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A LEAN APPROACH TO PRODUCTIVITY IMPROVEMENT IN ROOF PANEL MANUFACTURING FOR MODULAR OFF-SITE CONSTRUCTION USING DFMA AND EMERGING TECHNOLOGIES

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ABSTRACT

The study investigates the application of Lean Construction principles to enhance productivity in modular off-site construction, specifically focusing on roof panel production. A systematic framework was developed, emphasizing Standardization, Elimination of Waste, Continuous Improvement, and Minimization of Time and Effort, which was tested through a real-world case study. Conducted at a modular offsite construction project in Montreal, Canada, the study involved light gauge steel structure panels covering a total gross floor area of 2,500 square meters. The adoption of lean practices resulted in a notable 32% improvement in labor productivity.

Key strategies contributing to this success included the use of Design for Manufacture and Assembly tools, semi-automation, augmented reality for quality checks, and the 5S methodology (Sort, Set in order, Shine, Standardize, and Sustain). These strategies collectively minimized waste, streamlined production processes, and enhanced labor efficiency.

The findings validate the effectiveness of the proposed framework and offer a replicable model for future modular construction projects aiming for productivity enhancement. By integrating these lean principles, the study provides a proper approach to improving efficiency and quality in modular construction environments, setting a benchmark for subsequent projects in the industry.

KEYWORDS

Lean Construction Principles, Modular Off-site Construction, Productivity, DfMA

INTRODUCTION

The construction industry faces persistent challenges in productivity, resource utilization, and waste management, which have worsened due to increasing global demand for efficiency and sustainability (Hadi et al., 2023). These challenges are particularly pronounced in Modular

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Off-site Construction (MOC), a sector that aims to harness factory-based production's cost, time, and quality advantages (Hairstans, 2014). However, common inefficiencies, poor technology integration, and inconsistent workflows often undermine these benefits, resulting in suboptimal labor productivity and project outcomes (Hosseini et al., 2018; McKinsey Global Institute, 2017).

Modular off-site construction has emerged as a promising approach to address such challenges by transferring a significant portion of the construction process to controlled factory settings. This approach delivers potential advantages such as faster project completion, better quality control, and reduced environmental impact (Blismas et al., 2005). However, these benefits often remain underutilized due to a lack of systematic frameworks for optimizing workflows and ensuring consistent quality in modular component production (Ouda & Haggag, 2024). Traditional construction practices, marred by redundant processes and variability, hinder broader adoption of modular methods. Limited integration of advanced technologies further compounds these issues, preventing streamlined operations and precision in manufacturing (de Laubier et al., 2019).

This study seeks to overcome these barriers by integrating Lean Construction principles into modular off-site construction processes, specifically targeting the production of roof panels. Lean Construction, rooted in waste elimination, continuous improvement, and value maximization, has shown transformative potential in addressing inefficiencies within the construction sector. By leveraging tools like Design for Manufacture and Assembly (DfMA), the 5S methodology, and augmented reality (AR), Lean Construction can drive significant productivity gains in modular environments (Alwisy et al., 2019; Barkokebas et al., 2021; Ouda & Haggag, 2024; Wang et al., 2020). However, the application of these principles to modular off-site construction needs more investigation, particularly from the perspectives of digital integration, scalability across diverse construction settings, and long-term impact on productivity and sustainability.

This research bridges this gap by proposing a systematic framework for Lean Construction principles and tools in modular off-site environments. The framework's effectiveness is validated through a real-world case study conducted at a modular construction facility in Montreal, Canada, providing a benchmark for broader industry application.

The study's contributions not only advance modular off-site construction but also align with digitalization and sustainability trends, positioning modular methods as a critical enabler for future-ready construction solutions.

