of the transformative potential of robotics in construction including

Huoshenshan Hospital in China, Elysian Tower in Cork and Sky Habitat in Singapore. The adoption of robotics can enhance efficiency and productivity by automating repetitive tasks and streamlining construction processes. As Interviewee IE6 emphasized, "Production lines should be instituted. Speed and efficiency should also increase." Robotic technology ensures high-quality construction with minimal errors. As Interviewee IEI4 observed, robotics contributes to "time utilization and quality work," while Interviewee IE12 noted that robotics provides "the highest possible precision in construction tasks," thereby reducing mistakes and labour costs. Safety remains a critical concern in construction. Robotics can mitigate risks by taking over hazardous tasks and reducing exposure to dangerous conditions. Interviewee IE8 highlighted the role of robotics in "preventing hazards or accidents," a sentiment supported by Interviewee IE12, who emphasized the importance of "robust safety protocols and continuous training for safe operations."

4.2 BARRIERS IDENTIFIED IN THE LOCAL CONTEXT

This section presents the findings from Round I Phase 02 and Round II Phase 02 of the study. Initially, a literature review identified ten (10) barriers associated with the application of robotic technology in precast high-rise construction, as illustrated in Figure 1. During the expert interviews conducted in Round I, Phase 01, the experts were asked to identify barriers associated with the application of robotic technology in precast high-rise construction. Experts agreed to all ten (10) barriers identified through literature and a further thirteen (13) barriers were identified as barriers to the integration of robotic technology in precast high-rise construction. As a result, a total of twenty-three (23) barriers were identified as barriers to the integration of robotic technology in precast high-rise construction by the conclusion of Round I Phase 01.

In Round II, Phase 01, experts were further asked to identify barriers specific to integrating robotic technology into precast high-rise construction processes in Sri Lanka. Three (03) barriers were excluded due to insufficient expert responses, as they did not meet the 75% consensus cut-off. Consequently, after Delphi Round II, Phase 01, a final set of twenty-eight (28) significant barriers was confirmed for the local context, as demonstrated in the 'bold' text in Table 3.

Table 3, Barriers of integrating robotic technology in the precast high-rise construction processes in Sri Lanka

Barriers	**Findings from the Literature**	**Round I Findings**	**Round II Findings (Agreement more than 75%)**
Technological feasibility	✓	✓	✓
Union resistance	✓	✓	✓
Social & ethical implications	✓	✓	✓
Legal and Ethical Issues	✓	✓	✓
Level of Automation	✓	✓	✓
Role of workers	✓	✓	✓
Future Scenarios of robot ecosystem	✓	✓	✓
Government incentives and policies	✓	✓	✓
External environment	✓	✓	✓
Concerns on monopoly markets		✓	✓
Resistance to change		✓	✓
Unemployment concerns		✓	✓
Lack of technological readiness		✓	✓
High financial cost of adoption		✓	✓
Skills and expertise gap		✓	✓
Absence of formal regulations		✓	✓
Payload requirements		✓	✓
Lack of Cultural and industry awareness		✓	✓
Maintenance and Repair Concerns		✓	✓
Regulatory uncertainty		✓	✓
Infrastructure deficiencies		✓	
Transportation issues		✓	
Infrastructure and vendor availability		✓	

According to Table 2, the implementation of robotics in Sri Lanka's precast high-rise construction processes faces several barriers. As noted by IE10, the lack of advanced technologies and infrastructure is a significant impediment. Additionally, union resistance poses a challenge, with concerns about job losses due to automation. IE8 expressed that unions resist change, fearing that automation could displace workers. Social and ethical implications also present barriers, with IE2 and IE12 highlighting the ethical risks associated with potential job losses and the societal impact of robotics. Legal and regulatory issues further complicate the adoption of robotics, as unclear legal frameworks around liability and intellectual property discourage implementation, a point echoed by IE5. High initial costs were another frequently cited barrier, as most interviewees pointed out that despite long-term savings, upfront expenses are often prohibitive for many companies. Lastly, the shortage of skilled workers was identified as a key barrier, with IE1 noting that the lack of trained technicians and engineers to operate and maintain robotic systems must be addressed through targeted training programs.

