Robot-Oriented Lean Construction: A Toolkit Primer and the Pathway Forward

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Abstract –

The construction industry faces persistent economic, social, and environmental challenges. Construction robotics and lean construction have emerged as potential solutions, yet their integration remains underexplored. This paper introduces the notion of Robot-Oriented Lean Construction (ROLC) – a toolkit that adapts lean principles to the characteristics of construction robots, emphasizing synergy between people, processes, and technology. Drawing on a case study of the research, development, and deployment of construction robots in Singapore, the paper demonstrates how lean methods such as Deming cycle, Last Planner System, 6S, Gemba Walk, and Total Productive Maintenance can guide the planning, development, deployment, and continuous improvement of construction robots. Findings with empirical evidence indicate that the toolkit enhances safety, efficiency, and collaboration, while reducing waste and highlighting respect for people. The paper concludes by outlining pathways for development, education, and standardization to advance the emerging research direction of ROLC.

Keywords –

Construction Robotics; Continuous Improvement; On-Site; Singapore; Toyota Production System

1 Introduction

The construction sector plays a crucial role in the global economy. Yet, it is constantly facing enormous economic, social, and environmental challenges. Economically, the sector shows slower productivity growth than any other industry, with low levels of digitization and lengthy planning and execution phases [1]. Socially, it faces a widespread shortage of skilled labor, worsened by hazardous working conditions and an aging population [2]. Environmentally, it is one of the most resource-intensive industries, making it central to efforts in combating climate change and achieving a circular economy [3]. These persistent challenges in the construction sector are largely caused by on-site production, the uniqueness of each project, and the high level of complexity involved [4]. As a result, the construction industry is in urgent need of innovative technologies and methods to tackle these challenges. Construction robotics and lean construction have emerged as promising potential solutions.

1.1 The Coming Ubiquity of Robots in the Construction Industry

Emerging in the late 1970s in Japan through the leading efforts of general contractors known as the "Big Five", construction robots began tackling major challenges in the industry by enhancing working conditions, safety, productivity, and quality [5]. Over the past decade, demand for construction robots has resurged, driven by government initiatives in regions like Hong Kong and Singapore that encourage the use of emerging technologies in the construction sector [6], [7]. Researchers have reported many advantages of robotic construction compared to manual work [8], [9]. However, there are still barriers to the full implementation of construction robots in the construction industry mainly due to fragmented nature of the industry, high initial investment, low level of standardization, resistance by workers and trade unions, lack of expertise, and lack of support from top management [10], [11].

1.2 The Evolution of Lean Construction

For the past fifty years, Western manufacturers have looked to Japanese manufacturing management practices as a benchmark, recognizing them as an innovative production paradigm widely known as lean manufacturing [4]. One of the most notable examples of lean manufacturing was Toyota Production System (TPS) invented by T. Ohno who leveraged just-in-time and autonomation to eliminate waste and increase value for customers, while maintaining high quality [12].

Inspired by lean manufacturing, the construction industry expectedly adopted lean methods and formed the lean construction theory. It is generally believed that "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 [13]. Lean Construction Institute (LCI), an organization formed in 1997 by G. Ballard and G. Howell to develop and disseminate knowledge of lean construction, further refined its definition as "a culture of continuous improvement and collaboration among all project participants to maximize efficiency, minimize waste, and deliver exceptional project outcomes" [14]. Lean construction, ever since its advent, has continuously delivered a wide range of economic, social, and environmental benefits to the construction industry [15]. Over the years, many tools have been developed and successfully applied to lean construction including but not limited to Deming Cycle, 5S, Big Rooms, Daily Huddles, Kanban, Andon, Poka-Yoke, Heijunka, and Last Planner System [4], [16]. However, to continue advancing and benefiting the construction industry, lean construction must adapt to the transformations driven by Industry 4.0 while preserving its foundational focus on the synergy between people, processes, and technology [17].

