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Integrated Framework and Impact Assessment of Design for Manufacture and Assembly (DFMA) In Modular Home Manufacturing Facilities: A Case Study

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Abstract: The growing demand for sustainable and efficient construction practices has led to an increased interest in modular construction, with Design for Manufacture and Assembly (DfMA) emerging as a pivotal approach to enhance efficiency in the production process. Despite its potential, the integration of DfMA in modular home construction faces significant challenges, including the lack of a structured methodology for its implementation and the need for alignment between design, manufacturing, and assembly processes. This paper introduces methodologies for data collection to inform the re-engineering of the design process. By including design considerations, manufacturing processes, and assembly methodologies, the methodologies aim to optimize the entire production lifecycle with the implementation of DfMA principles as the core focus. Key elements include modular design standardization and streamline assembly processes to achieve improved efficiency, cost-effectiveness, and quality. The methodology is partially validated through an industry case study with a modular home manufacturer in New Brunswick, Canada, and real-world implementation to understand the effectiveness and practicality, as well as the challenges encountered to inform continuing research efforts. This paper contributes to the evolving field of modular construction by presenting a novel assessment approach that integrates DfMA principles into modular home production facilities. The proposed methods not only serve as a guide for industry practitioners but also provides a basis for further research and development in advancing sustainable and efficient construction practices.

Keywords: Modular Construction, Design for Manufacture and Assembly (DfMA), Sustainable Construction, Construction Industry, Manufacturing

1 INTRODUCTION

The construction industry has witnessed a paradigm shift in recent years, with a growing emphasis on sustainable and efficient construction practices (Sajid et al. 2024). Among these practices, modular construction has emerged as a prominent approach, offering numerous benefits such as reduced construction time, enhanced quality control, and improved cost-effectiveness. Central to the success of modular construction is the integration of Design for Manufacture and Assembly (DfMA) principles, which play a pivotal role in optimizing the production process and driving efficiency throughout the construction lifecycle (Rankohi et al. 2022).

DfMA principles are rooted in the concept of designing products or buildings with the objective of maximizing their suitability for downstream manufacturing and assembly processes. This approach involves standardizing components, streamlining assembly processes, and integrating design considerations with manufacturing and assembly methodologies (Wasim et al., 2020). By doing so, DfMA aims to achieve improved efficiency, cost-effectiveness, and quality in construction projects. Despite its potential benefits, the integration of DfMA in modular home construction poses several challenges. One of the primary challenges is the lack of a structured methodology for implementing DfMA principles effectively. Additionally, there is a need for alignment between design, manufacturing, and assembly processes to ensure seamless integration and optimal performance (Montali et al., 2018; Langston & Zhang, 2021; Rankohi et al. 2023).

This research aims to address the challenges in modular home construction by introducing innovative data collection methodologies to inform the re-engineering of the design process. These methodologies include comprehensive considerations for design, manufacturing, and assembly, with a strong emphasis on implementing Design for Manufacture and Assembly (DfMA) principles. The core strategy of this research is to optimize the entire production lifecycle of modular homes, enhancing efficiency, cost-effectiveness, and quality.

This study represents the initial phase of a broader research project in collaboration with a modular home manufacturer in New Brunswick, Canada. The goal is to develop a structured framework for integrating DfMA principles into modular home production facilities. By focusing on the design and production processes of modular homes, this research aims to advance the field and demonstrate the significant impact DfMA can have on modular home construction. The insights and findings from this research will lay the groundwork for creating a practical guide for industry practitioners. This guide will offer effective and practical solutions to promote the adoption of DfMA principles in modular home construction.