RESEARCH BACKGROUND

LEAN PRINCIPLES AND TOOLS IN CONSTRUCTION

The integration of Lean Construction principles into prefabricated construction has significantly advanced the industry by targeting the elimination of waste, promoting continuous improvement, and ensuring maximum value delivery (Du et al., 2023; Lean Construction Institute, 2022). Lean principles, as outlined in Koskela's Transformation-Flow-Value (TFV) theory, emphasize streamlining workflows, improving efficiency, and enhancing value generation across all construction phases (Koskela et al., 2002). These principles have demonstrated particular utility in modular and Off-site Construction (OSC), where their systematic application reduces non-value-adding activities and enhances project performance (Marte Gómez et al., 2021).

Principles and Tools Highlighted in Lean Frameworks

1. Standardization: Creating repeatable processes and components for efficiency and quality control. DfMA, widely used in OSC, is instrumental in achieving predictable outcomes (Marte Gómez et al., 2021). Standard Operating Procedures (SOPs) further

enhance standardization by ensuring consistency and quality control across repetitive tasks (Koskela et al., 2002). Goh and Goh (2019) also identified that simulation techniques could support standardization by modeling variations and optimizing repetitive processes in modular construction.

2. Elimination of Waste: Techniques such as the 5S methodology and material tracking systems improve resource utilization and workflow organization. DfMA also contributes to waste minimization by reducing errors during the prefabrication and assembly phases (Abd Razak et al., 2022). The use of simulation to analyze waste streams, as discussed by Goh and Goh (2019), further strengthens this effort by identifying inefficiencies in real-time.
3. Continuous Improvement: Tools like Kaizen and Just-In-Time (JIT) evolve processes over time, aligning material delivery with project schedules to enhance efficiency. Regular feedback loops incorporated into Kaizen methodologies ensure adaptability and incremental process enhancements (Gunduz & Naser, 2019). Simulation-based Lean techniques offer additional pathways for continuous improvement, enabling data-driven decision-making and iterative process refinements (Goh & Goh, 2019)
4. Minimization of Time and Effort: Training programs for skill development and Total Quality Management (TQM) systems reduce rework and maintain quality standards. By integrating TQM principles, organizations achieve continuous monitoring of quality metrics, facilitating proactive adjustments to workflows (Salah et al., 2010). Furthermore, according to Phan et al. (2019), the implementation of TQM practices has been shown to prevent rework and reduce redundant steps in production processes (Phan et al., 2019).

LEAN INTEGRATION IN OFFSITE CONSTRUCTION

Recent literature reflects a growing interest in integrating Lean principles with OSC to improve process efficiency, standardization, and responsiveness. Mostafa et al., (2016) combined Lean and Agile within OSC through discrete event simulation to address production variability, yet lacked a mechanism for design automation or direct manufacturing integration. (Barkokebas et al., (2021) introduced a Building Information Modeling (BIM)-Lean framework focused on digitalizing early-stage planning and coordination, but did not extend into parametric configuration or manufacturing outputs. (Soares De Carvalho & Scheer (2019) presented a conceptual model aligning Lean Construction, Manufacturing, and Office practices across the modular lifecycle. However, their approach lacked digital implementation tools. Daniel & Oshodi (2023) explored Lean and simulation synergies in housing OSC, identifying optimization strategies but stopping short of an integrated design-production workflow.

Other studies focused on process coordination and collaboration. Robey & Issa, (2015) used BIM and Lean to support prefabrication through clash detection and planning, though their framework did not address automation of fabrication data. Shigaki & Yashiro (2023) documented a Japanese composite method as an “unconscious” Lean practice, showing organically achieved simplification and flow, yet without formalized digital support. Platform-based approaches are gaining traction. Kennedy et al., (2023) promoted a strategy to standardize housing components through a cross-disciplinary platform, though their model remains strategic rather than operational. Similarly, Etges & Caten, (2023) proposed a Lean-supported innovation framework for the construction sector, emphasizing adaptability and structured experimentation, while lacking implementation detail for digital design workflows.

Together, these works highlight the need for an integrated, automation-enabled framework that embeds Lean logic within digital design and manufacturing workflows, an identified gap this study aims to address.

