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APPLYING LEAN STANDARD OPERATING PROCEDURE TO PANELIZED PREFABRICATION IN THE FACTORY

Leyi Zhou and Xinming Li

ABSTRACT

This study investigates the application and significance of Lean Standard Operating Procedures (Lean SOPs) in panelized prefabrication within the construction industry, intending to improve efficiency, safety, and sustainability and accelerate the diffusion of Lean SOPs within the construction industry. As a component of off-site modular construction, panelized prefabrication is widely used for rapid on-site installation and a safer and more convenient off-site manufacturing process. This study develops a Lean SOP framework and evaluates it by tracking and monitoring operational performance using a structured approach of time study, ergonomic risk assessment and expert discussion. After implementing the SOP framework in a case study, the results show that Lean SOPs can reduce time consumption by up to 35%, improve ergonomic safety scores by more than 50%, and reduce hazard levels to acceptable levels, thereby increasing overall productivity.

KEYWORDS

Panelized prefabrication, off-site manufacturing, SOP, efficiency, safety

INTRODUCTION

Since 1945, manufacturing, retail and agriculture productivity has grown by as much as 1500 percent in the United States, while construction productivity has been underperforming (Filipe et al., 2017). Among these, the challenges faced by the industry in North America are efficiency, quality, sustainability, and meeting the increasing demands for housing and infrastructure (Abraham et al., n.d.). Lean Manufacturing offers a transformative approach to reducing waste, optimizing workflows, and improving project productivity and safety (Filipe et al., 2017). Despite the proven benefits of Lean Manufacturing, adopting lean manufacturing remains complex and inconsistent mainly due to limited technological infrastructure, cultural resistance to change, and a lack of knowledge of lean concepts and practices (Wandahl, 2014). Panelized prefabrication is an off-site manufacturing technique that shifts manufacturing activities from traditional on-site methods to a controlled factory environment. Consequently, this leads to more controlled, streamlined processes that offer consistency, deduce variability and enhance precision (Peiris et al., 2021). Thus, panelized prefabrication is the foundation for achieving widespread impact in lean manufacturing. However, due to the complexity and dynamic nature of the construction industry, a broader range of fully represented diverse construction processes, locations, and project sizes exists. These constraints affect the standardization of streamlined processes and make it difficult to generalize with Lean principles, and a clear understanding of technical requirements in Lean practices is highly demanded for standardization to initiate (Bayhan et al., 2019). Lean SOPs are sequenced detailed instructions that standardize workflow processes, minimize waste and encourage continuous improvements (Peiris et al., 2021). Although the application of Lean principles in the construction industry is becoming popular, there is still a significant research gap in their integration and development with SOPs, particularly in panelized prefabrication. Existing research has focused on on-site Lean Construction methods, thereby neglecting the process of manufacturing in factories. In addition, the ability of Lean SOPs to standardize production and share resources across different organizations has been overlooked. Standardized and replicable manufacturing methods do not address time efficiency, ergonomic safety, and cross-company collaboration issues. The spread of Lean SOPs has been hindered and limited. This paper examines how integrating Lean SOPs into panelized prefabrication processes can bridge the challenges between Lean theory and practical implementation and ultimately provide a more sustainable and productive manufacturing industry while reducing waste and fostering continuous improvement environments.

LITERATURE REVIEW

SOPs are often associated with standardization, defined as a sequence of instructions that solve repetitive applications to problems in various disciplines (Akyar, 2012a). SOP forms the framework for a quality management system (Endrullat et al., 2016). The goal is to present detailed, written instructions to achieve uniformity in performing a specific function that defines SOP (Manghani, 2011). Following SOPs within an organization will ensure consistency and compliance, reduce errors, improve efficiency, and enhance overall job quality, and industries such as healthcare, aerospace, and automotive manufacturing have long utilized SOPs to maintain consistency and compliance with regulatory standards (Akyar, 2012b).

Adopting SOPs can significantly benefit the prefabricating manufacturing industries since high safety risks often characterize them, especially companies specialized in the production process (Arumbasari et al., 2021). Common hazards such as slips, falls, and equipment mishandling lead to substantial financial and human costs. Integrating SOPs into health, safety, and environmental protocols can minimize potential manufacturing accidents.