2 LITERATURE REVIEW

2.1 DfMA Principles

Design for Manufacture and Assembly (DfMA) principles are fundamental concepts in construction engineering and management that aim to optimize design and manufacturing processes for improved productivity, quality, and sustainability (Rankohi et al. 2022). DfMA involves designing products or buildings with the goal of maximizing their amenability for downstream manufacturing and assembly processes (Wasim et al., 2020). It encompasses a combination of design for manufacture (DfM) and design for assembly (DfA) principles, focusing on rationalizing technology, integrating product and process, optimizing logistics, and specifying materials (Rankohi et al. 2023).

The benefits of incorporating DfMA principles are well-documented. These benefits include reduced production time, incurred costs (Lu et al., 2021; Tan et al., 2020), and waste generation (Roxas et al., 2023), as well as enhanced productivity and quality (Bao et al., 2022a; FAVI et al., 2017). Additionally, DfMA can contribute to safer and healthier workplaces and support sustainable practices (Montazeri, Lei, and Odo 2024). The systematic integration of DfMA principles into operations involves developing industry-specific guidelines, flexibility in guideline generation, and the integration of DfMA with emerging technologies to enhance construction efficiency and productivity (Roxas et al. 2023).

Despite the recognized benefits, challenges persist in the adoption and implementation of DfMA. These challenges include contractual complexities, technological limitations, cultural resistance, and the lack of coordination between stakeholders (Montali et al., 2018; Langston & Zhang, 2021; Rankohi et al. 2023). Furthermore, lag in technology adoption can oftentimes be a barrier, highlighting the need for further research to understand the full potential of DfMA, the ideal level of technology implementation, and the impact of DfMA on project performance (Montazeri, Lei, and Odo 2024, Rankohi et al. 2023).

The literature review highlights the fundamental role of Design for Manufacture and Assembly (DfMA) principles in optimizing design and manufacturing processes in construction engineering and management. DfMA combines design for manufacture (DfM) and design for assembly (DfA) principles, aiming to streamline production, reduce costs, and enhance quality and sustainability. The documented benefits of DfMA include reduced production time, lower costs, minimized waste, and improved productivity and quality. However, challenges such as contractual complexities, technological limitations, cultural resistance, and stakeholder coordination issues hinder its widespread adoption. This project aims to address these challenges by developing a structured framework for integrating DfMA principles specifically in modular home production facilities. By focusing on overcoming these barriers, the project seeks to enhance efficiency, productivity, and sustainability in modular home construction, ultimately providing practical solutions for the industry.

2.2 DfMA in Modular Home Construction

Design for Manufacture and Assembly (DfMA) principles play a crucial role in optimizing the construction process, particularly in modular home construction. This approach encompasses several key principles, as summarized by Table 1.

Table 1: DfMA Guidelines and Benefits (Gao, Jin, and Lu 2020)

N	DfMA Guideline	Benefits
1	Aim for mistake-proof design	Avoid unnecessary re-work, improve quality, and reduce time and costs.
2	Design for ease of fabrication	Reduce time and costs by eliminating complex fixtures and tooling.
3	Design for simple part orientation and handling	Reduce time and costs by avoiding non-value adding manual effort.
4	Design with predetermined assembly techniques in mind	Reduce time and costs when assembling.
5	Consider modular designs	Reduce time and costs due to simplified design and assembly.
6	Consider design for mechanized or automated assembly	Improve assembly efficiency, quality and security.
7	Use standard and off-the-shelf components	Reduce purchasing lead time and costs.
8	Use as similar materials as possible	Reduce time with fewer manufacture processes and simplified jointing.
9	Use as environmentally friendly materials as possible	Reduce harm to the environment.
10	Minimize precast component types	Reduce time and costs with simplified design, manufacture, and assembly.
11	Minimize connector types and quantity	Reduce time and costs with simplified design, manufacture, assembly, repair and maintenance.
12	Minimize the use of fragile parts	Reduce costs due to fewer part failures, and easier handling and assembly.
13	Do not over-specify tolerances or surface finish	Reduce costs with easier manufacture.

