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IMPLICATIONS OF CONSTRUCTION ROBOTS FOR ON-SITE LEAN CONSTRUCTION: AN IN-DEPTH CASE STUDY

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ABSTRACT

The construction sector plays a crucial role in the global economy. At the same time, it is constantly facing enormous economic, social, and environmental challenges. Lean construction practices, ever since their emergence, have continued to bring many benefits to the construction industry. Studies showed that construction robots as an emerging technology have the potential to improve lean construction particularly around off-site construction, but the implications of robots for on-site lean construction have been rarely discussed. Therefore, this study aims to evaluate the implications of single-task construction robots for on-site lean construction on the micro, meso, and macro levels based on an in-depth case study in Singapore. The results show that construction robots can provide many lean construction-related positive implications for on-site lean construction in economic, social, and environmental aspects, indicating that construction robots together with their compatible operating environment and optimized work processes can be a meaningful and powerful tool for on-site lean construction practices. Furthermore, this study provides the first empirical evidence of the benefits of adopting construction robots in Singapore's construction industry. Various key stakeholders in the construction industry can benefit from the analysis framework in this study at various levels when implementing on-site construction robots.

KEYWORDS

Construction robotics, lean construction, on-site construction, plastering, Singapore.

INTRODUCTION

The construction industry plays a crucial role in the global economy. The industry is not only a major employer in society which contributes significantly to the global GDP growth, but also responsible for the maintenance of essential and critical infrastructures such as the built environment, energy, water and communication networks. At the same time, the construction industry is constantly under enormous economic, social and environmental pressure. Economically, the sector records lower rate of productivity gain than any other industries and has one of the lowest degrees of digitization and is characterized by long planning and

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implementation phases, which have a negative impact especially in today's high inflationary environments (McKinsey Global Institute, 2017). Socially, it suffers from a ubiquitous shortage of skilled workers which is particularly aggravated by difficult and dangerous work conditions as well as population aging (Tender et al., 2022). Environmentally, it is seen as the most resource-intensive industry and thus plays a crucial role in fighting climate change and achieving a circular economy (Benachio et al., 2020).

In recent years, lean construction has been widely implemented to address these challenges. It is generally believed that the term "*lean construction*" was coined by the International Group for Lean Construction (IGLC) in 1993 to describe the methods of planning and executing construction tasks that reduces waste in materials, time, and effort, while maximizing cost-efficiency (Aziz & Hafez, 2013). Lean Construction Institute (LCI), an organization formed in 1997 to develop and disseminate knowledge of lean construction, further defined lean construction as "*a project delivery process that uses lean methods of maximizing stakeholder value while reducing waste by emphasizing collaboration between teams on a project*" (Lean Construction Institute, 2024). It can be therefore argued that lean construction is defined more by the results it achieves, rather than by its own unique characteristics or methods it uses, as long as it can increase stakeholder value and reduce waste, while promoting collaboration between teams. Lean construction practices, ever since their advent, have continued to bring numerous benefits to the construction industry economically, socially and environmentally. Over the years, many tools have been developed and successfully applied to lean construction such as 5S, Big Rooms, Kanban, Andon, Poka-Yoke, Heijunka, Last Planner System (LPS), Building Information Modelling (BIM) (Singh & Kumar, 2020).

Meanwhile, since its emergence in the late 1970s in Japan, construction robots started to address key issues facing the construction industry by improving working conditions, safety, productivity, and quality (Bock, 2015). In the recent decade, there has been a boom in the demand for construction robots largely due to initiatives of governments such as Hong Kong and Singapore that promote the adoption of emerging technologies in the construction sector (Ang et al., 2024). Researchers have reported the implications of robotic construction compared to manual work. For example, Brosque at al. (2021) introduced the key aspects and procedures of a framework for comparing robotic and conventional construction methods based on a concrete drilling robot. In a more comprehensive follow-up study, the safety, quality, time, and cost impacts of 10 more construction robots around the globe were further analyzed compared to conventional methods (Brosque & Fischer, 2022). In the perspective of lean construction, however, the implications of construction robots need to be further discussed.

Studies showed that automation and robotics has the potential to improve lean construction particularly around off-site prefabricated construction (Brissi et al., 2022; Cardenas et al., 2024; Du et al., 2023; Feldmann, 2022; Pan et al., 2020). However, there are few studies on the implications of robotics for on-site lean construction, and in-depth case studies are also scarce. Therefore, it is important to evaluate whether and how robotic technology can be a method for on-site lean construction through an in-depth case study of its implications.