Prefabricated manufacturing has inadvertently begun formulating a Lean SOP by prefabricating building elements in advance and transporting them to the project site. This reduces the time and effort involved in on-site manufacturing, simplifies and fixes the workflow, and reduces manufacturing waste. Various precast concrete building systems were built and assembled to form the complex public housing development. This manufacturing concept was developed to reduce project time, reduce the skilled workers needed, increase project quality, increase on-site labour productivity (Caldeira, 2010), reduce the adverse effects of environmental impacts of manufacturing operations, increase the safety performance on-site and reduce the effects of incremental weather conditions (Lu & Liska, 2008).

Panelized prefabrication is one of the manufacturing methods of modular prefabrication. Framers manufacture all the wall, floor, and roof panels off-site in a factory and then transport them to the manufacturing site, which can reduce manufacturing time and waste (Shroff & Joshi, 2022). Panels can be customized and pre-installed with insulation, windows, doors or plumbing, resulting in increased installation efficiency and design flexibility, and panelized prefabrication can also improve safety, reduce waste and comply with lean manufacturing principles by minimizing material waste and maximizing productivity (Shroff & Joshi, 2022).

Lean principles have three important components: Lean Manufacturing, Lean Production, and Lean Management. These can be integrated with SOPs to obtain our Lean SOPs.

The efficiency and quality of the manufacturing factory need to pursue the optimal data from the previous data when the situation applies and even go beyond the optimal historical data when the optimal situation also reveals problems or improvement methods (Du et al., 2023). The Lean Manufacturing concept is better used in the off-site factory by continually improving the efficiency of the manufacturing process, increasing worker safety and reducing potential ergonomic risks (Kumar et al., 2022). When manufacturing processes and standards are standardized, the quality of the panels will be guaranteed and improved, and customer satisfaction with the product will increase.

Lean production is not limited to the optimized building components; it also represents the use of Lean Concepts by employees and managers (Cagnetti et al., 2021). Implementing Lean principles into production and management can reduce waste, optimize workflows, and improve efficiency. This helps transport processed materials to the next station in a timelier manner and minimizes waiting time for production workers. At the same time, the risk of workplace injuries is significantly reduced by fostering safer work habits.

Lean Management focuses on maximizing value for customers and minimizing waste for the company (Eldeep et al., 2022). It provides continuous improvement, streamlined workflow and reduces the waste of resources through the application of Lean Principles. Lean management requires employees at all levels of a company to work together to improve collaboration and innovation between different departments. It prioritizes customer needs, reduces inefficiencies such as overproduction, excess inventory and delays, and improves adaptability to changing conditions. It has improved the effectiveness of actions and plans by thinking and planning before acting and avoiding ineffective actions and those that pose a risk to human safety.

Traditional SOPs often focus on fixed operational processes, making it difficult to consider the ever-changing realities of the manufacturing environment. Lean concepts, on the other hand, incorporate the principles of continuous improvement, allowing processes to be more flexible, adaptable and optimized to respond to various needs. (Gil-Vilda et al., 2021). SOPs provide detailed step-by-step guidelines necessary for standardizing prefabrication workflows, while Lean principles provide guides for continuous improvement and alignment with aimed goals (Peiris et al., 2021). Lean principles and prefabrication lean manufacturing emphasize minimizing waste and maximizing value through systematic workflows and collaboration. Prefabrication methods align well with Lean principles due to their potential for standardization and repeatability (Du et al., 2023).

However, integrating Lean principles with prefabrication lean manufacturing SOPs requires a lot of data and tracking of actual production, so this is a topic that has not yet been researched; therefore, many companies continue to rely on outdated SOPs, which makes it challenging to adapt to evolving environments and technologies. By linking Lean principles and SOPs in prefabrication, Lean manufacturing, precision, efficiency, and waste reduction become the key evaluating factors.