METHODOLOGY

APPLICATION OF LEAN PRINCIPLES AND TOOLS IN MODULAR OFF-SITE CONSTRUCTION

Building upon established Lean principles discussed in the Research Background, this study develops a targeted framework to enhance productivity in roof panel manufacturing within MOC. The proposed approach focuses on the practical application of four Lean focus areas: Standardization, Elimination of Waste, Continuous Improvement, and Minimization of Time and Effort, as illustrated in Figure 1. Each principle is supported by targeted tools and strategies designed to maximize efficiency and reduce waste.

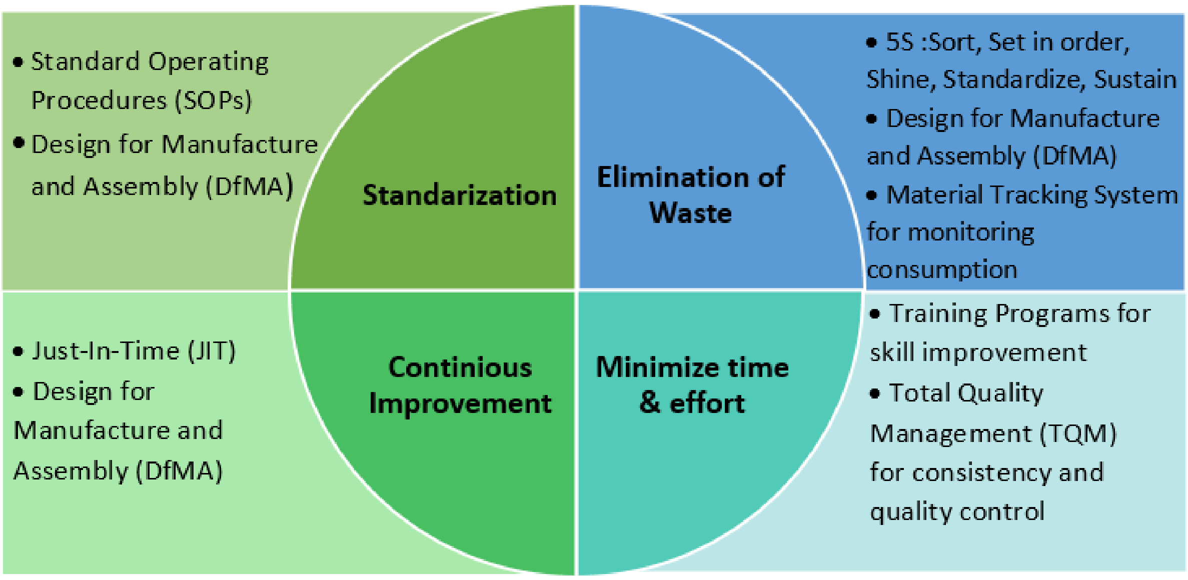

Figure 1 - Proposed Framework for Lean Principles and Tools for Roof Panel Manufacturing in MOC

1. Standardization

To ensure consistency and reduce variability in roof panel production, the methodology integrates:

- Standard Operating Procedures: Clear, task-specific guidelines that support repeatability and reduce errors.
- Auto-framing via DfMA tools: Automates component standardization and simplifies downstream assembly processes.

2. Elimination of Waste

To address inefficiencies in material usage and workflow organization:

- 5S practices are adopted to structure workspaces and sustain operational clarity.
- Material Tracking Systems are implemented to monitor inventory and avoid overproduction.
- DfMA strategies are employed to reduce design complexity and minimize fabrication waste.

3. Continuous Improvement

This principle is operationalized by:

- Just-In-Time coordination, aligning material deliveries with actual production schedules to minimize storage delays.
- Iterative refinement of design outputs using parametric tools, enabling feedback-informed updates to panel designs for smoother manufacturing.

4. Minimization of Time and Effort

To optimize labor efficiency and reduce rework:

- Targeted training programs are introduced to upskill workers on SOPs, tools, and Lean workflows.
- Total Quality Management is used to ensure adherence to quality standards across production phases.
- Augmented Reality is integrated for real-time validation of assembly tasks, reducing on-site errors and rework.