The adoption of DfMA principles in modular home construction can lead to significant benefits, including 51% reduction in parts count, a 37% decrease in parts cost, a 50% faster time-to-market, a 68% improvement in quality and reliability, a 62% drop-in assembly time, and a 57% reduction in manufacturing cycle time (Gao, Jin, and Lu 2020). Furthermore, integrating advanced technologies, such as Building

Information Modeling (BIM) and digital fabrication techniques, can further optimize the design and manufacturing processes, leading to even greater improvements in efficiency and quality (Tan et al. 2023).

The literature review has highlighted the fundamental role of DfMA principles in enhancing efficiency, productivity, and sustainability within the modular home construction industry. Despite the notable advancements and documented successes in the application of DfMA principles, several critical gaps remain apparent in the body of research and industry practices, necessitating further investigation and development.

While the benefits of DfMA in modular home construction are well-documented, there is a distinct lack of structured methodologies for its effective implementation (Roxas et al. 2023). The literature indicates that the successful application of DfMA requires a holistic approach that seamlessly integrates design, manufacturing, and assembly processes. However, existing research falls short in providing a comprehensive framework that addresses this need, particularly in the context of modular home production facilities. Furthermore, the literature reveals a significant challenge in the alignment between design considerations and the practicalities of manufacturing and assembly processes. This misalignment suggests a research gap in the development of design guidelines and standards specifically tailored for DfMA in modular construction. Such guidelines would need to encompass not only the technical aspects but also the economic and environmental implications of modular home construction.

The literature review underscores the crucial role of Design for Manufacture and Assembly (DfMA) principles in enhancing efficiency, productivity, and sustainability in modular home construction. Despite well-documented benefits, including significant reductions in parts count, costs, assembly time, and manufacturing cycle time, there remain critical gaps in the structured implementation of DfMA methodologies. The review reveals a lack of comprehensive frameworks that integrate design, manufacturing, and assembly processes, and highlights the misalignment between design considerations and practical manufacturing and assembly needs. This project aims to address these gaps by developing a structured framework for DfMA integration tailored specifically for modular home production facilities. By doing so, it seeks to optimize design and manufacturing processes, reduce waste, and enhance overall productivity and quality in the modular home construction industry.

3 RESEARCH METHOLOGY

3.1 Research Design

The methodology for this research includes the development of a data collection and process evaluation framework using a case study to establish baseline data and allow for assessment and the development of implementation strategies for DfMA principles. The proposed framework considers design and production processes, current state data collection, detailed process task analysis, determination of process bottlenecks, future state data collection, and re-engineering of the design process as required, as described by Figure 1. The research has taken an exploratory approach to develop this DfMA framework and impact assessment that can be used within the modular home manufacturing industry for further production improvement efforts. The research completed to date has been limited to identifying applicable DfMA principles to address bottlenecks. Future work will implement the DfMA principles identified in an effort to improve the processes and collect future state data to execute an impact assessment of these improvements.

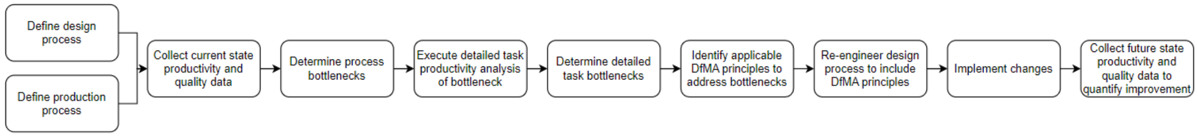

Figure 1: DfMA Evaluation Framework

3.2 Data Collection

To evaluate the effectiveness of Design for Manufacture and Assembly (DfMA) principles in modular home construction, a DfMA data collection methodology was established and implemented for the research, as described by Figure 2. This methodology was designed to capture essential metrics pertaining to both the design (in blue) and production cycles (in green), facilitating the identification of improvement areas to later enable the quantification of DfMA's impact (in yellow). For this research project, data was collected from an industry partner in the modular home construction sector.

