Assessment of Traditional and Robotic Approaches to Interior Construction Layout: A Framework and Comparative Study

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Abstract –

As the construction industry witnesses a growing integration of robots and automated systems on complex construction sites, project teams exhibit varying definitions of successful robot employment. Notably, there is an absence of standard criteria for stakeholders to assess the impacts of these technologies on productivity, cost, safety, and pertinent human factors. Existing studies suggested key framework elements, yet none provided a comprehensive, quantitative means to assess on-site construction robots. In response, this study introduces a holistic framework of Key Performance Indicators (KPIs) as a reference for researchers to evaluate single-task robots. A case study was conducted using a set of extracted KPIs, comparing the traditional construction interior layout method with the performance of a single-task mobile layout robot. The study demonstrates a comparative approach that project teams can adopt to maximize robot benefits and meet project-specific goals.

The case study accounts for the unpredictability of robot implementation that project teams may need to adapt to. The results highlight drawbacks of recent automation, such as technological inefficiencies. Depending on the application, these challenges can increase project completion time and affect space utilization. This research presents a comprehensive productivity analysis of a recently introduced mobile layout robot. Additionally, we highlighted robot advancements in comparison to previous layout robots assessed in past studies. These advancements provide positive cost and safety implications. The conclusions offer insights into the feasibility of adopting these technologies and considerations for stakeholders seeking to implement them.

Keywords –

Robotics, Automation, Single-task Robots, On-site, Construction, Interior Layout, Key Performance Indicators (KPIs), Efficiency, Productivity

1 Introduction

The construction industry is a leading driving force in any nation's economy. In the United States (US), the construction industry contributes 4% to the Gross Domestic Product (GDP) [1]. In 2022, the value added to the US GDP by the construction industry amounted to one trillion US dollars [2]. A look ahead to 2024, and as the global market is witnessing inflation rates, it is evident that the construction industry will face challenges with wage cost increases, supply chain disruptions, skilled labor shortages, and rising construction costs [3]. In addition to the prolonged safety and productivity issues the industry has suffered, these forecasted challenges add another layer of complexity for decision-makers to integrate and implement emerging technologies and automation into the construction workflows and to upskill the workforce. Thus, construction automation can be viewed simultaneously as an opportunity and a challenge.

There are three major opportunities for construction automation: 1) automating traditional redundant physical tasks on sites, for instance, robots laying bricks; 2) off-site modular construction such as the use of 3D-printed construction components; and 3) digitization of the design, planning, and management procedures [4].

Adopting robots in construction requires an upfront investment, making it prohibitive for small construction organizations that lack the necessary resources. Also, there are concerns about the safety risks of integrating robots into a volatile and hazardous environment such as construction sites. The construction industry is a dynamic environment that requires immediate interventions and workflow changes; however, including robots might restrain the needed flexibility. As construction companies adopt automation and try to use robots on and off construction sites, barriers among stakeholders limit their usage, mainly due to the resistance to change and lack of skilled workforce [5]. Thus, the degree to which robotics are adopted in the construction industry relies on the awareness and perceptions of their advantages and disadvantages concerning these barriers [6]. Conversely, understanding robot types and their applications among stakeholders can expand their adoption.

The types of construction robotics can be generally classified into four categories: 1) off-site prefabrication, 2) on-site automation, 3) drones and autonomous vehicles, and 4) exoskeletons [7]. This broad categorization can cause an overlap of robot identification terms and definitions [8]. Robots can be further categorized according to their applications. Robot technology applications in the construction industry vary, including, but not limited to, painting and spraying, demolition, brick and concrete laying and plastering, construction welding, drilling, bolting, drywall and façade installation, steel-truss assembly, transportation, inlaying, surveying, inspection and monitoring, roadwork, excavating and earth moving, and interior decoration [7, 9–11].