Incorporating Lean methods and digital technologies in this study was strategically chosen to address specific inefficiencies observed in the modular off-site construction of roof panels. The selection of tools like DfMA, AR, and the 5S methodology was driven by their proven ability to streamline processes, reduce waste, and enhance productivity. DfMA was utilized for its effectiveness in simplifying designs and minimizing errors during prefabrication, while AR was chosen for its capability to provide precise quality checks and configuration validation, ensuring optimal assembly. The 5S methodology was implemented to organize workspaces efficiently, ultimately facilitating a smoother workflow. These digital technologies were integrated to align with Industry 4.0 advancements, enhancing real-time data sharing and decision-making, and contributing to the overarching goal of this research.

The production line for the modular off-site construction of roof panels was designed as a semi-automated process where products moved through various workstations. This dynamic configuration ensured efficient flow and minimized idle time between tasks. The production flow began with raw material preparation and progressed through stages such as framing machine setup, panel assembly, and quality inspections, culminating in the final stacking and labeling for transportation. This approach facilitated streamlined operations and enhanced productivity by aligning task sequences with Lean Construction principles.

Moreover, this methodology provides a suitable framework for enhancing productivity in MOC. Each principle is supported by well-established Lean tools aimed at reducing inefficiencies, improving quality, and ensuring streamlined project execution. This holistic approach fosters a culture of efficiency, quality, and continuous improvement in modular construction environments.

PROCESS PLAN AND FRAMEWORK APPLICATION

The step-by-step process plan derived from the proposed framework in Figure 1 is as follows:

Standardization:

- Develop and train workers on SOPs for repetitive tasks: Establish standardized workflows for frequently occurring tasks like component assembly, cutting, and inspections. Conduct hands-on training sessions and provide visual aids such as flowcharts and checklists to ensure adherence. Use performance metrics to track compliance with SOPs.
- Use DfMA tools for modular design and AR technology for pre-configurations based on as-built models: Leverage DfMA software to create standardized modular components. For example, use auto-framing tools to design light gauge steel (LGS)

panels and ensure precise dimensions. AR systems can then overlay digital designs onto the physical workspace for real-time configuration validation.

Workspace Organization (Elimination of Waste):

- Apply the 5S methodology to organize workspaces and improve accessibility to tools and materials: Begin with decluttering (Sort) and arranging tools systematically (Set in Order). Use visual labels and storage bins to make tools easily identifiable. Regularly conduct audits to maintain the 5S system (Sustain).
- Implement material tracking systems to monitor inventory and prevent overproduction: Use digital tracking tools such as barcoding systems. Train staff to regularly update inventory logs for accuracy.

Material Procurement and Delivery (Continuous Improvement):

- Align procurement with JIT delivery to reduce storage costs and ensure timely availability: Coordinate with suppliers to deliver materials in smaller, manageable batches that align with the production schedule. Establish a supplier relationship management system to communicate delivery timelines and prioritize high-usage materials.

Production and Assembly (Minimization of Time and Effort):

- Improve framing machine setup using digitalized design of panels and implement automated framing for faster production and efficient assembly with minimal manual adjustments.
- Implement AR-based quality checks to validate panel assembly, ensuring alignment with design specifications.
- Using a digitalized production plan incorporating JIT principles to optimize framing machine setup time based on the type of LGS panels and the stacking plan prior to transportation.

Feedback and Refinement (Continuous Improvement):

- Conduct regular brief daily meetings to identify inefficiencies and implement incremental improvements in processes.
- Establish feedback loops with workers to capture insights and address bottlenecks.