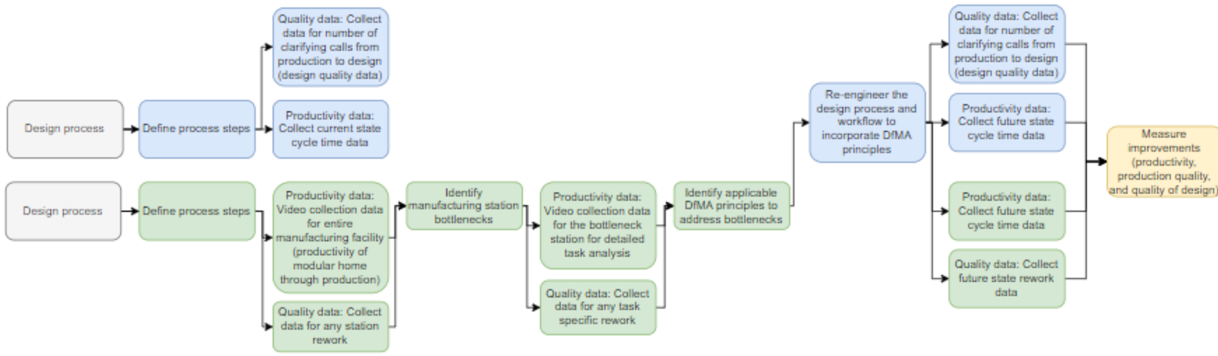

Figure 2: Data Collection Methodology for DfMA Evaluation Framework

The data collection process commenced with a focus on gathering information related to the design cycle times (start and end of a design task) through manual time tracking. This phase involved documenting the duration of the stages of the design process before the adoption of DfMA or advanced modeling techniques. This initial step aimed to establish a baseline scenario, allowing for a clear understanding of existing methodologies and potential inefficiencies.

Concurrently, as depicted by Figure 2, comprehensive data collection through video of the entire manufacturing facility was undertaken to evaluate the cycle times (start and end time) of each station within the production process. The term station refers to the 16 positions in the production line that the modular home passes through in order to be completed, in the context of the specified case study. This comprehensive assessment provided an overview of all stations and facilitated the identification of potential bottlenecks. Subsequently, specific attention was directed towards these bottleneck stations to conduct a thorough analysis and explore improvement opportunities through the application of DfMA techniques.

The primary objective of this benchmarking exercise was to establish a baseline to quantify future improvement efforts with respect to production and quality. By pinpointing areas of inefficiency, targeted improvement efforts could be formulated, and their impact assessed through data collected post-implementation. This iterative approach allowed for the continuous refinement of processes, thereby driving productivity gains and optimizing the overall production lifecycle.

3.3 Data Analysis

3.3.1 Design Process

The analysis of the design process focuses on establishing the current cycle times of designs based on modular home types. A examination was conducted to determine the average time taken for each design phase, from initial concept development to finalization, before the implementation of DfMA principles or advanced modeling techniques.

The data collection and subsequent analysis of the design process are still ongoing, thus eliminating the ability to share any insights from the case study at this time. However, it has been noted that this analysis will provide valuable insights into the efficiency of the design process and enables the identification of potential areas for improvement to streamline the design cycle times, enhance overall productivity, and improve the quality of information from design to the manufacturing facility.

3.3.2 Production Process

A detailed analysis of the production process was conducted to identify the bottleneck within the manufacturing facility. This analysis involved observing several days' worth of modular home manufacturing data, including completion times at each station and the movement of homes down the production line.

The data collected was analyzed using box plot graphs to determine which station exhibited the longest processing time and the highest variability. This analysis helped pinpoint the bottleneck station that significantly impacted production efficiency.

3.3.3 Task Analysis

Building on the findings from the detailed analysis of bottleneck stations, the focus shifted to understanding the specific tasks that contributed most to delays. This involved identifying tasks that took the longest time to complete and assessing whether improvements could be made in the design phase to streamline these processes.