The opportunities for robotic employment across the entirety of the construction industry are extensive because of their growing versatility, which can cover a wide range of on-site and off-site activities [12]. However, implementing automation and robotics on construction sites is more challenging since they are implemented in highly unstructured, uncontrolled, and congested environments [13]. For instance, the need for error mitigation in exterior and interior layout amidst site congestion is critical, considering these tasks ensure that the project is accurately built according to design plans and budget [14]. Despite inconsistent site conditions, the layout precision and efficiency are contingent upon the ability of surveyors to provide accurate positioning according to acceptable tolerances with the use of a total station and Global Positioning System (GPS), among other geomatic instruments [15]. This process is fundamental to a project's short and long-term quality and schedule, as it establishes the structural integrity and upstanding of the designed structure [15]. As a result, the safety of on-site workers, building occupants, and other relevant stakeholders is an essential consideration of the layout planning phase [14]. Due to the emphasis on precise execution, surveyors are to be heedful; as a result, the time associated with rework and error mitigation affects the project's efficiency, cost, and schedule overruns [15]. Additionally, on sites that demand complex design plans and coordination between various trades, optimization of space and schedule is critical, as it combats the growing issue of low productivity and high costs [16].

The application of factory-based automation in construction can be viewed as a technology transfer from the manufacturing sector, albeit with some exceptions. In this context, automated tooling is adapted to manufacture building elements instead of traditional products [17]. Unlike factory automation, implementing automation on construction sites involves unique hurdles and prospects. It necessitates developing and deploying specialized equipment and processes, marking a departure from direct technology transfer [9]. For instance, mobile layout robots have recently been introduced to construction sites to mitigate the risks and limitations of traditional layout methods on complex project sites [18]. This implementation creates a fertile ground for research, new business ventures, and the emergence of start-ups in this innovative field.

Moreover, with the unceasing advancement of automation and robots, developing continuous assessment criteria and implementation frameworks is critical to evaluate the advantages and associated risks of implementing robots on construction sites [19]. As such, this study aims to investigate the metrics used by researchers and practitioners to evaluate the implementation of automation and robotics on construction sites and provide standard criteria to help the construction industry evaluate this implementation. Furthermore, a case study will be presented to test the applicable metrics by comparing the use of a construction robot versus the traditional method in conducting an interior construction layout.

2 Background

Considering the desire to integrate construction automation, the shortage of skills, and the emphasis on enhancing sustainability in the construction industry, it is probable that widespread acceptance of automation and robotics will be commonplace in construction soon [20]. This is largely because construction tasks can be repetitive and tiresome, and the collaboration of robots and humans can alleviate workload and exhaust [9, 21]. However, the industry is considered dangerous, complex, and unpredictable [22]. Therefore, anticipation and preparation are the keys to supporting the construction sector as it seeks new, tangible uses for automation [4].

Implementing construction automation equipment for on-site tasks necessitates the design of this equipment to be portable for transportation to various job sites, where it can be set up, utilized, and dismantled for relocation to the next assignment [20]. For instance, conventional equipment like heavy earthmoving machinery has undergone retrofitting, and there is a growing trend of manufacturing new equipment with a focus on an automated or semi-automated future [9]. Initially, on-site automation led to the creation of building systems tailored specifically to integrate with those automated construction systems. However, in many instances, this approach reduced the distinctiveness of each building [20]. In today's context, there is a renewed effort in automated construction that accommodates variations across units while incorporating standardized elements [20]. For instance, automated equipment designed for constructing concrete reinforcement reduces the labor demand of repetitive tasks on the construction site. It enables performance-driven variability in rebar tying. Moreover, precisely fastening material where needed helps minimize schedule without incurring additional costs [23].

