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BRIDGING THEORY AND PRACTICE: EVALUATING LEAN CONSTRUCTION WITH LEGO SIMULATIONS

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ABSTRACT

The construction industry faces ongoing challenges in quantifying the benefits of Lean Construction and the Last Planner System (LPS) in practical applications. To address this issue, the study examines data from 40 LEGO-based construction simulations designed to explore key parameters influencing project outcomes, including cost, waste, time, safety, defects, and Percent Plan Complete (PPC). Using statistical methods like correlation and sensitivity analyses can provide valuable insights. The research identifies cost as the most sensitive factor, while material waste management emerges as a critical driver for improving efficiency. Safety and defect reduction also significantly enhance PPC and overall project performance. By mimicking real-world construction scenarios, these simulations provide valuable insights into the practical application of lean principles. The findings highlight the effectiveness of LEGO construction simulations in bridging the gap between theoretical frameworks and on-site implementation, offering actionable recommendations for optimizing construction processes and advancing lean practices.

KEYWORDS

Lean construction, Construction simulation, Last Planner System, Project performance.

INTRODUCTION

Lean Construction is an approach to project delivery based on production management that aims to maximize value and minimize waste in the construction process (Moura et al., 2024). One of the fundamental principles of Lean Construction is continuous improvement achieved through collaborative planning, waste reduction, and all stakeholders in project management. The Last Planner System (LPS), a widely used lean tool, is a practical way to improve reliability and promote workflow stability through detailed short-term planning and commitment by all team members (Vieira et al., 2024).

Despite the proven benefits, applying lean construction and Last Planner Systems in real projects faces challenges, especially in quantifying results and translating them into measurable

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parameters for real-world implementation (Antonini et al., 2023). While much of the existing research focuses on the conceptual benefits of lean practices, there is limited research on how simulation-based approaches can generate data representative of real-world construction scenarios (Diaz, 2022). Furthermore, while interactive simulations have been used to teach lean principles, few have been used to evaluate key factors that impact project performance specifically. This limitation hinders bridging the gap between lean theory and its operational impact in field projects (Johansen et al., 2021). This highlights a gap in the empirical evaluation of lean tools, such as the Last Planner System, using data-driven simulation methods that accurately reflect actual project dynamics. Studies that systematically analyse which aspects of LPS most significantly influence project outcomes and how these simulation findings can be translated into practical applications in the construction industry lack

This study investigates Villego® simulations of the LPS delivery as measurable results representing real construction projects. By analysing the results of a series of simulations, the study aims to identify the key parameters and governing factors influencing project performance. The results aim to contribute to a deeper understanding of how lean principles, demonstrated in controlled simulations, can be effectively applied to optimize the outcomes of actual construction projects.

LITERATURE REVIEW

The Last Planner® System (LPS) is a structured project management approach widely applied in the construction industry to improve project efficiency, coordination, and waste reduction (Ballard, 2000). LPS consists of several key components, including lookahead planning, weekly work planning, and reliable promising, which are essential for ensuring continuous workflow and reducing uncertainties in project execution (Hamzeh et al., 2012) Studies have demonstrated that implementing LPS can improve project performance by minimizing delays, enhancing stakeholder collaboration, and optimizing resource allocation (Daniel et al., 2015). Furthermore, LPS incorporates collaborative planning techniques such as Pull Planning, which engages subcontractors and other key stakeholders in scheduling, ensuring better workflow synchronization (Brioso et al., 2024).

Several performance assessment parameters are commonly used in LPS to evaluate project success. One of the most significant metrics is the Percent Plan Complete (PPC), which measures the percentage of tasks completed as planned. PPC indicates planning reliability and has been widely studied in lean construction research (Ballard, 2000). Other crucial performance indicators include project duration, defect rates, cost efficiency, and waste reduction. For instance, simulation models have been employed to analyse potential scheduling delays and optimize resource allocation (Kithas, 2022). Reducing defects through better Planning and coordination has been shown to improve construction quality, while cost analysis helps project teams assess budget adherence (Lello & Emuze, 2024). Waste reduction, a core principle of lean construction, has been explored in multiple studies, emphasizing the role of structured Planning in eliminating non-value-adding activities (González et al., 2015).