This analysis used the video data collected to document the total time workers spent on each task within the bottleneck station, and provided a deeper understanding of the tasks contributing to the bottleneck and facilitated the development of targeted interventions to improve efficiency and streamline production processes.

4 RESULTS AND DISCUSSION

The research successfully developed a framework and methodologies for re-engineering the design process in modular home construction. This framework aimed to optimize the production cycle times by incorporating Design for Manufacture and Assembly (DfMA) principles to improve the productivity and quality of the designs that were delivered to the manufacturing floor.

The results of the data collection and analysis methodology with regards to the case study modular home manufacturer provided valuable insights into the cycle times for each station and process within the facility. The analysis highlighted that Station 3 had the longest average cycle time, which focuses primarily on the interior and exterior walls of the modular home, indicating a potential bottleneck in the production process, as described by Figure 3. The analysis of cycle times was completed for a total of 17 modular home units moving through the factory.

This finding informed the focus of detailed production analysis for individual tasks within Station 3 to understand what tasks could be contributing to the bottleneck of this station. This analysis was completed for a total of 8 modular home units moving through this station in the factory. The task analysis revealed that “fabricate sidewall 1” is taking the longest and is also taking longer than “fabricate sidewall 2”, which is the same scope of work, as described by Figure 4. “Sidewalls” in this case are the walls covering the long sides of the rectangular home units. Due to the layout of Station 3, “sidewall 1” is fabricated upright on a vertical stand, while “sidewall 2” is fabricated lying flat on a horizontal stand. Tasks that are incapsulated in the cycle time and man hours for the fabrication of both sidewalls includes:

- Positioning and installing frames and studs on the fabrication stands
- Measuring, cutting, and installing blocking
- Installing batt insulation
- Installing vapour barrier
- Installing air barrier
- Measuring, cutting, and installing drywall

From this information and in collaboration with the industry partner, several DfMA implementation ideas were generated to re-engineer the design process and improve the design information that is being provided to production. These include:

- Pre-determine the drywall cut list for the sidewalls to eliminate manual calculations and cut list preparation in production
- Deliver a detailed stud layout for the sidewalls that will allow the lumber preparation station to mark out stud locations and eliminate manual measuring at the station
- Provide a cut list for the lumber cutting shop to eliminate the manual calculation and preparation of the cut list within production

Other considerations within the manufacturing facility to reduce the average cycle time of framing the sidewalls include:

- Re-organize the plant layout to allow for horizontal assembly of sidewall 1 (currently happening vertically, in comparison to sidewall 2 which is happening horizontally and is more productive than sidewall 1)
- Reduce the amount of pre-requisite tasks for sidewall 2
- Identify tasks where people-hours applied will improve task cycle times and reduce the overall cycle time
- Investigate the impact of re-allocating tasks to station 2
- Change the location of the partition wall / end wall / sidewall pre-fabrication station to decrease crane time