RESEARCH METHODOLOGY

This study focuses on how Lean SOP can be applied to the off-site portion of panelized prefabrication. The study methodology for developing the Lean SOP application was designed in three steps and presented in the flowchart in Figure 1.

1. This study aims to create widely used Lean SOP guidelines for panelized prefabrication in the factory setting. Different companies can design their Lean SOPs using the same guidelines for their situation and conditions.
2. Establish a system for tracking and monitoring the Lean SOP and updating it in real time so that companies can adjust and adapt it to changes and updates in their manufacturing and management systems.
3. Hold an expert discussion with relevant staff (project managers, inspectors and staff) to provide high-quality information on the practicalities and challenges of implementing the Lean SOPs.

Figure 1 Methodology Overview

CREATE LEAN SOP GUIDELINES.

Lean SOPs can be applied to every aspect of the manufacturing industry, ranging from high-level strategies such as guiding a company's growth approach to granular details like standardizing the precise distance between screws for consistency and quality. This study provides insights into developing Lean SOPs for panelized prefabrication in two parts: 1. Develop Lean SOPs from Lean Manufacturing, Lean Production, and Lean Management. 2. Develop a clear guideline of how to create the Lean SOP for manufacturing panels in the factory

Develop Lean SOP from Lean Manufacturing, Lean Production, and Lean Management

By integrating the advantages of Lean Manufacturing, Lean Production, and Lean Management with SOPs, the Lean SOP is derived. This Lean SOP will emphasize to all team members within the company the importance of identifying and minimizing waste, which can occur in any process and at every level, e.g., overproductions, excess inventories, wait times, and unnecessary transportation, as well as discussions to reduce waste with team members and team leaders. Through periodical open discussions, all team members were encouraged to develop a culture of continuous improvement by developing standardized work instructions, checklists, and templates for everyday tasks to increase efficiency and reduce waste. The study process is identified and appropriately documented during station surveys. There are many uncertainties and variations in the manufacturing station, and data from special situations need to be flagged and categorized individually, such as delays due to a lack of human resources, machine breakdowns, and material shortages. Each station is inspected correctly based on current requirements and station compliance inspections. Once sufficient data has been collected based on all investigations, the SOPs are updated and revised at monthly and quarterly meetings, which is the initial version of the Lean SOPs.

When it is possible to design and implement some Lean SOPs, it is possible to look for patterns in the basis of the processes they create, summarize the methodology and refine a template that will provide a basis for promoting the application of Lean SOPs.

LEAN SOP TRACKING AND MONITORING SYSTEM

Lean principle in construction is an iterative approach characterized by perpetual refinement and innovation to optimize construction processes (Searcy, 2009). It requires constant reflection and modification based on evolving operational conditions and construction realities to respond to emerging challenges (Searcy, 2009). The following monitoring and updating systems are required for data spanning the entirety of the manufacturing lifecycle until the latest iteration of Lean SOPs is systematically collected, organized, and analyzed. This includes accessing multiple dimensions, including time, body position, risk, etc. This study emphasizes these two dimensions; however, more factors, such as Lean SOP, can be included in this analysis.

To optimize the initial version of the Lean SOP even further, a new cycle of observation, analysis, discussion and follow-up will be conducted. In the new observation and documentation, the manufacturing procedure is investigated and documented at each manufacturing station. These procedures are then cross-checked with the current Lean SOPs to evaluate the efficiency of the manufacturing process and to adopt more valuable SOPs. There is then a need to continue to track time and safety and analyze data to identify inefficiencies. Feasible recommendations for improvement are made to address these issues and prioritized according to the level of impact and feasibility. These issues are then discussed and researched with the relevant people for new findings and improvements. Finally, the findings are compiled into a detailed report with visuals to present to stakeholders and monitor the implementation of the proposed changes, refining the process as needed for continuous improvement.

Time Consumption

Time information is collected by monitoring and tracking the progress of construction in real time, recording the start and end times of each step, and summarizing this detailed information in a timesheet based on the Time Study Observation Form (Freivalds, A. (2014)).