A significant challenge in lean construction implementation is the effective transfer of lean knowledge and principles to practitioners. One of the emerging methods to overcome this challenge is using simulation games to facilitate experiential learning. Research has shown that simulation games effectively improve lean thinking and LPS adoption by providing participants hands-on experience in lean principles (Bhasin, 2012). For example, Villego® simulation is a widely recognized educational tool designed to train teams in lean project management by simulating real-world decision-making processes (Aisyah et al., 2023). Aisyah & Putra, 2024 reported that participants demonstrated a 25% increase in understanding of lean concepts after engaging in simulation games, supporting the effectiveness of such tools in lean education.

Several studies in educational research journals have specifically examined the impact of simulation games on lean thinking and construction project performance. For instance, Salazar et al., (2018) explored how simulation-based learning enhances participants' ability to identify and manage waste in construction workflows. Similarly, Bhatnagar & Devkar (2021) conducted an experimental study where participants engaged in the Villego® game, demonstrating measurable improvements in workflow efficiency, collaborative decision-making, and defect reduction. The game consists of three rounds, where teams must construct defect-free houses within a time limit while implementing lean techniques such as 5S, Kanban, Heijunka box, and Pull Planning. The iterative nature of the game reinforces the principles of continuous improvement and waste minimization, making it a valuable tool for both students and professionals in the construction industry.

Despite the promising findings, some studies highlight the limitations of simulation games in lean education. For example, there are concerns regarding the generalizability of simulation outcomes to real-world construction projects due to differences in complexity and scale (Sacks et al., 2010). Additionally, while games like Villego® focus on process efficiency, they may not fully capture the human and organizational challenges associated with lean adoption in large-scale projects. Therefore, future research should explore integrating simulation games with real-world case studies and digital twin technologies to enhance their applicability in professional training environments. In summary, the literature underscores the importance of LPS in improving construction project outcomes and highlights the role of simulation games as practical learning tools for lean construction education. However, further research is needed to critically evaluate the long-term effectiveness of simulation-based learning and its integration with emerging digital tools in lean construction training.

METHODOLOGY

DATA COLLECTION

This study collected data through 40 simulations organized into eight batches. Each batch included five simulations that explored various scenarios by systematically varying key parameters relevant to the research objectives. This approach ensured that the data comprehensively represented system performance under diverse conditions.

PT PP (Persero) Tbk., a leading construction contractor in Indonesia, conducted these construction simulations using LEGO models. The simulations took place from 2022 to 2024, with the company organizing 2–3 batches annually. Each batch involved 4–5 simulations with different participant groups. By adopting this approach, the study enhanced the understanding of construction practices and system performance while promoting diverse participation, which added depth to the findings.

This study aims to analyze data derived from Lego Performance Simulation (LPS) through a simulation-based approach using Lego models. The research data consists of eight batches, totaling 40 simulations, each considering six key performance aspects.

1. Order Cost (studs): Represents initial and additional material expenses.
2. Safety Incidents (occurrences): Number of safety incidents.
3. Waste Material (studs): Quantity of unused or discarded materials.
4. Defects (studs): Errors in assembly or construction.
5. PPC-Percent Plan Completed (Deviation in studs): Planned versus actual performance.
6. Completion Time (seconds): Duration of each simulation.

This approach is designed to identify factors with significant correlations to system performance, perform sensitivity analysis on the identified sensitive factors, and determine the weights of these factors using the weighted scoring method. The weights derived from this analysis are compared to those employed in Lego competitions held in Indonesia.

SIMULATION STEP

The Lego simulation was carried out by teams of 7 people, each consisting of 1 main contractor and six subcontractors. Each subcontractor has a role/color that each team has set. The simulation was run within a scheduled time of 100 minutes. 10 minutes for preparation, 25 minutes for planning, and 60 minutes for construction, of which 1 minute was for construction implementation and 9 minutes for evaluating and replanning; the construction session was carried out 6 times, the last 5 minutes for reporting. The assessment was done by analyzing the reporting of results that reflect cost, time, defect, PPC, waste, and safety.