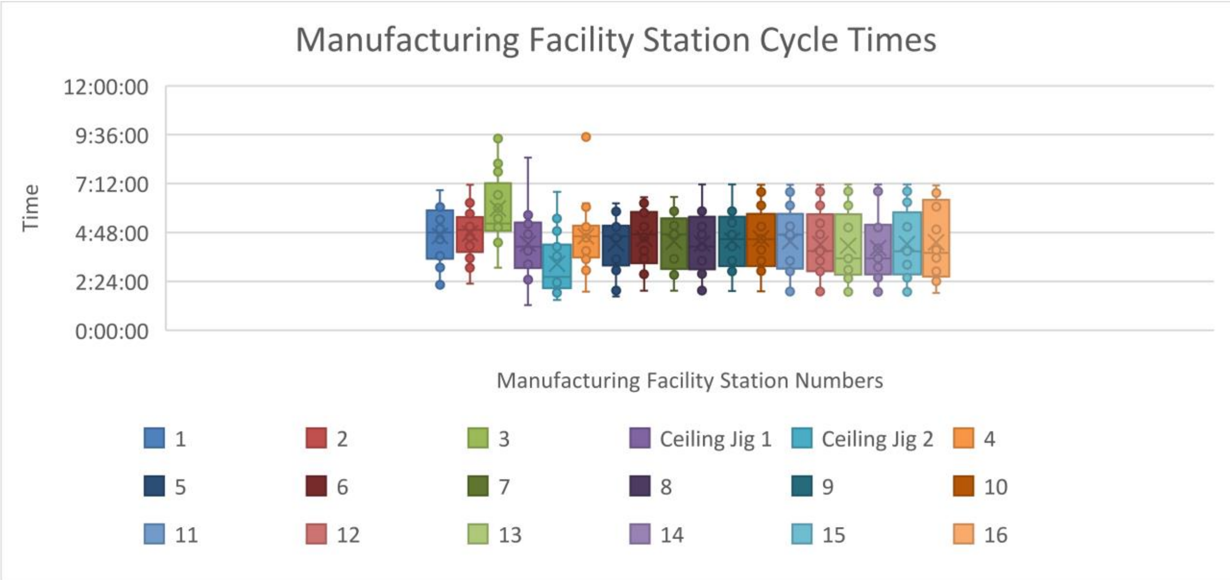

Figure 3: Boxplot of Modular Home Manufacturing Station Cycle Times

5 CONCLUSIONS

The research has provided valuable insights into optimizing modular home production facilities in preparation for integrating Design for Manufacture and Assembly (DfMA) principles. Additionally, it offers a replicable framework for assessing, analyzing, and using the data to inform the implementation of DfMA in other modular facilities. Our data collection and analysis revealed the importance of starting data collection at a high level and progressively narrowing down to the granular level of detail necessary for informing the design process effectively. Beginning with a comprehensive overview of the manufacturing process helps identify bottleneck areas, followed by focused analysis of these areas to pinpoint detailed task bottlenecks. This approach facilitates the extraction of essential information needed for optimization.