Final Quality Check and Documentation (Minimization of Time and Effort):

- Perform quality inspections with AR to detect and resolve issues before dispatch: Use AR devices to overlay digital designs onto physical components for precise comparison. Develop a checklist for inspectors to ensure consistency across all panels. Implement a quality assurance log to track inspection results and corrective actions.
- Label panels with Quick Response (QR) codes linking to onsite assembly documentation for traceability: Generate QR codes that store critical information like panel location, BIM data, and shop drawings. Test the QR codes during production to ensure they work seamlessly on-site. Train onsite staff to access and interpret the QR code data for efficient assembly.

The researchers participated in the study as a participant-observers, which involved direct engagement in implementing the Lean framework while maintaining an observational role to document outcomes. This dual role provided an in-depth understanding of the processes but may introduce potential biases. To mitigate this, multiple sources of data were cross-verified, and the findings were validated through discussions with company stakeholders and third-party reviews. While this study primarily employed quantitative observations and process analysis to evaluate productivity improvements, it did not incorporate qualitative data from stakeholders such as workers, supervisors, or project managers. This limitation was largely due to restricted on-site access and time constraints during the project's implementation phase. Consequently, triangulation, typically achieved through interviews or focus group discussions, was not feasible within the current study's scope.

QUANTITATIVE ASSESSMENT OF LEAN IMPLEMENTATION ON PRODUCTIVITY

This study employs a quantitative approach to assess the impact of lean implementation on labor productivity in the production of roof panels for modular buildings. The methodology involves calculating labor productivity rates before and after the adoption of lean manufacturing practices, followed by a comparative analysis to determine the percentage improvement in productivity. A real case study was used to implement the proposed framework and evaluate productivity improvement. The case study involved a modular offsite construction project located in Montreal, Canada, with an approximate total gross floor area of 2,500 square meters, utilizing light gauge steel structure panels. Productivity was assessed based on the production and assembly of roof panels in the case study.

Factors Considered in Measuring Productivity

The following factors are considered in this study to calculate and evaluate productivity:

- Labor Hours per Panel: The total labor hours required to manufacture and assemble a single roof cassette. This factor is critical, as it reflects the efficiency of the workforce in executing tasks.
- Number of Laborers Involved: The number of workers assigned to each task or set of tasks during the manufacturing and assembly process. This accounts for the distribution of workload and its impact on overall labor efficiency.
- Lean Process Adjustments: The implementation of Lean Construction principles, which aim to reduce waste, improve process flow, and optimize resource allocation. These adjustments influence labor efficiency by streamlining operations and eliminating non-value-adding activities.
- Task-Specific Improvements: Individual task durations (e.g., installing insulation, sheathing, waterproofing, etc.) are measured before and after Lean implementation. This allows for detailed analysis of how each step in the process contributes to overall productivity.
- Standardized Process Workflows: The adoption of standardized workflows to ensure consistency and reduce variability in the time required to complete repetitive tasks.

Measuring Productivity:

Labor productivity rate (LPR) is a key metric for evaluating the efficiency of labor utilization and is defined as the ratio of output quantity to total labor hours. The LPR for both scenarios were subsequently calculated by Equation 1: Output Quantity / Total Labor Hours. Output Quantity is the number of panels produced (assumed as 1 panel per calculation), and Total Labor Hours is the sum of labor hours required for all tasks in the process.

The total labor hours before lean implementation was calculated as the summation of task-wise labor requirements multiplied by the number of laborers assigned (Equation 2: Summation of labor hours per panel for each task × number of labor for each task). The same process was followed for calculating labor hours after lean implementation. To evaluate the improvement in productivity following the lean implementation, the percentage improvement in productivity was calculated using the Equation 3: (LPR After Lean implementation - LPR Before Lean Implementation) / LPR Before Lean Implementation × 100.

DATA ANALYSIS

Table 1 shows the work break down for manufacturing and assembly of roof panels with labor hours per panel before and after implementation of proposed framework to use lean in MOC with the number of labor required to complete each task.