The simulation process began with each team being given a digital model of the project that they had to plan and implement using Lego blocks as a physical representation of the construction elements. Each team applied the Last Planner System (LPS) principle to plan each stage of the project, from initial planning involving analysis of needs and resources to the implementation of the simulation, which included collaboration between various roles such as the main contractor, subcontractors, and suppliers and was carried out within 25 minutes. Next, the construction process is carried out, and the subcontractors must install the Lego blocks according to the plan in the LPS within 1 minute and continue with 9 minutes of evaluating and replanning for the following construction session. The construction session lasts 6 times and is repeated. During the simulation, the team must adapt to the challenges that arise, manage time and costs efficiently, and minimize waste. After the simulation is complete, the team prepares a report of the results that includes performance evaluation based on cost, time, defect, PPC, waste, and safety criteria so that this process not only improves the technical understanding of the participants but also strengthens cooperation and communication in the context of an actual construction project.

ANALYTICAL APPROACH

The analytical process began by identifying factors significantly correlated with the simulation outcomes. This was achieved through statistical methods, including linear regression and correlation analysis, which facilitated an evaluation of the relationships between variables. Significant factors identified through this process were subjected to a sensitivity analysis to quantify their influence on simulation results. Sensitivity analysis was conducted by systematically varying the values of each factor to observe the resulting changes in system performance, thereby identifying priority factors that require focused attention.

Subsequently, the weighted scoring method was employed to calculate the relative weights of the identified factors. This method integrated the sensitivity analysis results with the significance of each factor to derive weights that reflected their respective contributions to overall performance. These weights were then compared with those used in Lego competitions held in Indonesia to assess alignment and provide recommendations for potential enhancements.

To support the research, data visualization techniques such as scatter plots, heat maps, and sensitivity graphs were utilized to enhance the interpretability of the results. Additionally, simulation software was employed to ensure accurate and repeatable scenario execution under controlled conditions. The final step involved validating the findings by comparing simulation results with historical data from Lego competitions in Indonesia to ensure accuracy and relevance. Through this methodological approach, the study provides valuable insights into the factors influencing Lego system performance and offers data-driven recommendations for future developments.

RESULT AND ANALYSIS

CORRELATION BETWEEN PARAMETERS

The data analyzed in this paper was based on many simulations the contractor team had already conducted. There are forty-one times of construction simulations using Lego as a platform to exercise and understand how to implement the Last Planner System. Based on the simultaneous data, there are some correlations from each parameter: time with waste, cost and time, Percent Plan Complete (PPC) with waste, defect with waste, safety with waste, time with defect, cost and defect, PPC with time, and PPC with cost. Also, we got the weighted parameter average from all parameters.

This graphic from Figure 1 depicts the correlation between cost and waste (physical) in the LEGO simulation. The trend suggests that as cost increases, waste also increases. The regression analysis yields an R-value (or confidence level) of 0.2638, which indicates a low to moderate correlation. This suggests that while there is a relationship between cost and waste, it is not particularly strong and warrants further investigation to confirm its significance. However, the key aspect highlighted here is the positive gradient of the trend line, which indicates that as waste increases, the associated costs also rise. This emphasizes the critical impact of waste management on cost efficiency in construction projects, underscoring the importance of minimizing waste to control costs effectively. Cost refers to the resource expenditure required to produce. In this context, cost can be defined as variable cost that changes with production or activity level. The cost value is from the beginning of the material order.

Meanwhile, waste refers to materials or resources that have not contributed to values. In this context, waste is defined as more Lego than it should be. The people in that simulation who were responsible for causing waste failed to control the materials as specified in the shop drawing.