The extent to which companies and project teams implement on-site construction automation is contingent on known success indicators in similar application areas. However, construction companies cannot rely on historical data to evaluate and asses on-site construction automation due to the limited history of construction industry engagement with robots, and managers cannot determine the optimal robotic solution for a specific project [24]. Conversely, a substantial number of Key Performance Indicators (KPIs) can be applied to evaluate robot performance; however, it’s important to identify indicators that align with the set goals of the company or involved teams [25]. The indicators chosen to measure automated technology are specific to the objectives of each study and depend on the focus of the task and the robot used. Yet, there is an overarching framework of KPIs that are repeatedly addressed. In direct response to the main issues that the industry faces when integrating robots, improvement levels are often measured in terms of productivity, cost, safety, and human factors [26].

Robotics and automation in the manufacturing and production settings have become increasingly common [20]. Notably, the authors of [25, 31] provided a general structure of productivity metrics for manufacturing robots that could be manipulated and adopted to assess on-site construction robots. Given the unique challenges of construction sites, the authors of [10, 17, 27, 32] assessed the performance of on-site construction robots. Compared to the manual method, the robots provided higher quality with less working time and labor intensity, thereby providing insight into how robots can alleviate the issue of low efficiency within the industry, as it relieves skilled workers of tedious tasks and exposure to safety hazards [32]. The specific metrics used by researchers and practitioners to evaluate productivity improvement for off and on-site robot implementation are summarized in Table 1.

Table 1. Productivity KPIs for assessing automation in construction.

Productivity	
KPI	Reference
Cycle time	[10, 17, 25–27, 29, 31]
Cycles/Jobs completed	[25, 27, 31]
Efficiency	[17, 25, 26, 28, 31, 32]
Manpower	[27, 28, 32]
Quality/Accuracy (rework, repeatability, material waste)	[28, 32]
Set up time	[26]
Training hours	[26]
Utilization	[25, 26, 31]
Wait/Disconnected time	[25, 26, 31]
Working time/Speed	[17, 27, 28, 32]
Yield	[25, 28, 31]

Table 1. (Continued)

The large economic output of the construction industry contributes to its significance in the global industrial sector [5]. Therefore, perceptions of high costs can negatively influence robot adoption [33]. According to the schedule impacts of robot deployment, productivity assessment data can be monetarily quantified to compare manual and robotic work. The monetary transformation of performance indicators into financial indicators using engineering principles, such as return on investment, cash flow analyses, and benefit-cost ratio, enables companies to determine whether robot investment is economically beneficial [25, 27]. As such, the authors of [10, 27, 29], using a cost-benefit analysis of single-task construction robots, were able to monetize the impacts of productivity and speed. The direct costs associated with robot acquisition, operation, and maintenance, such as unit costs, savings in estimated schedule, and rework reduction, have been compared with traditional work's labor and material costs [26, 28]. Additionally, indirect costs, including costs of workforce training, waste mitigation, health damage, and other demands of robot deployment, are to be included in a comprehensive assessment of automation in construction [8, 30, 34]. The quantified measures of direct and indirect cost in existing studies, as Table 2 shows, are strategically chosen to support the project’s financial goals.

Table 2. Cost KPIs for assessing automation in construction.

Cost	
KPI	Reference
Benefit-cost ratio	[27, 28]
Health damage cost	[34]
Innovation (training, technology acquisition)	[8, 30]
Labor cost (number of employees, function, salary)	[8, 27–30]
Operational cost (maintenance, license, energy, resource costs)	[8, 27, 30]

Table 2. (Continued)

Cost	
KPI	Reference
Payback period	[8, 27]
Productivity (unit cost, construction cost, construction time, project dimensions)	[26, 30]
Profitability (revenue, market share)	[30]
Quality (cost of rework, delay)	[8, 30]
Return on investment	[8, 25, 27, 28]
Technology cost (hardware and software costs)	[8, 29, 30]

Besides cost and productivity, automated construction can further improve workers' health and working conditions – a highly prioritized objective of the construction industry. As such, authors of [10, 34] evaluated the health damage caused by robotic and manual methods in interior construction. The studies found that robot adoption yielded healthier working conditions [10, 34]. Despite the growing utilization of construction automation and robotics, there have yet to be specific Occupational Safety and Health Administration (OSHA) standards for the robotics industry [35]. Even though safety impacts may not be identifiable on the project level, their long-term effects and cost impacts are to be considered [36]. To a greater degree, robotic performance should be evaluated against the large-scale, global pushes toward sustainability [8]. Metrics of safety KPIs are presented in Table 3 as measuring progress towards achieving the prevention of existing or possible hazards.