The Time Study Observation Form divides the manufacturing of the panels into different phases and tasks and records task description, operator details, time, method description, motion analysis, and additional notes. In this study, performance rating (R), watch time (W), and observed time (OT) are the most critical data to record and observe, as these data can best visualize the time consumed by each task and phase in different situations. Effective and ineffective actions can be extracted by recording and analyzing the time spent on individual tasks. Ineffective actions must be minimized or avoided to save time to accomplish the task most efficiently. When each task is performed at maximum efficiency, the time for the entire project is reduced to the shortest possible time, which is the most idealized working time.

The time recording of the panel manufacturing is to record the time consumed for each step, and the number of workers required also needs to be recorded as changes in the number of workers directly affect the total number of hours required for the whole project. The total work time can be obtained by multiplying the time of each job by the number of workers needed for that job to get the total number of hours for the individual jobs and then adding up the total number of hours for those jobs for an entire project.

Ergonomic Assessment

Although many measurement tools are available that can accurately measure and calculate static and dynamic data about the human body, tools which are more convenient, cheaper, and do not interfere with the worker's work are necessary. In this study, the movements and body postures that workers on the manufacturing station would make at a high frequency were photographed from multiple angles. When selecting the subjects for filming, we avoided choosing inexperienced novices to prevent the data of the body in a dangerous state from being too high. Some of the incorrect movements and postures of these novices were the problems that had been emphasized in training before the official start of the work and belonged to the contents of the existing Lean SOPs. Workers' most common movements and postures when manufacturing panels are standing, squatting, bending and crawling (Ray & Teizer, 2012).

The camera was positioned parallel to the worker to ensure the center of gravity line was perpendicular to the photo's bottom for accurate analysis. Each photograph captured the full body, including the upper extremities, torso, and lower extremities, with visible positions of the neck, shoulders, arms, and wrists. Images clearly showed the task being performed and its context, with the date, time, task, and project details recorded. After organizing and archiving, the photos were categorized into four primary poses—standing, squatting, bending, and crawling. To account for varying durations of each pose, images were taken at one-minute intervals, and the average frequency per hour and percentage of movements across the project were analyzed to minimize errors from prolonged exposure to the same posture.

This study analyzed 235 images collected from three engineering teams working on diverse projects and environments. Each dataset underwent assessment using the Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) tools to evaluate ergonomic safety and categorize safety levels (Mechanical Department Agnihotri College of Engineering Wardha 442001; India et al., 2014). RULA focuses on upper limb ergonomics, analyzing posture details such as the angles of the upper arm, lower arm, wrist, neck, and torso, along with the weight carried. REBA provides a comprehensive head-to-toe analysis, considering the bending and rotation of limbs, torso, and neck, while also factoring in the ergonomic design of tools and handles for worker safety.

EXPERT DISCUSSIONS

The final step in each Lean SOP update is to put the latest Lean SOPs for panel prefabrication into expert discussion. The main goal is to evaluate if time, safety and productivity inefficiencies before implementation produce improvements after implementation as Lean SOPs continue to improve. The second step is to address the issues that still exist that affect efficiency and productivity and to check if there are still undetected problems and potential pitfalls that have not occurred. Relevant experts are invited, including Lean experts, safety experts and price estimation experts, to assess the reliability and accuracy of existing Lean SOPs, to show improvement data on metrics such as production speed, waste savings, safety and quality, and to make more specialized recommendations on, for example, time inefficiencies, safety issues or wasted resources. Discuss ongoing challenges and lessons learned from research and prevention of possible future scenarios. Maintain an open dialog to gather insights and future recommendations and iterate SOPs based on feedback to ensure continuous improvement.

RESULTS

GUIDELINES FOR DEVELOPING A LEAN SOP FOR PANELIZED PREFABRICATION

The factory specializing in manufacturing panels should follow the next six steps as their guidelines to develop their Lean SOPs:

1. Define the scope

The first step in developing a Lean SOP is to define the scope and objectives of the operation, which requires tailoring the process to workers' varying experience levels. Rather than simply dividing the process by task stage or skill set, SOPs should consider differences in worker expertise to ensure that each instruction is understood and implemented by the target audience. This approach allows workers of all experience levels to follow SOPs efficiently, resulting in a more consistent, safer, and efficient production process.