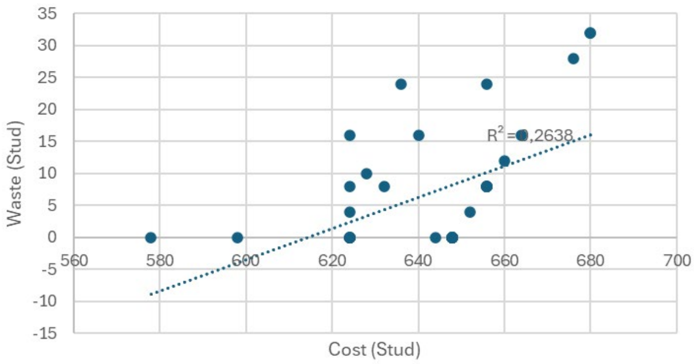

Figure 1: Corelation Between Cost and Waste

Uncontrolled waste will result in excessive costs and vice versa. Based on Figure 1, monitoring is essential, and mitigation measures to reduce the risk of waste are even better. The player responsible for causing waste is the one who failed to control the materials as specified in the shop drawing.

Figure 2 illustrates the relationship between time and variance derived from PPC (Percent Plan Complete), showing a moderate positive correlation. This indicates that as deviations in PPC (differences between planned and actual completion) increase, the time required to complete tasks also rises. In other words, lower PPC performance—reflecting poor adherence to planned schedules—directly affects project timelines and delays. These findings highlight the critical role of monitoring and improving PPC to optimize time management and ensure timely project delivery. Focusing on enhancing PPC performance can significantly mitigate schedule overruns and contribute to better overall project outcomes.

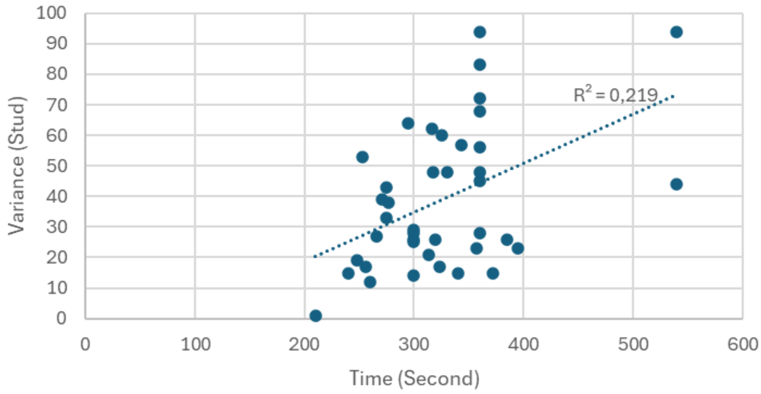

Figure 2: Correlation Between Percent Variance and Time

The data presented in Figure 3 highlights the relationship between time and waste in the LEGO-based construction simulation, illustrating that maintaining low levels of waste is critical for improving performance and reducing completion time. Simulations with an average waste of 1 stud were completed in under 300 seconds, while those with an average waste of 5 studs exceeded 300 seconds to reach completion. This indicates that teams that effectively minimize waste through better resource management and adherence to planned procedures could complete the simulation more efficiently. The significant reduction in time achieved by maintaining low waste levels underscores the importance of waste minimization strategies in enhancing overall project productivity.

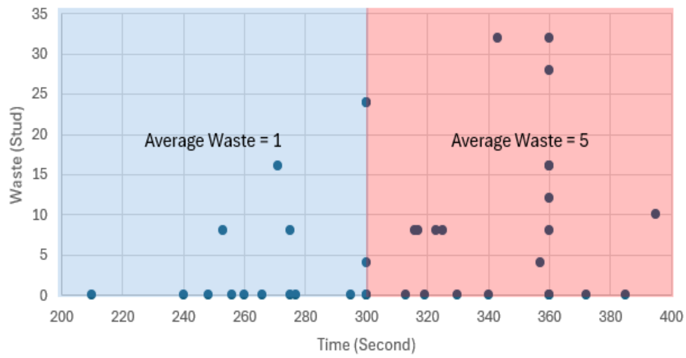

Figure 3: Comparison Between Average Waste

The findings further emphasize the compounding effect of waste on project duration. Increased waste, as represented by an average of 5 studs, likely reflects inefficiencies in material handling, decision-making, or task execution, which extend the time required to complete the project. This direct relationship suggests that waste reduction optimizes resource usage and mitigates delays, enabling timely completion. This insight highlights the critical need to implement waste management practices such as material monitoring, error prevention, and adherence to predefined workflows in real-world construction applications. These practices can ensure that projects remain on schedule while maintaining efficiency, mirroring the results observed in this simulation.