Table 3. Safety KPIs for assessing automation in construction.

Safety	
KPI	Reference
Harmful byproduct production (air pollution, dust or chemical concentration, noise levels, etc.)	[8, 10, 28, 32, 34]
Identifiable safety concerns	[32]
Muscle strain	[28]
Number of incidents, injuries, fatalities or hazards	[8, 26, 28, 30]
Safety inspection time	[28]

In conjunction with the quantitative performance indicators, the low level of automation in construction compared to other industries is also due to human and social factors, particularly perceptions and attitudes toward robots. Typical social barriers include lack of knowledge and familiarity, lack of training, fear of job loss, situation awareness, and distrust [5, 9]. Experts in related fields ranked "current work culture/aversion to change" as the 4th most significant factor limiting the adoption of robotics in the construction industry, behind cost and productivity factors [7]. Relevant human factors, as seen in Table 4, can lead to hesitancy and negatively influence the robot's improvement of construction efficiency.

Table 4. Human Factor KPIs for assessing automation in construction.

Human Factors	
KPI	Reference
Acceptability	[8]
Adaptability	[8]
Comprehensibility	[37]
Fatigue	[21]
Operator's average stress	[25]
Reliability	[8, 37]
Safety Perception	[21]
Situation awareness	[26]
Stakeholder satisfaction	[6, 8]
Trust	[17, 26]

3 Methodology

Given the lack of recent literature and case studies assessing robot task performance on construction sites, particularly in interior construction layout, this study aims to 1) develop a multifaceted framework of Key Performance Indicators according to metrics of productivity, cost, quality, and safety; 2) assess the performance of a single-task layout robot; and 3) conduct a comparative analysis of manual and robotic interior layout methods. In accordance with the sequence of steps shown in Figure 1, this section identifies the applicable KPIs extracted from existing literature to assess the robotic interior layout method compared to the traditional method.

The tasks preceding point data collection or layout are classified as set-up tasks. For interior layout, set-up tasks aim to mitigate the need for rework through proper instrumental and methodological steps to ensure precise locations of partitions and systems according to specified

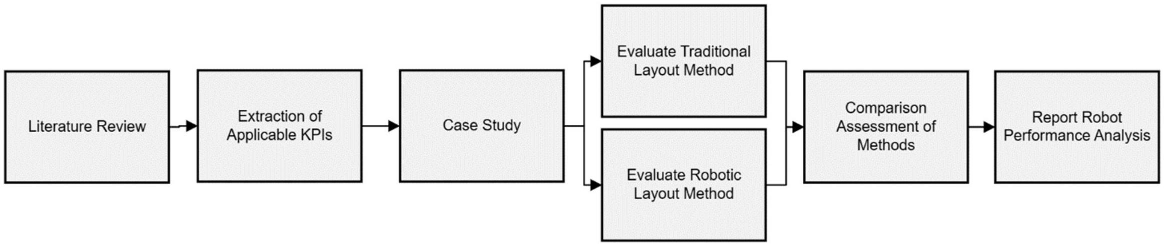

Figure 1. Research Methodology

design plans. The time associated with set up is often minimal, as it's completed once before the task begins. Therefore, set-up time is often not considered in large-scale productivity analyses, but it is a determinant for schedule efficiency depending on the frequency of rework.