Table 1 – Work breakdown for manufacturing and assembly of roof panels

Item No.	Description	Labor Hours per Panel Before Lean implementation	Labor Hours per Panel After Lean Implementation	No. of Labor
1	Material Preparation	0.5	0.2	1
2	Quality Inspection Materials	0.5	0.5	1
3	Verification of Design	1	0.3	1
4	AR pre-configuration of Panels	Not applicable	0.8	1
5	Framing Machine Calibration	0.8	0.25	1
6	Production and assembly of Light Gauge Steel Sections	4	2	2
7	Rigid Insulation Panels	1	0.8	2
8	Sheathing Boards Installation	2	2	4
9	Waterproofing Membrane	1	1	4
10	Vapor Barrier	2	2	4
11	Installation of Thermal Break	1	0.5	2
12	Roofing Material Installation	2	1	4
13	Fastener Installation	1	0.5	2
14	Sealants and Adhesives	1	1	2
15	Lifting Hooks/Brackets	1	1	2
16	Final Quality Check	0.5	0.25	2
17	Waste Collection	0.5	0.3	1
18	Labeling and Documentation	0.8	0.3	1
19	Stacking of Panels for Transport	0.8	0.25	2
20	Documentation for Transportation	0.5	0.25	1

The calculated total labor hours before lean amounted to 52.2 hours, while the total labor hours after lean implementation were reduced to 39.6 hours using equation 2. The labor productivity rates were subsequently calculated using the equation 1.

To evaluate the improvement in productivity following the lean implementation, the percentage improvement in productivity was calculated using the equation 3. LPR before lean implementation = (1 panel) / (52.2 labor hours) = 0.019 panels per hour, LPR after lean implementation = (1 panel) / (39.6 labor hours) = 0.025 panels per hour, improvement percentage = $0.00615/0.0191\times100=32.2\%$.

The calculated 32% improvement reflects a significant boost in labor productivity after Lean implementation. This gain stems from reduced total labor hours, highlighting the effectiveness of Lean strategies in modular roof panel production. Workflow efficiency improved through tools like 5S, which optimized workspace organization, and AR, which enabled accurate assembly and reduced rework. DfMA contributed by standardizing components and accelerating assembly. These Lean methods streamlined processes, minimized inefficiencies, and cut inspection time, collectively driving productivity gains and showcasing the impact of targeted Lean interventions in enhancing modular construction efficiency.

DISCUSSION

This study builds upon and diverges from previous research in key ways, particularly in its application and validation of Lean principles within MOC. While earlier studies (e.g., Koskela et al., 2002; Goh & Goh, 2019) established theoretical foundations for Lean concepts like waste elimination, standardization, and continuous improvement, their focus was largely on traditional construction or generalized modular workflows, without targeting specific components like roof panels. Compared to existing Lean models for OSC, this research offers a practical, rule-based system that automates the flow from design intent to production-ready outputs, embedding product-process logic in the digital workflow. Mostafa et al. (2016) combine Lean and Agile via simulation to manage variability but lack design automation. Our system bridges design and production through real-time data, enabling Lean flow operationally.

Barkokebas et al. (2021) apply BIM-Lean to premanufacturing planning using value stream mapping but lack parametric links to manufacturing. We address this using a BIM configurator tied to DfMA, reducing manual work and improving design-to-production handover. Carvalho & Scheer (2019) present a high-level Lean integration model across the modular lifecycle but omit digital automation. Our method extends this with a scalable, configurable system that generates production-oriented outputs. Daniel & Oshodi (2023) explore Lean-simulation synergies for OSC housing but provide no digital framework. We contribute an integrated, bidirectional system where real-time production data informs design, enabling iterative Lean refinement. Robey & Issa (2015) enhance collaboration with BIM-Lean but lack fabrication automation. We extend this by generating CAM and assembly docs from parametric rules, reducing lead times and waste. Shigaki & Yashiro (2023) describe Japan's composite construction as "unconscious" Lean, but lack a formal digital model. Our system formalizes Lean outcomes via repeatable, configurable digital workflows. Kennedy et al. (2023) propose a strategic platform-based OSC model focused on standardization and collaboration. Our method brings this platform thinking into action through a BIM-based configurator that auto-generates modular assemblies. Etges & ten Caten (2023) outline a Lean innovation model emphasizing adaptability; we operationalize this by enabling DfMA and Lean-driven design through digital automation.