Sensitivity Analysis

This research focuses on examining the sensitivity of critical parameters that impact the effectiveness of construction systems. The data used include six main parameters, namely COST, SAFETY, WASTE, DEFECT, PPC, and TIME, which were measured from the results of construction process simulations. The analysis was conducted by calculating the absolute average sensitivity of each parameter to changes in other parameters. This sensitivity was then normalized into percentage contributions to the total system sensitivity. The results show that COST is the most sensitive parameter, contributing 10.44% to the total system sensitivity.

Conversely, SAFETY is the least sensitive parameter, contributing only 0.06%. The other parameters exhibit varying levels of sensitivity, namely TIME (5.26%), PPC (0.61%), DEFECT (0.18%), and WASTE (0.12%). The calculation began by measuring the average changes in each parameter relative to the others in the dataset. For each parameter, the sensitivity formula is: where represents the sensitivity of the parameter to the parameter. These values were averaged in absolute terms to obtain the overall sensitivity scores for each parameter. Subsequently, these sensitivity scores were normalized by comparing the contribution of each parameter's sensitivity to the total sensitivity of all parameters.

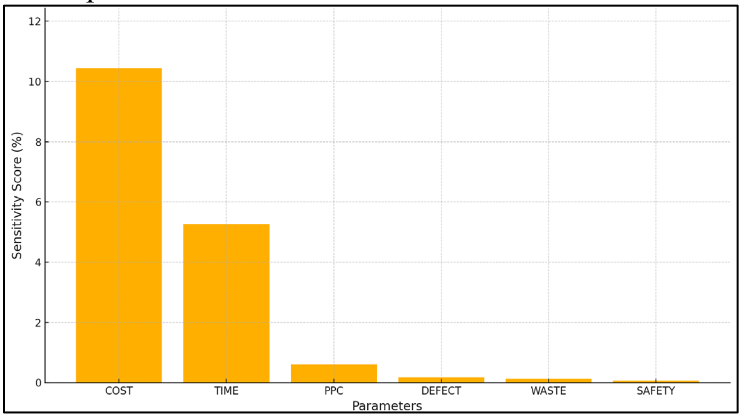

Figure 4: Sensitivity Scores of Parameters

The figure of 10.44% for COST indicates that changes in this parameter contribute 10.44% to the total system sensitivity, making it the most sensitive parameter. This implies that small changes in COST can significantly impact other parameters, such as project completion time (TIME) and resource efficiency (PPC). Conversely, the figure of 0.06% for SAFETY shows that changes in this parameter contribute only 0.06% to the total system sensitivity, making it the most stable parameter with minimal influence on others. In this context, SAFETY is not significantly affected by changes in the system but remains important due to its relevance to workplace safety and project sustainability.

These results provide crucial insights into the planning and control of construction projects. In simulations, greater attention should be given to the COST parameter to minimize its adverse impacts on other parameters. Meanwhile, although SAFETY has low sensitivity, risk management in safety should remain a top priority to maintain the sustainability and reputation of construction projects. The TIME parameter also demonstrates significant sensitivity, underscoring the importance of effective schedule management measures. In actual field practices, these findings highlight the critical importance of strict cost control as a primary strategy for achieving project success without neglecting safety risk management, which remains fundamental to the overall sustainability of project operations.

WEIGHTED SCORING APPLICATION

In a simulation project using LEGO, the distribution of weights assigned to various parameters demonstrates critical insights into project management performance. Based on 40 simulation iterations conducted across eight batches, the resulting weight distribution deviates significantly from the established benchmark used in previous LEGO competitions. The competition benchmark allocated equal importance to cost, safety, material waste, defect rate, time, and planning-production correlation (PPC), each weighted at 20%. However, the simulation-derived weights offer a more empirically grounded perspective, reflecting the actual performance of the participating teams.