The consistency of robot implementation, including higher levels of repeatability and speed, with proper rework mitigation, can reduce the time it takes to complete a given task. As a result, the time saved during a robot's working time indicates increased productivity and a basis for future robot process improvement.

Other studies did not address the time the robot was static or did not perform productive work. In response to this limitation, this study separately assesses wait time as an individual KPI to provide an accurate account of a limitation of layout robots. This cannot be mitigated like other set-up preventative measures and can contribute to increased working time. Thereby, these unforeseeable disadvantages of implementation can pose hindrances to productivity. Congested sites, often those with small areas or complex design plans, result in similar impacts when using the traditional methodology.

Similarly, reducing wait time increases efficiency. On a larger project level, efficiency studies can quickly assess if the project's schedule and cost are well optimized. Measures of robot efficiency assess productivity from workflow initiation to completion and improvement points expected to expedite a project's schedule if implemented.

Of the extracted KPIs, this study adopted 4 KPIs that assess productivity: 1) set-up time, 2) working time, 3) wait time, and 4) efficiency. For additional clarification on how this study categorized the adopted productivity KPIs, the formulaic definitions are provided in Table 5.

Table 5. List of KPIs and their corresponding formulas used to assess performance quantitatively.

KPI	Equation	Reference
Set Up Time	$Set\ up\ Time = \sum Task\ set\ up\ time$	[26]
Working Time	$Working\ Time = Time\ task\ ends - Time\ task\ started$	[26]
Wait Time	$Wait\ Time = \sum Static\ Times$	[31]
Efficiency	$Efficiency = \frac{Working\ Time}{Total\ Time}$	[31]

4 Case Study Comparison Results

We conducted a case study to analyze HP's single-task layout robot compared to the manual layout method. The case study intends to provide a practical means of highlighting the impact and challenges that can further contribute to adopting robots in interior layouts on construction sites.

The *HPSitePrint*, an autonomous printing robot size *50.5x31.7x26.1 cm,* is a portable device that a single operator can transport easily. The performance process was evaluated to determine if the robot was feasible and fit for task employment. Figure 2 details how this study categorized the robot's workflow process according to the adopted KPIs. The implemented workflow provides an organizational framework of productivity metrics for direct comparison to the traditional method.

Unlike the traditional method, the cloud-based management system controlled and organized the robot