2. Select data collection methods

Next, selecting a suitable data collection method is a critical step in the research task, as a reasonable method can significantly improve the efficiency and accuracy of data collection. Emphasis will be placed on ensuring the authenticity and reliability of the collected data while also considering that the data collection process may interfere with the regular work of the field workers, which may unintentionally affect the manufacturing progress. To this end, this study used on-site observation and manual data recording methods, including time tracking, visual recordings, interviews, and communication and discussion with workers and managers.

3. On-site Observation and Collection

On-site observation and data collection at the manufacturing station is done by visual observation and documentation, taking photographs and recording video. Employees are first notified that their consent is sought to ensure that they agree to be in the photographs and videos and that the observation and data collection do not interfere with their normal work. Initial study and hands-on practice of the content to be studied to understand the details of the workflow and identify key activities. Then, systematically record tasks, time and environmental factors while noting anomalies or inefficiencies.

4. Data analysis

These collected data, images and videos will be sorted, visualized in a consistent language and saved on a computer. Use data such as mean, median, or standard deviation to summarize overall trends. Apply charts or graphs to visualize and look for underlying correlations or anomalies. Compare these data and trends with historical databases to find similarities and differences and document and analyze them. Filter the images, analyze the videos frame by frame, filter out the important actions and save them separately, and extract the needed data from the videos to add to the previous database. Records of workflows need to be detailed and accurate, ensuring that details are not overlooked and that the number of workers and skill levels for each task are recorded in detail. Data, photos, and actions of uncertain reliability need to be communicated to workers or management to ensure reliability.

5. Report findings and provide recommendations

Once all the data and results are organized, there is still a need to further validate and fine-tune the accuracy of the data, a validation process that includes presentations, interviews, and discussions with manufacturing personnel and managers, integrating their opinions and ideas through different perspectives of requirements and situations. This collaborative approach ensures that data and results are more relevant to the situation and the client's needs. The involvement of different workers and managers not only identifies and solves problems in the data from different perspectives but also significantly improves the reliability and accuracy of the analyses. From this validated dataset, complete processes and critical steps can be inferred, enabling a complete and detailed organization of the workflow and the identification of bottlenecks in manufacturing and management processes that lead to inefficiencies or potentially lead to safety issues. The key insights from the analysis can be put into a Lean SOP after being agreed upon.

6. Review and approval process

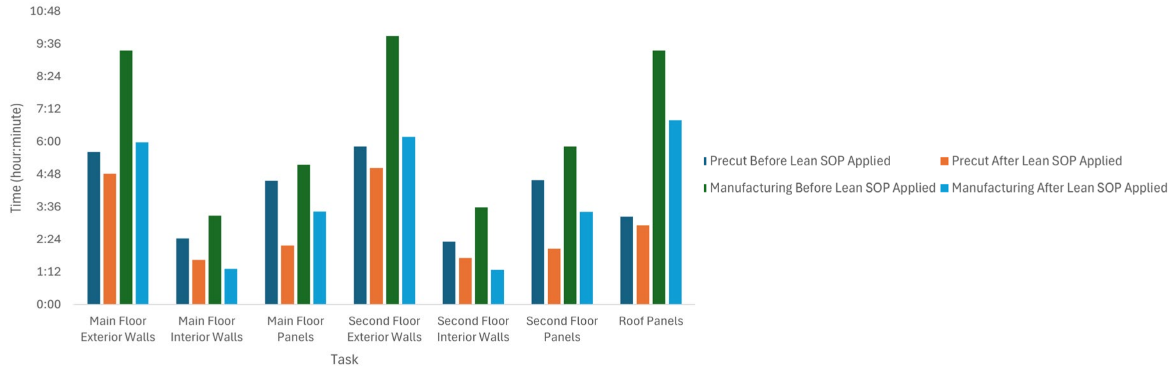
The collated data and results are combined with a complete workflow to create the initial version of the Lean SOP. The findings are presented in the form of a full Lean SOP and presentation with visuals such as flowcharts, diagrams, and charts with annotations. After management review and approval, a qualified guidance methodology will eventually be established for the creation of the Panelized Prefabrication Lean SOP. This study can be used to propose a template for the development of the panelized prefabrication Lean SOP by discussing its application in different work situations.