4.3 TECHNICAL FEASIBILITY OF INTRODUCING ROBOTIC TECHNOLOGY INTO PRECAST HIGH-RISE CONSTRUCTION IN SRI LANKA

This section presents the findings from Round I Phase 02 and Round II Phase 03 of the study. Initially, a literature review identified four (04) criteria, including precision and repetition, integration with advanced tools, improved safety and speed and production scalability, which are associated with assessing the technical feasibility of introducing robotic technology into precast high-rise construction. During the expert interviews conducted in Round I, Phase 02, the experts were asked to identify the technical feasibility of introducing robotic technology into precast high-rise construction, along with the identified criteria. Then, in Round II Phase 03, the experts were asked to examine the technical feasibility of introducing robotic technology into precast high-rise construction in Sri Lanka.

Similar to global applications, robotic technology can significantly enhance the precision and quality of precast components in Sri Lanka. Its ability to minimize human error in repetitive tasks, such as cutting and assembling precast elements, remains relevant. However, according to IE8, the limited availability of advanced robotic machinery in the local market necessitates partnerships with international vendors to achieve globally comparable precision. Reliability and robustness are critical, as robotic systems need to endure prolonged operations under challenging conditions without frequent maintenance. Experts unanimously emphasized the synergy between robotics and BIM, which optimizes workflows by enabling data-driven design and manufacturing processes. According to IE7, robotics integrated with BIM enhances efficiency, reduces errors, and streamlines the production and assembly of precast components. IE1 pointed out that BIM adoption in Sri Lanka is still emerging, with low penetration rates in the construction sector. For robotics to achieve its full potential, Sri Lanka must further develop its ecosystem for digital design and data sharing. This lack of readiness limits the seamless integration of robotics into existing workflows. IE8 elaborated that, robotic systems, such as automated cranes and robotic arms, minimize human involvement in hazardous tasks, thereby improving safety on construction sites.

According to IE9, in Sri Lanka, evolving safety standards make robotics a promising solution for addressing existing safety gaps. However, challenges such as limited local expertise in robotic maintenance and troubleshooting may hinder immediate safety improvements. Safety concerns also extend to human-robot collaboration. IE3 emphasized the importance of stringent safety measures to ensure smooth interactions between human workers and robots. The complexity of robotics, including calibration, programming, and maintenance, further requires skilled labour to avoid system failure, as stated by IE14. Moreover, unpredictable construction site conditions, such as varying terrains and weather, complicate the application of robotics, as noted by IE6. Robotics offers scalability in manufacturing, especially for high-rise projects that require the mass production of identical precast modules. As stated by IE8, controlled environments, such as centralized precast factories, enable robotic fabrication to improve both quality and production speed. Sri Lanka's urbanization demands make this scalability particularly relevant. However, as noted by IE9, establishing robotic facilities involves high initial investments, posing a significant challenge for local contractors and developers. Addressing this financial barrier will require policy support, public-private partnerships, or external funding.

4.4 EFFECTIVE STRATEGIES THAT CAN BE EMPLOYED TO SEAMLESSLY INTEGRATE THE ROBOTIC TECHNOLOGY IN THE PRECAST HIGH-RISE CONSTRUCTION PROCESSES IN SRI LANKA

The findings from Round I Phase 03 and Round II Phase 04 are presented in this section. At the end of the literature review, fourteen (14) were identified as strategies that can be employed to integrate robotic technology in the precast high-rise construction processes, as demonstrated in Table 4. Subsequently, through expert interviews in Round I Phase 03, fourteen (14) strategies were universally accepted from the literature, while seventeen (17) strategies were newly identified as strategies that can be employed to integrate robotic technology in the precast high-rise construction processes. In Round II Phase 04, three (03) strategies were omitted due to insufficient responses from Experts, not meeting the 75% response cut-off. Following Delphi Round II Phase 04, twenty-eight (28) significant strategies were identified as effective strategies that can be employed to seamlessly integrate the robotic technology in the precast high-rise construction processes in Sri Lanka, as demonstrated in the 'bold' text in Table 4.