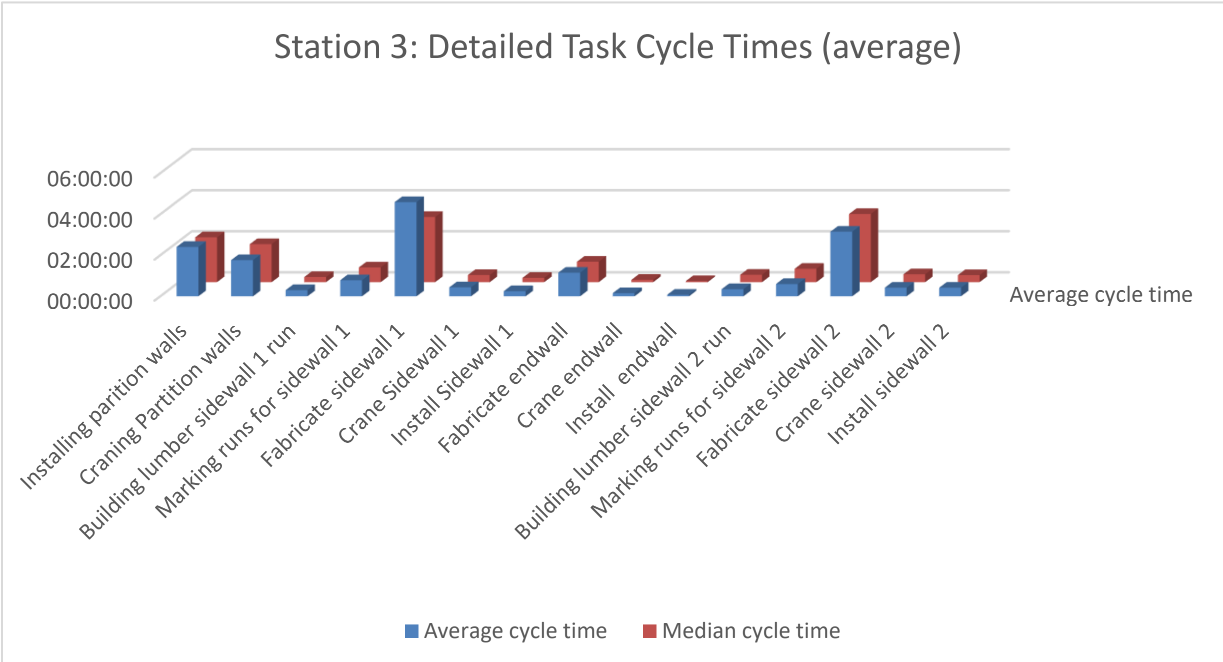

Figure 4: Station 3 Task Average Cycle Times

The results from our data collection and analysis methodology, in the context of the case study modular home manufacturer, have provided crucial insights into cycle times at each station and process within the facility. Station 3 emerged as a potential bottleneck, with the longest average cycle time among stations. This finding directed our detailed production analysis towards individual tasks within Station 3, specifically focusing on "fabricate sidewall 1," which was identified as taking the longest time compared to similar tasks. Future work will determine whether the bottleneck is a product design related problem, which can be improved upon through DfMA principles, or whether it is a process related problem, which can be improved upon with process improvement strategies. On a more general scale, this case study shows the applicability of the DfMA evaluation framework in industry and provides an example of how this can be replicated in other organizations to collect data and analyze it to inform the process of re-engineering the design process.

Our research contributes to the research base by introducing a comprehensive data collection framework that offers other organizations a systematic method for assessing, analyzing, and providing the information needed to implement DfMA principles. This framework encompasses data collection methodologies, detailed production analysis, and impact assessment techniques, providing a structured approach for optimizing modular home production facilities. By offering a step-by-step guide, industry practitioners can efficiently identify bottlenecks, enhance production processes, and measure the tangible benefits of DfMA implementation.

In collaboration with industry partners, several DfMA implementation ideas were generated to re-engineer the design process and improve the quality and productivity of designs delivered to production. These ideas include pre-determining the drywall cut list for sidewalls, providing detailed stud layouts, and optimizing lumber cutting processes. Additional considerations within the manufacturing facility were also identified to reduce cycle times, such as reorganizing plant layouts and reallocating tasks to optimize productivity.

Moving forward, our future research endeavors will focus on using the data analysis findings to re-engineer the design process, incorporating things like Building Information Modeling (BIM) elements and DfMA principles to improve design outputs that are information the manufacturing process. This integration will enable a seamless transition from design to production, ensuring effective implementation of DfMA principles across the entire lifecycle. Quantifying improvements based on station productivity enhancements and design quality improvements will be a critical aspect of our ongoing research.

In summary, our research establishes a baseline for continuous improvement and innovation within modular home construction. By embracing advanced technologies, systematic methodologies, and data-driven decision-making processes, organizations can unlock new levels of productivity, efficiency, and sustainability in their production operations. This holistic approach ensures that industry standards are elevated, leading to enhanced project outcomes and long-term success in the construction sector.

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7 CRediT author statement

Zhen Lei: conceptualization, methodology, writing – review & editing, supervision, funding acquisition. **Nicole Odo:** conceptualization, methodology, writing – original draft, visualization, supervision, project administration, funding acquisition. **Sadaf Montazeri:** methodology, writing – review & editing, supervision. **Katherine deWinter:** validation, formal analysis, investigation, data curation, writing – review & editing, visualization. **Amir Shokouhy:** validation, formal analysis, investigation, data curation, writing – review & editing, visualization, methodology, supervision.

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