As a highly developed city state, Singapore boasts a thriving economy and serves as a key financial center and innovation hub in Southeast Asia, linking the East and the West. Its construction sector is one of the most important sectors, employing more than 450,000 workers. Similar to many other countries, Singapore's construction industry is plagued by a series of problems, including but not limited to productivity decline, construction waste, safety concerns, and labor shortages in Singapore (Dulaimi et al., 2004; Gan & Koh, 2021; Yin et al., 2018). The COVID-19 pandemic has further exacerbated these problems (Gan & Koh, 2021).

In this context, Singapore's government agencies have launched a series of incentives to support local and global innovation in the construction sector. For example, the Building and Construction Authority (BCA) provides several funding opportunities to the construction industry such as Productivity Innovation Project for all enterprises (BCA, 2024c), and Productivity Solutions Grant for small and medium-sized enterprises (SMEs) to adopt emerging technologies (BCA, 2024d). Meanwhile, since all construction projects in Singapore are required to meet minimum Constructability Score (C-Score) during the construction stage, BCA will grant bonus C-Scores to contractors who adopt robotic solutions for construction (BCA, 2024a). Furthermore, BCA and JTC Corporation co-led the Robotics and Automation Implementation Committee (RAIC) to further drive adoption of robotics and automation in public projects (BCA, 2023). In addition, the Housing & Development Board (HDB) has announced to scale up the use of robotics and automation at construction sites to increase productivity (HDB, 2024). On the other hand, the Ministry of National Development (MND) led the multi-agency effort to initiate the Cities of Tomorrow (CoT) R&D programme for academia and industry to promote research and development in topics including robotics and automation (MND, 2023). These government initiatives provide critical support for the construction robot applications to thrive in Singapore in recent years. At the same time, lean construction has gained significant attention in Singapore in recent years. BCA not only promotes Integrated Digital Delivery (IDD) as a tool to achieve lean construction (BCA, 2024b) but also offers industry professionals a specialist diploma in lean construction through its education and training arm, BCA Academy (BCA Academy, 2023). As a result, Singapore has become an ideal location for studying the intersection of construction robotics and on-site lean construction.

METHODS

In this study, first, an overview of potential implications of lean construction practices is summarized through a literature review. Furthermore, an in-depth case study of a novel construction process using a construction robot in Singapore is conducted and the benefits and over conventional construction techniques on micro, meso, and macro levels are analyzed.

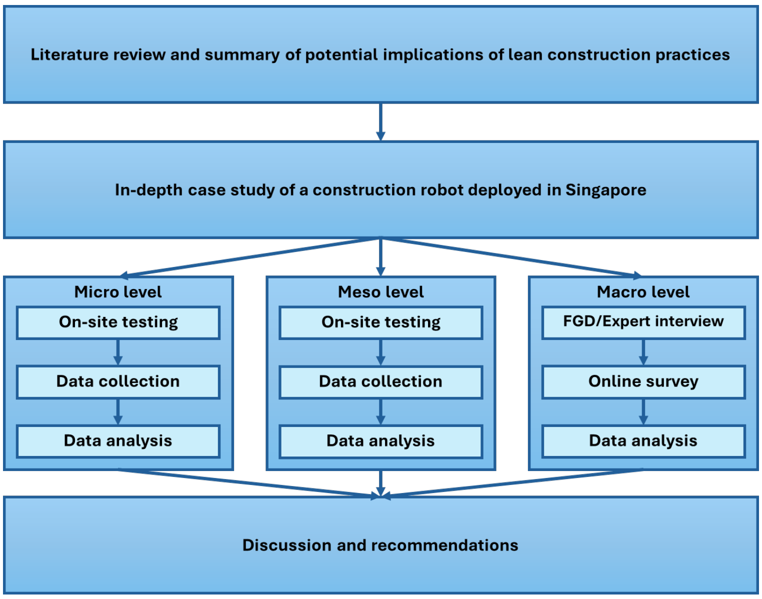

Figure 1: Methodology of the case study

LITERATURE REVIEW OF POSITIVE IMPLICATIONS OF LEAN CONSTRUCTION

The benefits of lean construction for the construction industry have been well discussed. There have been many case studies reporting the benefits of lean construction practices in recent years (Ahiakwo et al., 2013; Al-Aomar, 2012; Andersen et al., 2012; Nowotarski et al., 2016; Vaidyanathan et al., 2016). A recent literature review study reported that lean construction practices can bring up to 20 types of positive implications to the construction industry in terms of economic, social, and environmental aspects (Babalola et al., 2019). These benefits can be further categorized into benefits that can reduce waste, increase value, and improve collaboration, which will be the basis for the investigation in this study.