Table 4, Strategies to seamlessly integrate robotic technology in the precast high-rise construction processes in Sri Lanka

Strategy	Findings from the Literature	Round I Findings	Round II Findings (Agreement more than 75%)
Start with User Needs	✓	✓	✓
Choose the Right Early Adopters	✓	✓	✓

Strategy	Findings from the Literature	Round I Findings	Round II Findings (Agreement more than 75%)
Address Financial Concerns	✓	✓	✓
Incentivize Technology Use	✓	✓	✓
Invest in Infrastructure	✓	✓	✓
Understand Governance and Policy	✓	✓	✓
Pilot Projects	✓	✓	✓
Partnerships and Collaboration	✓	✓	✓
Develop a roadmap for robotics adoption	✓	✓	✓
Establish a collaborative network among stakeholders	✓	✓	✓
Enhance the skills and competencies of the workforce	✓	✓	✓
Promote the awareness and acceptance of robotics	✓	✓	✓
Focus group discussions	✓	✓	✓
Cost/benefit analysis	✓	✓	✓
Early Planning in Design Phase		✓	✓
Cross-disciplinary or Interdisciplinary Collaboration		✓	✓
Training and Skill Development		✓	✓
Quality Control Measures		✓	✓
Research and Case Studies		✓	✓
Safety Focus		✓	✓
Simulation and Virtual Testing		✓	✓
Identifying Repetitive Tasks		✓	✓
Small Scale Pilot Projects		✓	✓
Government Incentives and Policies		✓	✓
Promotions and Awareness		✓	✓
Flexibility and Customization		✓	✓
Integration of 3D Modelling		✓	✓
Consideration of Sustainability Aspects		✓	✓
Precision Fabrication		✓	
Logistic and On-site Assembly Challenges		✓	
Risk Management and Regulatory Compliance		✓	

To effectively integrate robotic technology into precast high-rise construction processes in Sri Lanka, a multi-faceted approach is essential. Starting with pilot projects emerges as a practical strategy, allowing stakeholders to test scaled-down implementations and identify both enablers and barriers to adoption. As highlighted by experts, early planning during the design phase is foundational for ensuring seamless integration, while cross-disciplinary collaboration between engineers, architects, and technology providers enhances feasibility and cost-effectiveness. According to IE6, training and upskilling the workforce are crucial to bridging the knowledge gap, addressing resistance, and equipping employees to adapt to new technologies. Moreover, IE4 and IE11 highlighted that government incentives, such as tax benefits and funding schemes, along with streamlined regulatory frameworks, are vital for mitigating financial constraints and encouraging investment. According to IE15, raising awareness through targeted campaigns and leveraging virtual testing and simulations further aids in overcoming resistance and ensuring technological readiness. Collectively, these strategies address key challenges, including high initial costs, lack of expertise, and regulatory uncertainties, positioning Sri Lanka for the successful adoption of robotics in the precast high-rise construction processes.

4.5 FRAMEWORK TO INTEGRATE ROBOTIC TECHNOLOGY IN THE PRECAST HIGH-RISE CONSTRUCTION PROCESSES IN SRI LANKA

Based on the findings, finally a framework was developed to integrate robotic technology in the precast high-rise construction processes in Sri Lanka, as demonstrated in Figure 2.