1.3 The Crossroads

We are reaching a crossroads where two major emerging fields in construction, namely construction robotics and lean construction, need to synergize to further tackle the enduring challenges in the construction industry. Lean construction practices should consider the upcoming ubiquitous application of robotics in the construction industry [5]. In recent years, the Lean Construction 4.0 framework has emphasized integrating lean construction principles with advanced technologies like robotics [17]. Based on scientometric analysis, Cardenas et al. advocate for more synergies in the intersection of lean construction and construction robotics [18]. In a recent study, Hu et al. further reported that construction robots can potentially bring at least 17 lean related benefits to construction sites [7]. These studies indicate a strong potential for integrating lean construction with construction robotics.

As a highly developed city-state, Singapore has a strong economy and plays a unique role as a center of finance and innovation in Southeast Asia, bridging the East and West. The construction industry is one of its key sectors, employing over 450,000 workers [19]. Like many other countries, Singapore's construction sector faces many challenges such as stagnant productivity, construction waste, safety risks, labor shortages, and a heavy reliance on foreign workers [20], [21]. These issues were further intensified by the COVID-19 pandemic [19]. In response, Singaporean government agencies have introduced various incentives to foster both local and international innovation in the construction industry. This makes Singapore an ideal place for testing novel construction technologies including lean construction and construction robotics.

2 Methods

This paper aims to introduces the notion of Robot-Oriented Lean Construction (ROLC) and provide empirical evidence of how lean construction methods can be adapted to suit the characteristics of construction robots with a focus on the synergy between people, processes, and technology through a best-practice case study in Singapore. The study is primarily based on a case study of the planning, development, and deployment activities around construction robotics in the Construction Robotics Lab. Furthermore, a unique feature of this lab is its close link to several ongoing construction projects across Singapore, serving the ideal live testbed for the technologies developed in the lab environment or co-developed with partners. In this study, qualitative methods such as on-site observations, case study, and expert interviews are adopted. Specifically, various lean methods applied in the planning, development, and deployment of construction robots are shown in Figure 1.

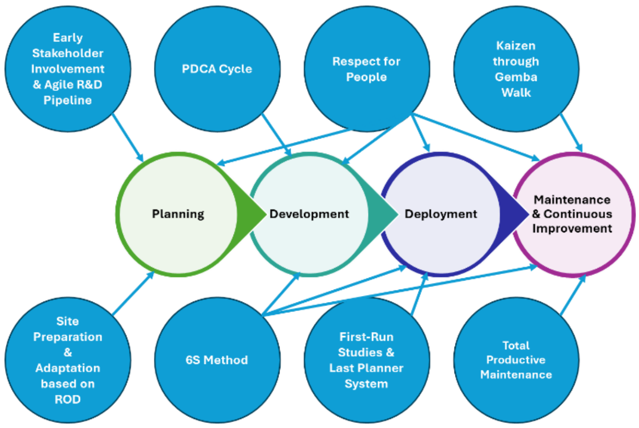

Figure 1. Non-exhaustive lean tools applied during construction projects' lifecycle

3 Results

The following sections will explain how these methods are applied in the case study in detail.

3.1 Planning

The lean methods applied in the planning phase of robots are reported as follows.

3.1.1 Early Stakeholder Involvement and Agile Research-Development-Deployment Pipeline

To begin the adoption process of robots on the construction sites, an agile research-development-deployment pipeline is adopted, involving all key stakeholders in the early stage (see Figure 2). The process begins with gathering requirements from the clients or general contractor affiliated departments, followed by assessing the availability of suitable technologies. If the target technology is already available and mature on the market, a market search is conducted, and collaboration with an external vendor is initiated to adapt the technology further to the site condition. If the technology is not available, R&D projects will be carried out in the Construction Robotics Lab to develop the technology (see Figure 3). In both cases, the developed or adapted technology is tested on affiliated construction sites. If the performance is found to be unsatisfactory, further improvements or iterations are made. Once the technology demonstrates satisfactory performance, it is deployed for use on real construction sites.