Table 1: Summary of benefits of lean construction practices for the construction sector

No.	Category	Benefits
1	Economic	Reduction in project time*
2		Reduction in project cost**
3		Improvement of project quality**
4		Continuous Improvement of process**
5		Better inventory control*
6		Market share growth**
7		Risk reduction**
8		Decrease in variability of workflow*
9		Improvement in project delivery method**
10	Social	Increased productivity**
11		Improved customer satisfaction**
12		Improved employee satisfaction***
13		Improved health and safety**
14		Improved supplier relationship***
15		Improved reliability, accountability, and certainty in projects**
16		Better cooperation among stakeholders***
17		Improvement in management and control***
18		Better coordination***
19	Environmental	Reduction of project waste*
20		Attainment of green construction*

Note: *Benefit that can reduce waste; **Benefit that can increase value; ***Benefit that can improve collaboration

IN-DEPTH CASE STUDY OF A CONSTRUCTION ROBOT DEPLOYED IN SINGAPORE

To date, the implications of automation and robotics for off-site lean construction have been discussed, but the intersection of construction robots and on-site lean construction is relatively rare even on a global scale, let alone in Singapore. Therefore, this study aims to investigate the positive implications of construction robots for on-site lean construction through an in-depth case study of a construction robot. The following sections will present an in-depth case study to compare one plastering robot to conventional method of plastering on a job site in Singapore, evaluating key performance indicators such productivity, time, waste reduction, safety improvement, and cost efficiency through the comparison of conventional and alternative (i.e., robotized and digitalized) scenarios, data collection and analysis, and focus group discussion (Nyumba et al., 2018).

Wall plastering is a fundamental task in modern construction projects, often consuming a significant portion of project timelines. For example, plastering with mortar typically accounts for 20-25% of the overall construction time (Wang et al., 2024). Given this substantial time requirement, automating the plastering process offers considerable benefits in terms of efficiency and resource optimization. In this case study, a wall plastering robot was among several construction robots deployed in the sites in Singapore that were available for data collection and the characteristics and performance data of this robot were collected and analyzed, enabling a comparison between robotic and conventional construction methods. The differences and similarities of conventional and robotized plastering processes are presented in Figure 2. As shown in Figure 2, the profile preparation process and the manual plastering process may be substituted by the digital positioning process and robotic plastering process respectively while the wall preparation process and follow-up process will remain the same.

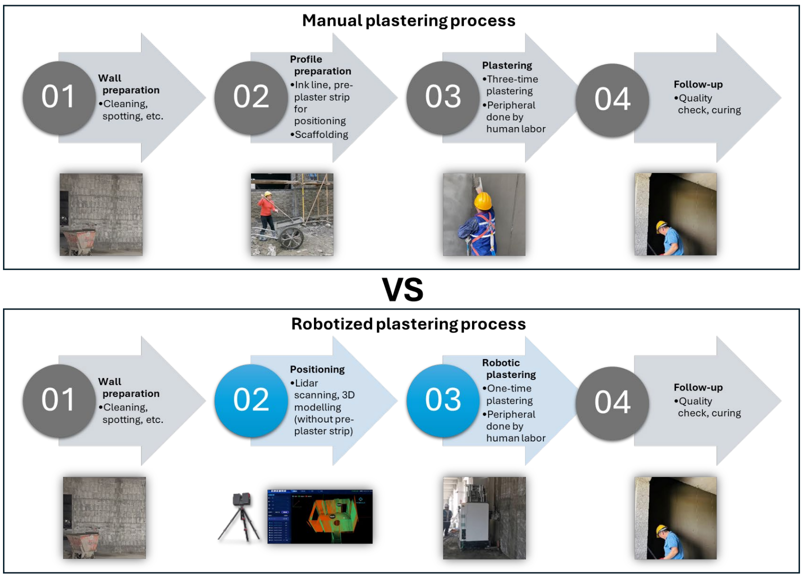

Figure 2: Comparison of manual plastering process and robotized plastering process

Scenarios for Analysis

Micro Level Scenario

In this scenario, a simple comparison of plastering 10 residential units in Singapore using the plastering robot and conventional manual technique will be made. The analysis is based on real data collected in the site deployment in Singapore. The analysis of this level is primarily meaningful for subcontractors and robot operators who use the robot as a simple tool to directly improve their performance.