The results indicate that the weight of the cost parameter decreased from 20% in the benchmark to 17% in the simulation, suggesting that, while cost remains a vital factor, it does not dominate as the primary determinant of project success. Conversely, the weight assigned to material waste increased significantly from 10% in the benchmark to 14% in the simulation. This adjustment highlights the heightened significance of material efficiency in ensuring project success, aligning with the broader emphasis on sustainability in project execution. The weight assigned to safety also experienced a slight decrease from 20% to 15%, which may reflect the controlled environment of the LEGO simulation, where safety risks are inherently lower compared to real-world construction settings.

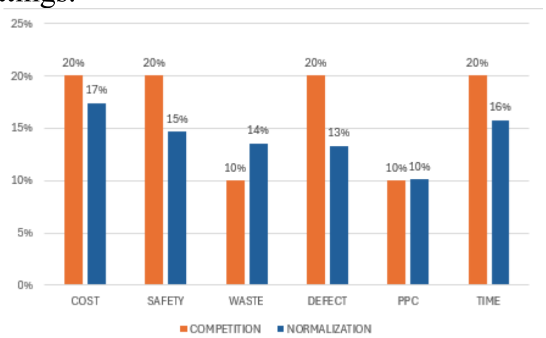

Figure 5: Comparison Between Weighted Score in Competition and Normalization

Additionally, the defect parameter reduced its weight from 20% in the benchmark to 13% in the simulation. This finding suggests that the teams involved in the simulations demonstrated relatively robust quality control, minimizing construction defects effectively. Meanwhile, the weight of time, which was set at 20% in the benchmark, was adjusted to 16% in the simulation, signifying that time management remains an essential factor but is balanced against other priorities, such as material waste and safety. Finally, the PPC parameter retained its weight at approximately 10%, underscoring its consistent importance in aligning planning and execution within the benchmark and simulation frameworks.

These differences reveal that the LEGO project simulation provides empirically derived insights that could serve as a basis for re-evaluating the priorities established in the competition benchmark. The simulation results emphasize the need to assign higher importance to material waste management and a more balanced approach to cost, time, and safety, reflecting these parameters' dynamic and interdependent nature in project performance.

The findings highlight the potential for using simulation-driven data to inform and optimize project management strategies, particularly in educational or competitive contexts such as LEGO-based simulations. By analyzing parameter weights, researchers and practitioners can identify key areas for improvement and alignment with real-world construction practices while addressing critical challenges such as resource efficiency, time optimization, and quality assurance.

KEY DRIVERS IN SIMULATION AND REAL CONSTRUCTION

LEGO Simulation is a method of simulating a project by implementing The Last Planner System (LPS). Through this activity, the project team, as players, is placed in conditions similar to those in the actual project. Reading the LEGO model design represents interpreting shop drawings on a project, calculating the number of LEGO studs and pieces illustrates calculating project work volumes, purchasing LEGO materials mirrors, procuring materials for a project, and devising gameplay strategies such as scheduling and construction sequencing simulates planning and construction strategies in a project. Scheduling is conducted through a collaborative approach involving all subcontractors/vendors on the project, called Collaborative Pull Planning. The game runs for 300 seconds and comprises five planning and construction phases. This simulates the project execution time allocated over five weeks, from start to finish.

Figure 6: A Piece of LEGO Simulation Documentation

The game is divided into several teams in a single simulation session, typically five or six. LEGO play represents actual project conditions and includes evaluations at the game's midpoint and end. These evaluations assess parameters representing project components, such as initial order costs, safety, material waste, defects, time, and Percent Plan Complete (PPC). The evaluation results from LEGO simulations conducted from early 2022 to early 2023 were analyzed.