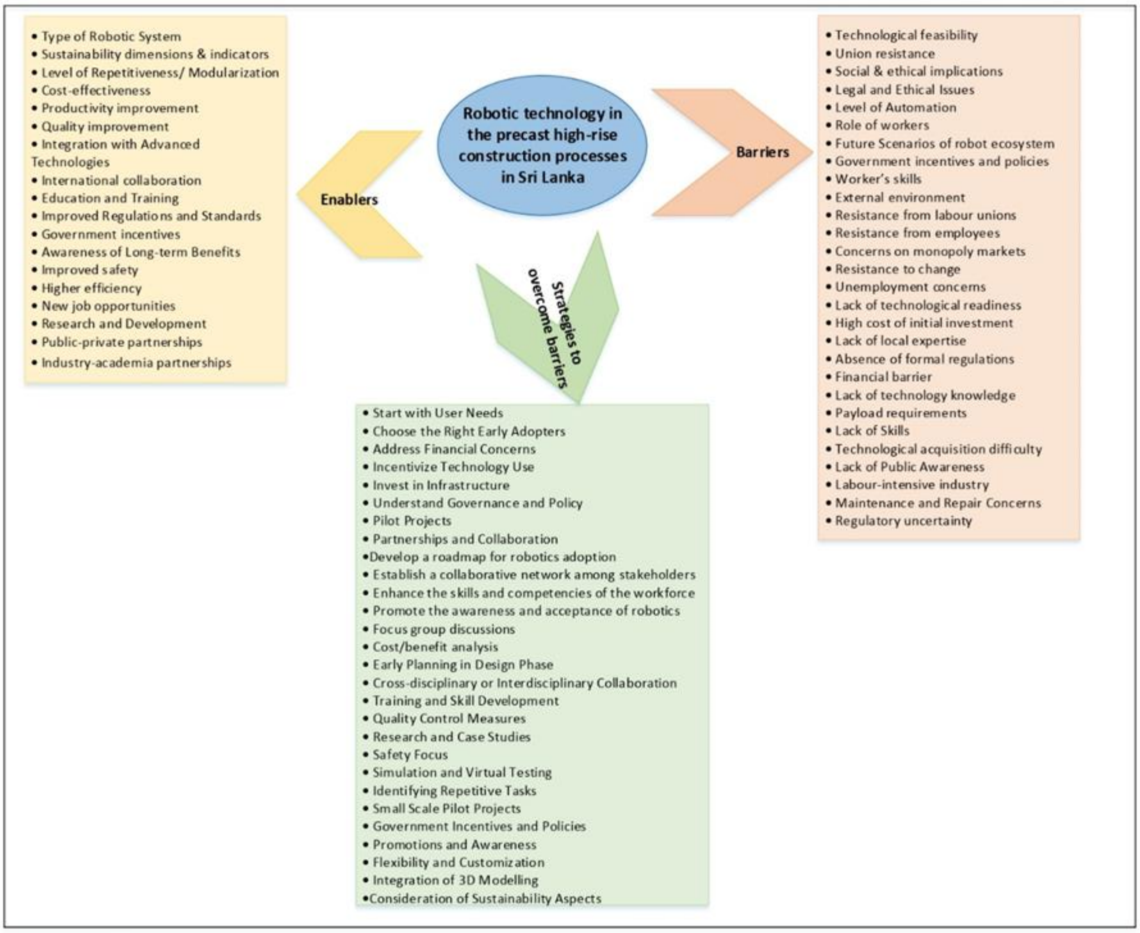

Figure 2, Framework to Integrate Robotic Technology in The Precast High-Rise Construction Processes in Sri Lanka

5. Discussion

The integration of robotic technology into precast high-rise construction offers significant potential, particularly in addressing the unique challenges faced by the construction industry in Sri Lanka. This study has identified and analysed enablers, barriers, technical feasibility, and strategies for implementing robotic technology within this context.

The identified enablers highlight a range of enablers that align with global advancements, including improved productivity, enhanced quality, and safety benefits. These enablers reflect the potential of robotics to address critical industry needs, such as reducing labour dependency, mitigating safety risks, and achieving higher precision in construction processes. This aligns with the findings of Cai et al. (2018), that repetitive processes in precast construction are ideal for robotic applications due to their structured nature, which enhances precision and productivity. Furthermore, advancements in robot-assisted additive manufacturing and prefabrication, as noted by Urhal et al. (2019), have demonstrated significant potential to streamline production workflows. Sri Lanka's growing interest in sustainable and innovative construction practices also supports the adoption of robotics.

Despite the promising enablers, significant barriers impede the adoption of robotics in precast high-rise construction in Sri Lanka. High initial costs and the need for specialised technical expertise remain critical challenges. As Mahbub (2008) noted, the capital-intensive nature of robotic systems often discourages investment in developing countries, where financial resources are limited. Moreover, the lack of technical expertise to operate and maintain robotics systems further exacerbates the issue, as highlighted by experts as well as by Pan and Pan (2016). Cultural resistance to change and union opposition are also notable barriers highlighted by many experts. According to Yahya, Lee Hui, et al. (2019), the integration of robotics often faces pushback from traditional labour markets due to fears of job displacement. This dynamic is particularly relevant in Sri Lanka, where the construction industry relies heavily on manual labour.

The integration of robotics into precast high-rise construction has shown substantial potential globally, particularly in improving precision, safety, and scalability. Studies such as Heikkilä et al. (2015) highlighted the ability of robotic systems to produce precast components with high accuracy and consistency in controlled environments, significantly reducing human errors. This aligns with findings from experts, who emphasized that similar benefits are achievable in Sri Lanka, though the country faces unique challenges due to limited access to advanced robotic machinery and skilled labour for system operation and maintenance. Globally, the synergy between robotics and digital tools like BIM has demonstrated significant efficiency gains in workflow optimization and error reduction during production (Bao et al., 2023). However, in

Sri Lanka, BIM adoption remains at an emerging stage, as noted by experts, indicating a need for a stronger digital ecosystem to fully leverage robotic technology. Safety is another critical dimension of feasibility. Robotic systems have proven to enhance safety on construction sites by automating hazardous tasks, as shown in global case studies (Mahbub, 2008). While these benefits are applicable to Sri Lanka, the country's evolving safety standards and limited expertise in maintaining robotic systems present barriers to immediate adoption. Scalability remains both a promise and a challenge. Centralized robotic precast factories could address Sri Lanka's urbanization-driven demand for mass customization, but the high initial investment required for such facilities, as noted by experts and supported by Pan et al. (2020) remains a major obstacle. Addressing this challenge will require strategic partnerships and policy interventions.