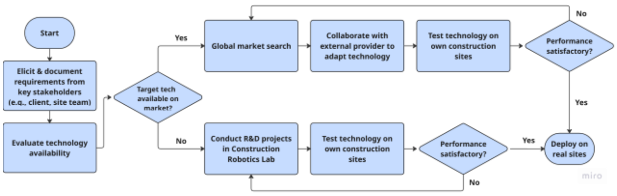

Figure 2. Research-develop-deploy pipeline for implementing construction robots

Figure 3. Construction Robotics Lab in Singapore

As shown in Figure 4, several construction robots including wall plastering robot, interior painting robot, floor grinding robot, mobile monitoring robot, and site inspection drone are deployed on the construction site of this case study. Methods such as Choosing by Advantages (CBA) workshops where key stakeholders quantitatively assess the advantages of all options by weighing the key criteria [22] are usually adopted to decide which technology to adopt for each task.

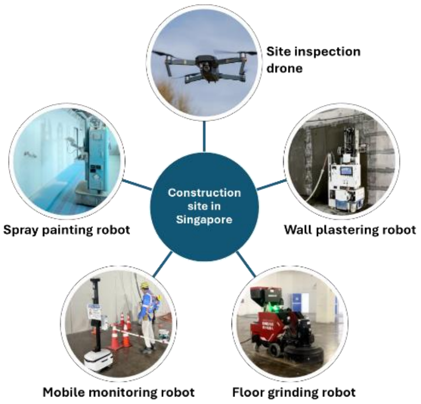

Figure 4. Examples of robotic solutions for various tasks tested for deployment on the real site

3.1.2 Site Preparation and Adaptation

The notion of Robot-Oriented Design (ROD) was first proposed by T. Bock, 1988, who emphasized that the final on-site construction operations shall already be considered at the design stage of building elements and construction methods in accordance with the characteristics of robots to improve their efficiency and usability [23]. This concept has also been applied to the site preparation process in this case study for better operation of robots. For example, a mobile monitoring robot is deployed on site to patrol in different rooms and spaces for site management. Barricades are modified so that the mobile robot's lidar sensor can detect which barricades are passable and which are not (see Figure 5). Also, slopes are added to the steps on the route of the robots to mitigate any height gaps.

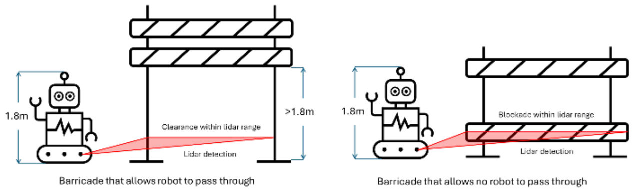

Figure 5. Example of site preparation and adaptation for implementing construction robots

Another common challenge for construction sites to adopt robots is network connectivity. Researchers have already discussed the strategy for deploying 5G infrastructure on construction sites [24]. However, connectivity may be limited in remote or underground locations where 4G/5G networks are unstable or unreachable. In such cases, it is necessary to assess network speed and signal strength in advance using tools such as Opensignal. Based on the results, the site team may need to establish a wireless mesh network (WMN) to support the smooth operation of multiple robots.

3.1.3 Respect for People

As a key pillar of lean construction, respect for people is implemented throughout the construction phase to ensure smooth and harmonious collaboration between teams. For example, all signs on site including the ones on the robots are written in English, Chinese, Tamil, and Bengali, considering the demographic composition of the workers (see Figure 6).

Figure 6. Multilingual signage deployed on site

Furthermore, because Singapore is a multicultural "melting pot" where many ethnic groups coexist peacefully side by side including but not limited to Chinese, Malays, Indians, and other minority groups, the construction workers' faiths are also respected on the construction site. Figure 7 shows a Muslim prayer room and a Chinese shrine installed on the construction site for workers of different beliefs to practice their religions.

Figure 7. Prayer room and Chinese shrine on the construction site for workers of different faiths

3.2 Development

The lean methods applied in the development phase of robots are reported as follows.

3.2.1 PDCA Model for Developing Construction Robotic Applications

The development of construction robots typically involves various stakeholders from the construction sector, non-construction sectors, and investors. A domain-specific systematic design management approach helps integrate the needs and goals of different stakeholders and team members during the development process. Therefore, the construction robot development in this case study follows a procedure model derived from the Deming Cycle designed to provide comprehensive guidance on how to systematically conceptualize requirements and how to design, develop, implement, evaluate, manage, and refine the construction robots (see Figure 8).