Meso Level Scenario

In this scenario, a team with a plastering robot and a conventional plastering team, presumably both achieving 300m^2/day productivity and working 250 days per year, will be compared to analyze the costs of each method. This analysis is based on the labor cost and operational data collected from Singapore. The analysis of this level is primarily meaningful for contractors and project managers of medium- to large-sized projects who integrate the robot as a comprehensive solution to improve the construction processes and condition of their projects.

Macro Level Scenario

In this study, the construction industry as a whole and society in general are defined as macro level. At the macro level, it is difficult to quantify the implications of robots for economy, society, and environment. Therefore, qualitative analysis was conducted to evaluate the macro implications of the robotic plastering method through a focus group discussion and expert interviews. Specifically, experts who have rich experience in the construction industry and are familiar with the research field of construction robotics are invited to provide opinion and insights. This scenario is meaningful for key stakeholders of the construction industry such as policymakers and developers to make decisions when it comes to adopting construction robots.

RESULTS

Micro Level Comparison

The data used in the scenario comparison of the conventional plastering method and robotic plastering method is summarized in Table 2. On the micro level, the plastering robot can reduce project time by 82.2% and increase productivity by up to 468.2% compared to skilled plaster workers in the conventional method. In addition, the robot can reduce high-risk operating time by 80.0% compared to the manual plastering process. The quality improvement (i.e., hollow rate reduction) is also remarkable, reaching 95.4% (see Table 3).

Table 2: Scenario comparison of the conventional and robotic plastering methods

	Conventional method	**Robotized method**	**Remarks**
Method description	Manual plastering with mortar performed by workers	Plastering robot	
Room plastering area	120m^2 x 10 units	120m^2 x 10 units	
Team composition	3 workers (1 plastering worker and 2 general workers)	3 workers using 1 plastering robot (1 robot operator, 1 plastering worker and 1 general worker)	The plastering worker in the robotized method will plaster corners and edges where the robot cannot reach
Preparation method	Manual wall preparation with ink line, framing, and spotting, and profile preparation	Manual wall preparation with ink line, framing, and spotting, and digital positioning	The robot's preparation time was not included in productivity calculation as the robot can work while workers are preparing other rooms
Preparation time	20h	20h	
Task execution time	160h	32h	
High risk operation time (man-hours for work at height)	80 man-hours	16 man-hours	Work at height can be reduced as humans only need to plaster high corners
Quality (hollow rate)	0.503%	0.023%	

Table 3: Key performance indicators for the plastering robot

Key performance indicator	**Value**
Time reduction	82.2%
Productivity increase	468.2%
Reduction in high-risk operating time	80.0%
Hollow rate reduction	95.4%

MESO LEVEL COMPARISON

In this scenario, a comparison is made between a team using a plastering robot and a traditional plastering team, both modestly assumed to achieve a productivity rate of 300 m² per day while working 250 days annually, excluding public holidays and downtime. The analysis focuses on costs associated with each method, using labor expenses and operational data sourced from Singapore. The detailed data is summarized in Table 4. It can be inferred that cost reduction of the robotic method may be possible at the meso level. The operating cost savings mainly due to manpower reduction are summarized in Table 5. The pricing of the plastering robot in Singapore is unknown in this study. However, key financial indicators (KFIs) can be easily calculated based on the cost of the robot, which will be decided on its pricing in each market. Other KFIs such as benefit-cost ratio (BCR), return on investment (ROI), initial investment value (IIV), net present value (NPV) can also be calculated according to the local pricing of the robot and local labor cost using the method reported by (Hu et al., 2021).