The data collection for this study began in early 2022 and concluded in early 2024, encompassing the entire process from familiarization with the production environment to SOP development, implementation, and performance tracking. The following results were obtained as a case study by applying Lean SOP to actual production activities with the cooperation of the partner companies:

TIME

Figure 2 illustrates the time spent on precutting and manufacturing various components in panelized prefabrication. The results before and after applying the Lean SOP are put together and compared separately. The time data is divided into four groups comparing seven tasks. After applying Lean SOP, all the time spent on the tasks decreased, and overall, the whole project saved 35.05% of time in the panelized prefabrication (precut time plus manufacturing time) preparation phase in the factory. In most cases, after applying the Lean SOP, the time required for manufacturing has been reduced even more significantly, with a total time saving of 28.76% at the precut station and 38.93% at the manufacturing station. Overall, the graph emphasizes the value of applying Lean SOPs in panelized prefabrication, which can lead to significant time savings in highly repetitive tasks such as pre-cutting and simple but easily disturbed tasks such as manufacturing.

Figure 2: Comparison of RULA and REBA Scores Before and After Applying Lean SOPs



SAFETY

The RULA and REBA analyses allow us to generate the scores and the level of safety of the four postures, thus deriving the safety situation at work and studying and identifying the causes and corresponding risks that lead to ergonomics being in a poor state based on the high scores. For this reason ten improvements were proposed in this study:(1) Adhere to standard use of tools (2) Limit reach (3) Use height-adjustable racks (4) Maintain work at elbow height (5) Equip workers with high-quality knee pads (6) Reduce twisting and bending of the body by accessing tools and materials directly in front of the body (7) Introduce stretching breaks (8) Use tools with trigger locks (9) Design tasks that alternate between sitting, standing, and walking (10) Improve equipment to reduce push/pull resistance. Figure 3 shows that significant improvements were observed for all postures in both precut and manufacturing tasks, demonstrating that Lean SOPs can change the posture of the work and increase the safety of the workers while working. Precut tasks can reduce the scores in RULA by 67.8% while decreasing from a risky posture to an acceptable posture, in REBA by 52.25%, and in RULA by 52.25% while decreasing from Medium Risk to Low Risk. Manufacturing tasks can reduce the scores in RULA by 67.8% while decreasing from risky posture to acceptable posture. Manufacturing tasks can reduce the score in RULA by 52.1% from Medium Risk to Low Risk while reducing the score in REBA by 49.7% from Medium Risk to Low Risk and reducing the score in RULA by 52.1% from Hazardous Posture to Acceptable Posture. Risk to Low Risk.