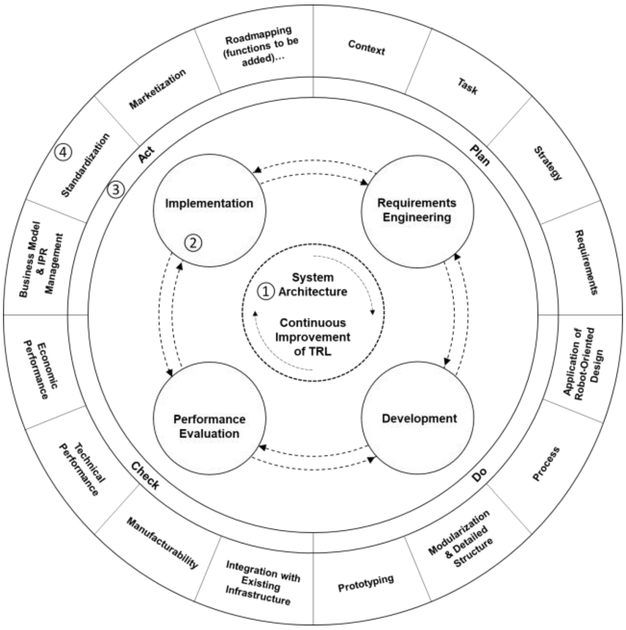

Figure 8. Procedure model for developing construction robots (adapted from [25])

Specifically, its foundation follows the Deming cycle for continuous improvement (Layer ③), enabling the cyclic and iterative development process to begin at any stage and to be applied not only to new concepts but also to existing and even relatively mature construction robot designs. The central components of the procedure model are the four main process steps (Layer ②) located at its core, namely requirements engineering, development, implementation, and performance evaluation. Each of these steps consists of a defined set of activities, tasks, and specified requirements (Layer ④). The primary aim of the proposed process is the continuous advancement of the system architecture and progression of its Technology Readiness Levels (TRLs) (Layer ①). This development procedure model has been validated and proven feasible in multiple R&D projects. The procedure model's core principle allows it to evolve with each usage cycle. Furthermore, customized elements can be inserted into the model based on region, robot typology, and technology maturity [25].

3.2.2 6S Method Emphasizing Safety

Derived from 5S, 6S is workplace organization method which refers to "sort", "set in order", "shine", "standardize", "sustain", and "safety" [26]. In the lab, 6S is strictly implemented due to high risks of robots, where actions such as risk management implementation plan, housekeeping, occupational health and safety (OHS) workshop are conducted periodically. On the construction site, 6S is also implemented with an emphasis on collaborating safely with robots on site. Workers must receive safety training and attend morning safety meetings. Moreover, incentives such as lucky draws for speaking up for safety and Why I Work Safe Cards are provided for workers on site to further strengthen their safety awareness (see Figure 9).

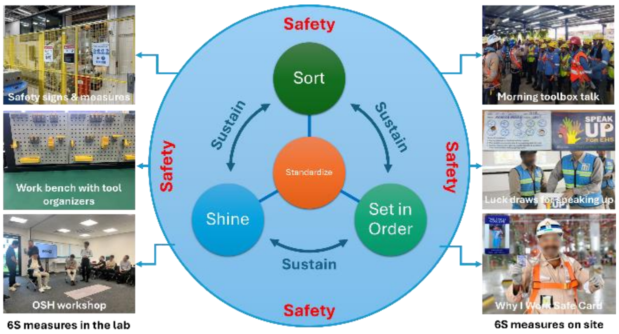

Figure 9. Use of 6S Method during R&D and deployment phases of construction robots

3.3 Deployment

The lean methods implemented in the deployment phase of robots are reported as follows.

3.3.1 First-Run Studies Before Robot Deployment

First-run study is a lean technique used to optimize a work process by conducting a controlled experiment to evaluate performance and uncover potential issues [27]. Because of high deployment cost, robotic technologies cannot be directly deployed before proven feasible by first-run studies.