Table 4: Operating cost comparison of the conventional and robotic method (unit: SGD/m^2)

	Conventional method	Robotized method	Remarks
Productivity	300m^2/8h	300m^2/8h	1 robot operator + 1 plastering worker + supportive worker for the robotized method
Number of workers to achieve same productivity	12 workers	3 workers	120SGD/day for robot operator and 180SGD/day for plastering and supportive workers
Wall preparation	2.0	2.0	Ink line, framing, etc.
Mortar transportation	1.0	1.0	
Plastering cost	7.0	1.6	
Peripheral plastering cost	2.0	2.3	The plastering robot will leave some gaps in corners and edges on wall
Facility cost	2.0	2.5	Cost increases due to cleaning, mixing, equipment, and utility
Management cost	2.0	1.6	Management cost reduces due to less workers involved
Overall cost per m^2	16.0	11.0	

Table 5: Key financial indicators for the plastering robot method (unit: SGD)

Key performance indicator	Value
Cost savings per m^2	5
Daily savings (8h work time)	1,500
Annual savings (assuming working 250 days)	375,000

MACRO LEVEL COMPARISON

On the macro level, a focus group discussion and a follow-up online survey was conducted to assess the overall implications of construction robots on on-site lean construction in a qualitative manner, as it was difficult to quantify several implications especially the social ones within the scope of this study. A focus group discussion was organized among six experts based in Singapore who were highly familiar with construction robotics, four of whom were highly familiar with the plastering robot in the case study, including one who participated in the robot's development process. The demographics of the experts are summarized in Figure 3. The number of participants was appropriate because usually six to eight participants are considered suitable in focus group discussion (Nyumba et al., 2018). Two experts participated in the discussion online due to location constraints. At the beginning of the focus group discussion, videos were shown showing how the robot works. The focus group discussion was instrumental in helping all participants understand the background of the study and the significance of the questions. Afterwards, all participants were asked to complete the online survey independently.

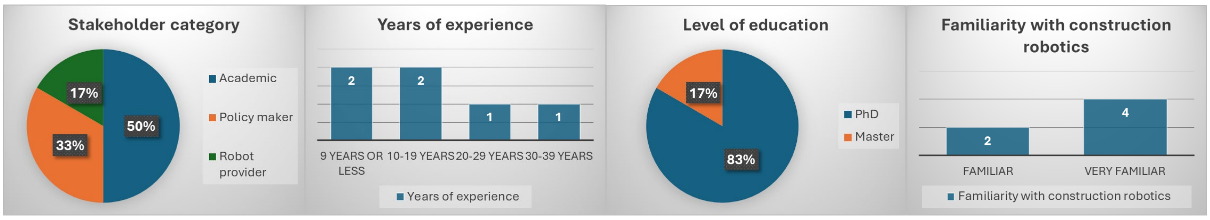

Figure 3: Demographic information of the experts

Survey Results

According to the results of the survey, any benefit with an average score of more than 4.0 was considered highly relevant (marked in green). Any benefit with an average score of 3.0-4.0 was considered relevant (marked in blue). Any benefit with an average score of 3.0 and below was defined as less relevant (marked in red). The results are summarized in Table 6.

The survey results indicate that construction robots are highly promising in improving project quality, reducing variability of workflow, increasing productivity, improving health and safety, and increasing reliability and certainty in projects. Construction robots also have potential for reducing project time and cost, driving continuous process improvement, enhancing inventory control, growing market share, reducing risks, improving project delivery methods, boosting customer and employee satisfaction, improving project management and control, facilitating better coordination, and reducing project waste. On the contrary, construction robots are less relevant in improving supplier relationship, improving cooperation among stakeholders, and achieving green construction at the moment. The results align with the findings of the micro and meso levels.

Table 6: Results of the survey of the experts

No.	Category	Benefits	Average score
1	Economic	Reduction in project time	3.67
2		Reduction in project cost	3.17
3		Improvement of project quality	4.33
4		Continuous Improvement of process	3.67
5		Better inventory control	3.5
6		Market share growth	3.17
7		Risk reduction	4.00
8		Decrease in variability of workflow	4.33
9		Improvement in project delivery method	4.00
10	Social	Increased productivity	4.17
11		Improved customer satisfaction	3.33
12		Improved employee satisfaction	3.67
13		Improved health and safety	4.67
14		Improved supplier relationship	2.50
15		Improved reliability, accountability, and certainty on projects	4.17
16		Better cooperation among stakeholders	2.83
17		Improvement in project management and control	3.33
18		Better coordination	3.67
19	Environmental	Reduction of project waste	3.83
20		Attainment of green construction	2.67

DISCUSSION

KEY FINDINGS

According to the case study, construction robots, together with the optimized work process and ecosystem that comes with them, can be a powerful tool for on-site lean construction as they have the potential to bring up to 17 lean construction related benefits that can reduce waste, increase value, and improve collaboration in the construction sector in economic, social, and environmental aspects, according to data analyses and experts' opinion (see Table 7).