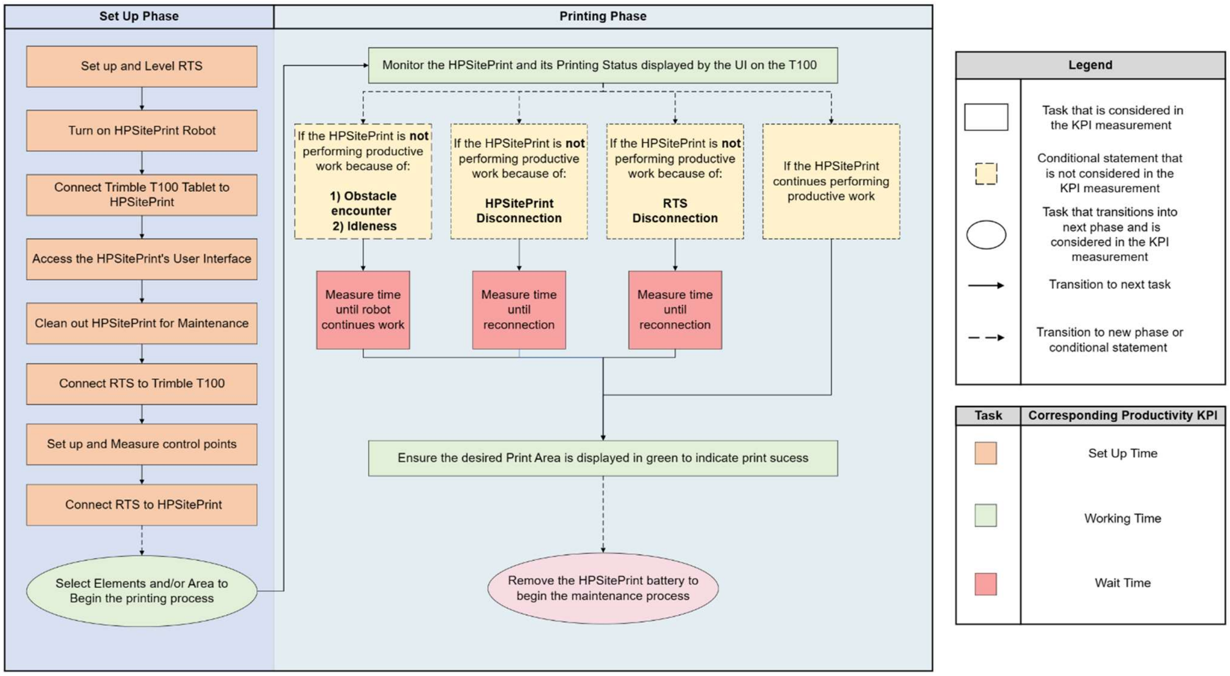

Figure 2. *HPSitePrint* workflow and breakdown of tasks into KPIs to assess productivity.

layout process. This system uses a CAD file with three layers specifying the objects to be printed, objects to be considered obstacles, and objects representing the total station reference points and lines. To initiate the layout, the Trimble Robotic Total Station's (RTS) 573 laser was manually aimed at control points to ensure correct orientation. The operator of the T100, a data collection and processing tablet, could then select the area or components to be printed. The robot autonomously printed the lines and texts based on its self-determined path, tracked by the RTS. However, the autonomous printing path made the implementation of safety controls difficult.

Robots implemented on-site can face interruptions from human and material traffic. Known obstacles from the CAD file can be addressed, but an advancement of the *HPSitePrint* is the ability to add unanticipated obstacles after arrival on-site. The operator could manipulate the robot's movement using the remote-controlled joysticks to avoid oncoming or unanticipated obstacles.

The robot was tasked with printing wall and window lines, door arcs, and text over a 9.17 m^2 area within an enclosed, controlled room. The robot is compatible with ink fluids and can overcome irregular surfaces up to 2 cm thick. Therefore, it can be employed on a wide selection of porous and nonporous surfaces, including builders' paper, the printing surface used in this study. The robot's performance was compared to that of the traditional method using the same CAD file. Once the workflows of both processes were established, we could quantify productivity, cost, and quality measures by completing three trials for each method. There were no measurable safety issues encountered. However, the robot's safety attributes will be briefly discussed in the subsequent safety analysis.

Productivity: Unlike existing studies assessing mobile layout robots, this study analyzed productivity in terms of four separate KPIs instead of dividing total time over a given area. When the robot arrived at the layout area, the time taken to activate the robot was recorded. Once printing began, we recorded the time it took for the robot to finish the desired layout. If the robot were to disconnect from the RTS or T100, encounter an obstacle, or remain idle, the time until reprinting began was measured. At the beginning of each trial, the robot underwent a self-calibration process. This wait time minimally affected the robot's productivity, as the idleness lasted an average of 19 seconds. The total time (i.e., the set-up, working, and waiting times) was calculated to determine the robot's efficiency, defined as the ratio of working time to total time. Compared to the average efficiency of the manual method, the robot method was 17% less efficient. The robot was tasked with a small print area of architectural elements. If tasked with a larger layout containing plans of multiple trades, the robot is anticipated to increase efficiency. The averages of the three trials for the robot and manual methods in terms of the four applied productivity KPIs are shown in Table 6.

Table 6. Productivity comparison results of the manual and robotic layout methods.