For instance, the site team considered deploying a novel floor grinding robot. However, due to the robot provider's start-up nature, how different parameters of the robot settings will affect the task performance and quality was still unclear, especially for the concrete used on the construction site in Singapore (i.e., C40). With assistance from the R&D team, a first-run study was designed using a room of 2000 m^2 to evaluate the performance of the concrete grinding robot. As there are two main parameters in the robot's settings, namely robot moving speed (mm/s) and diamond grinding wheel's rotational speed (rpm), the first 500 m^2 was divided into 9 equal areas to test 9 combinations of both parameters. Two 3D scans were performed respectively before and after the test grinding to compare the height differences. After the test, the parameters of the A1 area were considered efficient, which was applied to the rest of the room as well as other areas for the floor grinding task (see Figure 10).

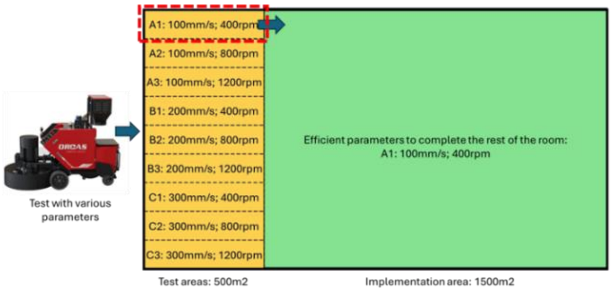

Figure 10. First-run study design for the floor grinding robot before implementation

3.3.2 Last Planner System for Robot Deployment

Due to their consistent performance, robots can help optimize construction processes and support the application of on-site lean construction. In this case study, robots were integrated into project planning through a flexible Last Planner System [28], with their deployment as key milestones integrated in the master schedule. Weekly work plans were developed using pull planning, supported by site preparation to ensure readiness. Daily coordination meetings between the robot operators and site team defined work scopes, while activity reports were submitted by operators and shared with stakeholders to enable systematic data collection and continuous improvement.

3.3.3 Evaluation Framework

After the first deployment, the R&D team developed a comparison and evaluation framework comprising quantitative and qualitative methods to measure the implications of the construction robots for various stakeholders on micro, meso, and macro levels based on the data collected in the deployment phase. In a case study, by evaluating the performance of wall plastering robot and interior spray painting robot using the evaluation framework, the R&D team reported that the robots have the potential to bring at least 17 lean related benefits that can reduce waste, increase value, and improve collaboration [7]. Specifically, for example, the plastering robot recorded a 462.5% productivity gain and 95.4% quality improvement (i.e., hollow rate reduction) compared to the conventional plastering method, whereas the spray painting robot achieved 28.6% productivity gain and 39.6% material saving [7].

3.4 Maintenance and Continuous Improvement

The lean methods used in the maintenance phase of robots are reported as follows.

3.4.1 Total Productive Maintenance

Total Productive Maintenance (TPM) is an equipment management method based on total participation to maintain equipment to improve productivity, quality, and safety [29]. Due to its sophistication, all critical robotic equipment, whether in the lab (e.g., robotic arms, air compressors, automated guided vehicles, etc.) or deployed on site (illustrated in Figure 4), undergoes TPM periodically depending on its usage. TPM deeply connects to 6S methodology which ensures optimal total cost-efficiency, balancing between high preventive cost and high repair cost.

3.4.2 Kaizen Through Gemba Walk

Kaizen (Japanese term for "change for the better") is a lean philosophy that aims to make incremental, continuous improvements for long-term success. It is deeply rooted in the philosophy of Hansei (Japanese term for "self-reflection"), referring to deep introspection to identify own mistakes and pledge improvements. Gemba (Japanese term for "real place") Walk is a lean management term referring to physically going to the real site where leaders can identify areas for improvement and cultivate a culture of continuous learning [30]. On one hand, safety Gemba Walk by professional safety inspectors has already been implemented on a regular basis to ensure a safe working environment both in the lab and on site. On the other hand, Gemba Walk also plays a crucial role in the successful on-site implementation of construction robots.