This research builds on foundational studies by offering a systematically developed Lean framework tailored to modular roof panel production. Beyond overall productivity gains, Lean methods and digital tools delivered notable intermediate improvements, such as reduced cycle times, better WIP control, and shorter lead times. DfMA optimized design configurations, streamlining production and cutting cycle times. AR enabled real-time quality checks, improving WIP control and maintaining workflow consistency. JIT in material procurement aligned deliveries with production needs, reducing lead times and enhancing efficiency.

Eliminating non-value-adding tasks was crucial. Lean principles like 5S and DfMA helped identify and remove inefficiencies. AR reduced redundant inspections, and JIT minimized storage tasks through timely deliveries. These efforts streamlined workflows, reduced variability, and optimized resource use, driving labor productivity in MOC.

The proposed approach integrates Lean across four key dimensions: standardization, waste elimination, continuous improvement, and time/effort minimization, forming a cohesive system. Applied in a case study with light gauge steel panels, the study showed a 32% improvement in labor productivity. It also demonstrates the integration of tools like AR for quality checks and semi-automation in framing, which are underexplored in previous research. This paper demonstrates a focused and measurable approach to productivity optimization. Specifically:

- Quantifiable Results: The 32% improvement in labor productivity achieved in this study is a substantial outcome that exceeds typical gains in other modular construction studies, often ranging from 15–25%.
- Task-Specific Insights: By breaking down productivity improvements into individual tasks, this study offers granular insights often absent in broader analyses. Significant reductions in labor hours for framing machine setup (from 0.8 to 0.25 hours) and raw material preparation (from 0.5 to 0.2 hours) highlight the effectiveness of specific Lean tools.
- Broader Applicability: While studies like Barkokebas et al. (2021) focused on integrating Lean with BIM, this research emphasizes AR and semi-automation as alternative pathways, especially in projects with limited BIM adoption.

This paper introduces several new dimensions to the existing body of knowledge:

- Focus on Roof Panel Production: Unlike most studies that address modular construction broadly, this research narrows its scope to roof panel production, allowing deeper exploration of task-specific Lean applications and impacts.
- Comprehensive Framework: The proposed framework integrates traditional Lean tools like 5S and DFMA with emerging technologies such as AR for pre-configuration and material tracking systems. This hybrid approach bridges Lean principles with Industry 4.0 advancements.
- Empirical Validation: Findings are grounded in a real-world case study involving a modular construction project in Montreal. The quantitative analysis of labor productivity before and after Lean implementation offers robust evidence of the framework's effectiveness.
- Technological Integration: This research highlights the role of digital tools in enhancing Lean outcomes, such as AR for quality checks and auto-framing tools to streamline production, representing a step forward from prior studies that relied on manual Lean tools or limited digital use.

CONCLUSION

This study highlights the potential of Lean Construction principles to address productivity challenges in MOC. Using a systematic framework centered on standardization, waste reduction, continuous improvement, and time efficiency, labor productivity for modular roof panel production improved by 32%. Tools like DfMA, AR, and the 5S methodology played key roles in streamlining workflows, enhancing quality, and reducing inefficiencies.

The findings validate the applicability and effectiveness of LC in MOC, offering a robust, replicable framework that practitioners can adopt to boost productivity and reduce costs. Although based on a single case, the framework provides generalizable insights for various MOC projects. While focused on modular roof panels, the demonstrated principles and tools, such as standardized processes, lean waste elimination techniques, and tech integration, are applicable to other modular systems. These insights create a foundation for adapting LC practices across construction contexts. However, some limitations exist. The study's single-case focus may affect its generalizability. Additionally, it does not fully explore advanced digital tools such as BIM, AR, or IoT, which could support real-time decision-making and workflow optimization. Therefore, future studies addressing these limitations are recommended.

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