Effective strategies to integrate robotics into precast high-rise construction include fostering public-private partnerships, piloting robotics projects, and investing in workforce development. Experts emphasized that collaboration between industry stakeholders is essential for overcoming financial and logistical challenges. Similarly, Leng et al. (2023) advocated for pilot projects to demonstrate the practical benefits of robotics, which can help build stakeholder confidence and drive wider adoption. Workforce training is also a crucial strategy highlighted by many experts. As noted by Hack and Lauer (2014), equipping workers with the skills to operate and manage robotic systems is a critical step toward successful implementation. In Sri Lanka, such initiatives could be supported through academic and industry collaborations, ensuring a steady supply of skilled professionals to meet the demands of a technologically advanced construction sector.

6. Conclusions and recommendations

The study on the adaptability of robotic technology in precast high-rise construction within the Sri Lankan context provides significant insights The findings reveal that while the technical feasibility of robotics is clear-supported by the modularity and repetitiveness of precast systems-adoption remains constrained by locally specific barriers such as high initial investment costs, limited technical expertise, and resistance to technological change, while enhancing precision and productivity in construction processes. Key enablers identified include the modularity and repetitiveness of precast systems, potential cost-effectiveness, and the technological feasibility of robotics integration. Nevertheless, to implement this technology effectively, a comprehensive approach that includes strategies for skill development, financial planning, and policy support is required. The technical feasibility of robotics in the Sri Lankan context is evident, but full-scale implementation demands overcoming infrastructural, financial, and cultural barriers. If addressed, robotic technology can significantly elevate construction standards, making the industry more competitive globally while meeting local demands for quality and efficiency. To integrate robotics into Sri Lanka's precast high-rise construction, collaboration between the government and industry is essential to establish supportive policies and financial incentives. Awareness campaigns should highlight the long-term benefits of robotics, while educational initiatives must address skill gaps by training professionals. Pilot projects can demonstrate feasibility and partnerships with global tech providers can aid technology transfer. Continuous research and development will ensure robotic solutions are adapted to local needs, enhancing construction efficiency, safety, and sustainability. Collectively, final framework provides a structured pathway for integrating robotics into Sri Lanka's precast high-rise construction sector enhancing competitiveness globally while meeting local demands. By prioritizing these locally relevant factors, the framework provides a structured, context-specific pathway for adoption, enabling improved construction standards, greater competitiveness, and alignment between technological adoption and local industry needs.

6.1 IMPACT ON THE INDUSTRY AND RESEARCH

The findings of this study have significant implications for both the construction industry and academic research, particularly in the context of developing countries. Practically, the integration of robotic technology in precast high-rise construction offers a sustainable pathway to address critical industry challenges, such as labour shortages, inefficiencies, and quality control. In developing countries, where the adoption of advanced technologies often lags due to financial, technical, and institutional constraints, this study provides a blueprint for overcoming barriers and highlights the feasibility of leveraging robotic technology in precast construction processes. Encouraging the adoption of such innovations in high-rise construction can drive the modernization of the industry, making it more competitive while aligning with the Sustainable Development Goals.

From a research perspective, this study contributes to the emerging discourse on construction automation by addressing a critical gap in understanding the contextual challenges and enablers specific to developing economies. By focusing on Sri Lanka, the research underscores the need for localized strategies that consider economic feasibility, workforce dynamics, and technical readiness, providing a model for other developing nations to follow. It also lays the groundwork for future research on scaling robotic technology in resource-constrained environments, bridging the gap between theory and practical application. Nonetheless, the findings are based on a limited sample of experts and Delphi rounds, which may affect generalizability. Further empirical studies are needed to validate the proposed framework in real-world construction settings. By highlighting the potential of robotic integration to transform high-rise precast construction, this study inspires policymakers, industry practitioners, and researchers to collaboratively drive technological adoption, ensuring long-term sustainability and growth in developing construction sectors.

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