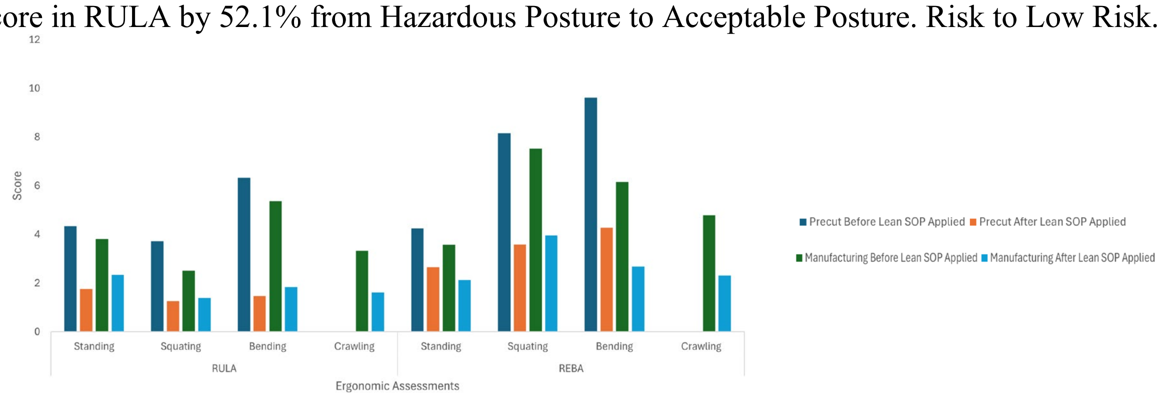


Figure 3: Comparison of RULA and REBA Scores Before and After Applying Lean SOPs

EXPERT DISCUSSIONS

In the same case, ten framers and ten employers who used the new SOPs were interviewed. Their responses to the questionnaire (Figure 4,5) indicated their feelings and feedback in different situations before, during and after the use. Lean SOPs are popular and treated as a tool for necessary change by both framers and employers. The initial learning investment is acceptable compared to the long-term gains in safety and efficiency.