Table 7: Summary of positive implications of construction robots on each level

No.	Category	Positive implications	Micro	Meso	Macro
1	Economic	Reduction in project time*	✓	✓	✓
2		Reduction in project cost**		✓	✓
3		Improvement of project quality**	✓	✓	✓
4		Continuous Improvement of process**			✓

Table 7: continued: Summary of positive implications of construction robots on each level

No.	Category	Positive implications	Micro	Meso	Macro
5		Better inventory control*			✓
6		Market share growth**			✓
7		Risk reduction**			✓
8		Decrease in variability of workflow*			✓
9		Improvement in project delivery method**			✓
10	Social	Increased productivity**	✓	✓	✓
11		Improved customer satisfaction**			✓
12		Improved employee satisfaction***			✓
13		Improved health and safety**	✓	✓	✓
14		Improved supplier relationship***			
15		Improved reliability, accountability, and certainty on projects**			✓
16		Better cooperation among stakeholders***			
17		Improvement in management and control***			✓
18		Better coordination***			✓
19	Environmental	Reduction of project waste*			✓
20		Attainment of green construction*			

Note: *Benefit that can reduce waste; **Benefit that can increase value; ***Benefit that can improve collaboration

In addition, in order to increase the value of robotic solutions, new approaches are needed to change the current work process to successfully adopt robotic systems, including change of design, work sequences, techniques, and materials. The digitalization of the construction site and process is a critical factor for the successful realization of on-site lean construction.

Fully automated construction sites remain unrealistic at this stage. While robots can handle certain tasks, others still require human involvement to maximize the efficiency of robotic deployment. It is recommended to align robot development criteria with project demands and site conditions to refine robot design for optimal performance in the current site condition.

Providing support to robot providers is also crucial. From the end users' perspective, technically, they need to provide opportunities to robotic providers and startups to make adaptations and improvements because the existing technologies might not work for different regions and site standards. Economically, they need to support robot providers and start-ups to grow their global markets. From the policymakers' perspective, favorable policies and flexible incentives provided by the Singapore government to support both local and global contractors and robot start-ups are crucial for the successful deployment of construction robots.

Although studies on the implementation of construction robots in similar urban settings such as Hong Kong already exist (Pan et al., 2018), the topic has not been extensively explored in Singapore. This study represents one of the first efforts to examine the implications and offer valuable insights into the deployment of construction robots within Singapore's unique context.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

Admittedly, several limitations remain in this study. In the case study, only one single-task construction robot was analyzed. Other types of robots (e.g., painting robot) need to be integrated into a whole construction process and analyzed to better understand their implications on on-site lean construction in future studies.

This study focuses on analyzing the benefits of construction robots on on-site lean construction. The barriers for implementing construction robots on the other hand also need to be analyzed and discussed in future research.

The data collection on the micro level and meso level were only conducted in Singapore. The situation could be vastly different in other countries, thus impacting on the results. In addition, many data employed in the case study are only rough estimations. Hence, further investigations are needed.

The implications for on-site lean construction are only analyzed by a few experts through reasoning and empirical knowledge in an ideal situation, which necessitates further studies to obtain a global perspective of construction robots' benefits on on-site lean construction.

CONCLUSIONS

This study preliminarily demonstrates that construction robots can offer many positive implications that can reduce waste, increase value, and improve collaboration for on-site lean construction in economic, social, and environmental aspects, which indicates that construction robots together with their compatible operating environment and optimized work processes can be a meaningful and powerful tool for on-site lean construction. The findings align with the principles and roadmap laid out in Lean Construction 4.0, which emphasizes the need for integrating lean and digital technologies (González et al., 2022). More importantly, this research is among the first efforts to investigate the implications and offer evidence-based insights regarding the adoption of construction robots within Singapore's distinctive context and beyond. Key stakeholders in the construction industry, including policymakers, developers, contractors, subcontractors, project managers, and robot operators, can all benefit from the analysis framework at various levels in this study when implementing construction robots and other emerging technologies on-site.

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