KPI	Manual	Robot
Set Up Time	8:08	15:28
Working Time	26:59	23:29
Wait Time	---	0.19
Total Time	35:07	39:16
Efficiency	76.8%	59.8%

Cost: Secondly, we considered the costs required to print the layout. Depending on the need, the robot can be rented instead of bought. To provide a way for project teams to predict and allocate costs, *HPSitePrint* includes all costs in a single fee per square foot of executed layout. Once the layout is completely printed or a month has passed, the cloud software marks the CAD file as completed, and users are billed according to the layout area(s). If implemented, trades can combine their layouts into a single CAD file to be printed within one month to avoid duplicate charges and accelerate the schedule. HP charged 20 cents per square foot or 0.093 per square meter. The printing cost for the 9.17 m^2 area was $19.74. To compare, the mean hourly wage of a construction laborer, including those who operate surveying and measuring equipment, in 2022 was $22.29 in Virginia, according to occupational employment and wage estimates [38].

Safety: Comparable to previous case studies of ergonomic measures, robot implementation alleviated bodily demand, as the conventional approach involved frequently bending down to establish the chalk line. Due to the unpredictability of construction sites, robots need the capability to detect real-time changes in the environment, respond promptly, and navigate present obstacles [11]. An advantage of the *HPSitePrint* is its obstacle avoidance and cliff safety sensors, as shown in Figure 3. These reduce risks by stopping robot movement when encountering elements not included in the CAD file. Ensure the sensors correctly identify obstacles; a daily check of sensor functionality is mandatory.

Quality: Lastly, we evaluated the quality of the robot's print. We overlayed two layout prints using the

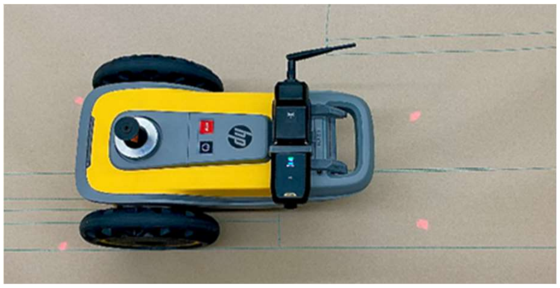

Figure 3. *HPSitePrint* Safety Sensors

same control line and RTS orientation. The robot's repeatability in printing sequential layouts ranged from 0 to 6.35 mm. This variance may pose an issue on-site, depending on the allowable tolerance. Traditionally, the process required two workers to mark point locations within a 6.35 mm tolerance, which the software audibly confirmed. The workers were prompted to relocate the point if staked out of tolerance. Similarly, the workers re-joined the points if chalk lines failed to connect points or were not visible.

5 Conclusion, Limitations, & Future Work

The fast evolution of robots poses challenges to adoption, emphasizing the need for current studies on practical ways to measure their impacts. The absence of a definitive evaluation method underscores the need for a systematic guide when comparing robotic and traditional approaches.

To address this gap, the study's first aim was to address the lack of a recent performance assessment method for on-site construction robots. We achieved this by consolidating KPIs from existing literature into a concise framework to quantify the impacts of robot deployment. Using applicable KPIs, the second aim was to analyse the application of an interior layout robot compared to the traditional method. The analysis showed the robot offers preventative safety measures, expanded printing abilities, and cost-saving opportunities. Also, it identified limitations of the robot, such as inconsistent repeatability.

Given that robots are recent additions to the industry, challenges in revolutionizing assessment methods are anticipated. In this study, our assessment of the robot's performance was limited due to the off-site location. For instance, data collection pertaining to safety and human factors was not feasible without interruptions and interactions with on-site activities. Subsequent studies will allow us to further assess these factors on a larger-scale construction site. Also, the use of trade-collaborated plans can be evaluated in a longer case study period. The results indicated that the traditional method is more efficient, but these changes are anticipated to alter the outcome in favor of the robot.

Based on the insight of the case study, we demonstrated the significance of using a multi-metric framework. Future research should validate the proposed framework's reliability, inclusiveness, and efficacy.

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