Implementing LEGO play produces numerous outputs and lessons that reflect project conditions. These outputs and lessons are presented by each player at the end of the game, starting with the subcontractors/vendors as end-users in the field. Additionally, field teams, including the Superintendent (SP), General Superintendent (GSP), and Quality and Healthy Safety Environment (QHSE) Team, also share their insights. Furthermore, engineering teams, such as the scheduler, methods team, BIM Engineer, and Supply Chain Management (SCM) team, contribute their findings. Insights are also provided at the management level by the Site Engineer Manager (SEM), Site Operational Manager (SOM), and Project Manager (PM). The lessons and outputs obtained span various aspects, including:

1. **Material Management**: Lessons learned include cross-checking materials against the reference drawings and material forms provided (SCM).
2. **Collaboration and Coordination**: Each trade ensures sequences do not overlap, promotes collaboration, and maintains calmness and precision during activities (HCM-human capital management).
3. **Leadership**: Implementing a single-command system led by one designated leader while avoiding situations where everyone acts as a leader.
4. **Planning** and Scheduling: Emphasizing the need for thorough planning and accurate forecasting of future progress.
5. **Defect Prevention**: Rework due to defects can delay subsequent tasks, underscoring the need to avoid errors in methodology and task completion.

Findings from the LEGO simulations reflect challenges commonly encountered in real-world construction projects:

1. **Time Management**: As observed in the simulations, deviations in the Percent Plan Complete (PPC) often lead to project delays. This mirrors the findings of Ballard & Tommelein (2021), who emphasize PPC as a key performance indicator in the Last Planner System (LPS) to improve schedule reliability. The importance of accurate planning and continuous monitoring is further supported by Rouhana & Hamzeh (2016), who found that increasing PPC leads to improved workflow and reduced project duration.
2. **Safety and Waste Management**: Safety issues and material waste were prominent in the simulations, underscoring their critical role in project performance. This is consistent with the

lean principle of waste elimination (muda) described by Koskela (2000), which includes both material waste and safety-related inefficiencies. Implementing rigorous safety protocols not only aligns with lean goals but also supports creating a safer and more productive work environment, as demonstrated in field studies by Formoso et al. (1999).

3. **Cost Efficiency**: The simulation highlighted the impact of effective budget tracking and resource planning. This reflects the findings of Rafael et al., (2010), who emphasize cost efficiency through lean practices such as just-in-time delivery and pull-based planning. Financial discipline through cost monitoring in the simulation parallels real-world applications where lean techniques have significantly reduced unnecessary expenditures and enhanced value delivery.

CONCLUSIONS

The LEGO-based simulation provides a simplified yet insightful representation of construction project dynamics, focusing on critical parameters such as cost, waste, time, safety, defects, and PPC (Percent Plan Complete). While the simulation environment does not replicate the full complexity of real-world construction, it offers a controlled setting to examine interactions between these parameters and their impact on project performance. For instance, the positive correlation between cost and waste and cost sensitivity are the most influential parameters that reflect challenges often encountered in construction projects, such as budget overruns caused by resource inefficiencies. Additionally, the observed relationship between PPC and time delays mirrors real-world scenarios where poor schedule adherence disrupts project timelines, making this simulation aspect highly representative.

However, certain limitations must be acknowledged when considering the representativeness of the simulation. The controlled and structured environment of the LEGO simulation inherently lacks the unpredictability of real-world construction, such as weather conditions, labor dynamics, regulatory constraints, and stakeholder interactions. For example, the reduced weight assigned to safety in the simulation reflects the absence of real-world hazards and risks, critical components of construction project management. Similarly, while the simulation provides valuable insights into material efficiency, it does not fully capture the logistical and supply chain challenges that often influence material waste and availability in actual construction scenarios. These limitations suggest that while the simulation effectively models fundamental principles, it does not entirely replicate the multifaceted challenges of real-world construction projects.

Incorporating additional real-world variables and complexities would be essential to enhance the applicability and representativeness of such simulations in construction. Integrating scenarios that mimic environmental factors, labor fluctuations, and regulatory requirements could provide a more comprehensive understanding of project dynamics. Furthermore, coupling simulations with advanced technologies, such as Building Information Modeling (BIM) or virtual reality, could bridge the gap between simulated and real-world conditions. In conclusion, while the LEGO-based simulation is a valuable educational and analytical tool for understanding core project management principles, its current scope is better suited as a foundational model rather than a direct representation of real-world construction project performance. Adapting and extending the simulation to include real-world complexities would significantly enhance its utility in practical applications.

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