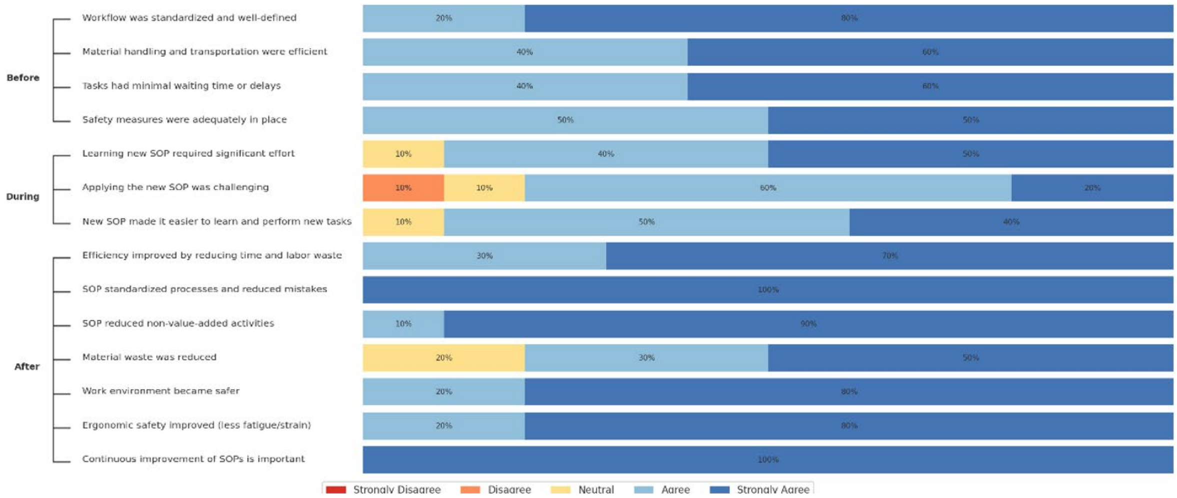


Figure 4: Framer Responses to Lean SOP Survey

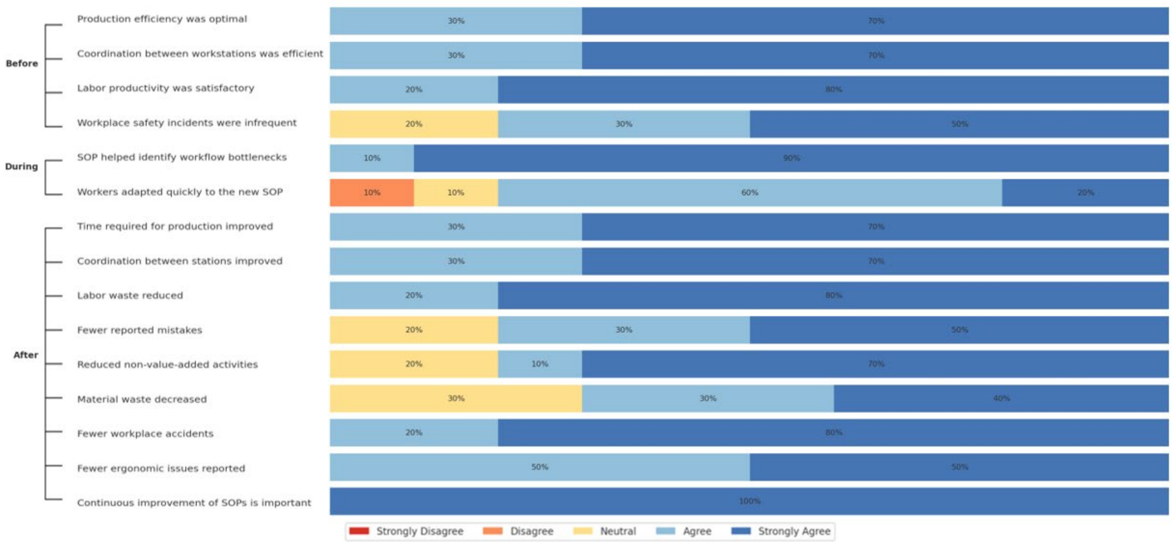


Figure 5: Employer Responses to Lean SOP Survey

DISCUSSION

This study establishes guidelines for Lean SOPs in the construction industry to facilitate the standardization and harmonization of the industry, to be able to share the same set of standards under different companies in the future, and to have the ability to have a platform for sharing resources in the future. However, due to the large differences in production technologies and methods among different enterprises, Lean SOPs under the same set of guidelines cannot be directly applied to the same products and need to be adapted to their technologies and tools.

This study also demonstrates the great utility of Lean SOPs in addressing time inefficiencies and high safety risks in panelized prefabrication. Traditional SOPs often struggle to proactively respond to changing technology and product demands, which can easily lead to productivity failing to keep up with technology and tooling updates and increase ergonomic risks. By integrating lean principles, this study improves the standardization of processes and enhances their autonomous adaptability. While increasing productivity, it effectively protects workers' safety.

The key finding of the study was the significant optimization of Lean SOPs for task completion time and ergonomic risk, using ergonomic assessment tools, such as RULA and REBA, to validate Lean SOPs for improved worker posture and overall safety. Corresponding improvements need to be recommended for each posture and activity in subsequent studies to meet the ergonomic demands of manufacturing work, prevent the potential for musculoskeletal strain, and further reduce the human health issues that still exist. In addition, expert discussions provided a theoretical and empirical basis for the practical challenges of implementation, increasing the trust of organizations and individuals in the new Lean SOPs and their willingness to actively use them.

CONCLUSIONS AND LIMITATIONS

This study establishes a guideline for Lean SOPs in the construction industry to facilitate standardization and harmonization across the industry. This provides the ability for different companies to share the same set of standards in the future. This study also demonstrated the ability of Lean SOP in addressing panelized prefabrication to improve time utilization efficiency and ergonomic safety. This ultimately promotes the possibility of wider application of Lean SOP. In the future, more specific and generic templates will be designed.

This study shows that Lean SOPs have the potential to be a platform for future resource sharing and easy cross-comparison of products. Integrating Lean SOPs into the panelized prefabrication process can significantly improve time efficiency and safety, thereby increasing overall productivity. The homogenization and simplification approach adopted can be adapted to different construction environments and product requirements, achieving a high degree of replicability and thus providing a reliable reference and standard for relevant practitioners and policymakers.

The study also recognizes some limitations that restrict the scope and applicability of its findings. The study was conducted on a limited number of panel prefabrication projects, and the sample was drawn entirely from single-family homes in North America, which may not be fully representative of the diversity of construction methods, geographic settings, or project sizes. The limitations in the scope of the sample may limit the generalizability and reliability of the Lean SOP framework to other regions or situations. Due to the confidentiality requirements of each company for internal information, this study could not demonstrate the specifics of Lean SOP in the case study. A broader application of Lean principles, including Takt time and system-wide flow optimization, is important but lies beyond the scope of this study and would be better suited for a future, more detailed investigation.

Furthermore, the study also recognizes the need for ongoing research to explore the potential for the continued expansion of Lean SOPs in different environments and the face of projects of different sizes. The involvement of more companies, workers, and experts is a critical part of the continuous improvement of Lean SOPs and can provide a better foundation for a more sustainable, efficient, and safe construction industry.

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