For example, during a Gemba Walk session, the R&D team found two practical flaws of the spray painting robot: 1) Due to the inconsistent quality of certain brands of paint, solid impurities in the paint may clog the robot's nozzle, forcing the operator to stop and manually clean the nozzle before continuing to operate; 2) In some occasions, the cable carrier track of the vertical robotic movement which is slightly higher than the robotic arm may accidentally hit some fixtures hanging on the ceiling during operation, causing potential damage to building fixtures (see Figure 11). After the discovery of these two flaws, the R&D team requested the operator to provide feedback to the robot manufacturer, who decided immediately to improve the robot design in the next iteration by 1) adding a filter net in the paint feeding system and 2) flipping the cable carrier track to lower than the robotic arm.

Figure 11. Discovery of flaws during Gemba Walk for continuous improvement

4 Discussion

In this section, implications of this research are summarized. Furthermore, limitations are analyzed and future research directions are suggested.

4.1 Implications

This paper introduces ROLC as a practical guideline for integrating lean principles with the growing adoption of construction robotics. Through a case study in Singapore, it demonstrates how lean tools such as PDCA, Last Planner System, 6S, Gemba Walk, and TPM can guide the planning, development, deployment, and continuous improvement of construction robots while emphasizing respect for people, which resonates with the Lean Construction 4.0 initiative. The findings suggest that ROLC can enhance efficiency, safety, and collaboration, while reducing waste, eventually achieving an optimal balance between site preparation effort and robot development complexity (see Figure 12). As robotic applications become increasingly ubiquitous in the construction industry, further research, development, education, and standardization are needed to refine and expand this emerging interdisciplinary topic.

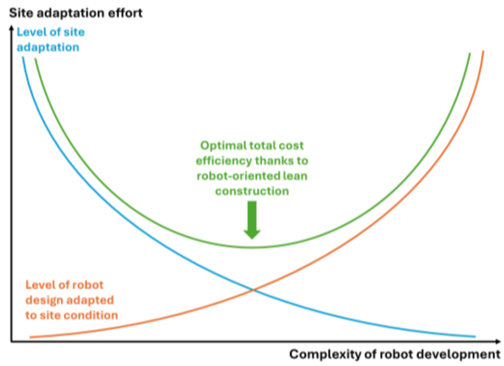

Figure 12. ROLC ensures an optimal balance between site adaptation and robot complexity

4.2 Limitations

Admittedly, limitations remain in this study. For example, the case study approach has several drawbacks, including challenges in generalization and replication (due to Singapore's unique policy environment and labor force structure), potential researcher bias, an intensive data collection and analysis process, and restricted scientific rigor [31]. Furthermore, more quantitative methods need to be employed to demonstrate evidence-based advantages and benefits of the proposed toolkit. In addition, other potentially promising lean methods and principles may not have been covered in this early-stage investigation. Further research is needed to refine and advance the topic.

4.3 The Pathway Forward

To overcome these limitations, the following aspects point to the directions and priorities for future research:

- Synergy between the two domains: Keep the upcoming ubiquitous adoption of construction robots in mind to optimize the process and flow of lean construction. Meanwhile, keep lean principles (e.g., respect for people, eliminating waste, optimizing process and flow, continuous improvement, increasing value for customers, etc.) in mind when developing robotic solutions.
- Education and training: Make training and education programs about the intersection of lean construction and construction robotics (i.e., ROLC) to construction managers, workers and students.
- Generalization and standardization: The feasibility of ROLC in other parts of the world needs to be assessed on a case-by-case basis. Furthermore, multi-case comparative studies in one region and cross-regional studies are necessary to further validate the effectiveness and performance of ROLC. In addition, the possibility of standardization especially related to construction robotics and lean construction needs to be investigated.
- More respect for people: The goal of implementing ROLC is not to replace human workers, but to empower the existing workers with emerging technologies to increase their work efficiency and enhance safety while mitigating labor shortages that are prevailing in the global construction sector. Therefore, the needs and fear of human workers towards AI and robotics need to be understood to increase the acceptance of emerging technologies.
- Continuous improvement of the toolkit: Admittedly, this paper only provides an introductory guideline for ROLC as a starting point. Further development is needed to enrich both theoretical and methodological aspects of the interdisciplinary field.

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