Title

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AUTOMATION OPPORTUNITIES FOR FABRICATION OF MASS TIMBER BUILDING COMPONENTS

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ABSTRACT

As demand for mass timber building structures rapidly increases, project production systems must increase their delivery efficiency in order to keep pace. This study, focused on the fabrication of glulam columns and beams, therefore proposes that production systems integrate automation into a number of fabrication steps, such as machining, sealing or coating, and metal hardware installation. Three production cells were conceived, each with specific automated solutions aimed at alleviating production bottlenecks, improving production consistency and product quality, reducing cycle times, and increasing production throughput. This paper emphasizes the importance of aligning automation investments with overall production system design to ensure system-wide efficiency and effectiveness. The findings of this study contribute to advancing automation in mass timber fabrication, supporting sustainability and improving production efficiency.

Keywords: mass timber; industrialized construction; off-site construction; project production system design; automation; robotics.

RESUMO

À medida que a demanda por estruturas de edifícios em *mass timber* aumenta rapidamente, sistemas de produção de projetos devem aumentar sua eficiência de entrega para acompanhar esse crescimento. Este estudo, focado na fabricação de colunas e vigas de *glulam*, propõe, portanto, que sistemas de produção integrem automação em várias etapas da fabricação, como usinagem, selagem ou revestimento e instalação de conexões metálicas. Três células de produção foram concebidas, cada uma com soluções automatizadas específicas, visando aliviar gargalos de produção, melhorar a consistência da produção e a qualidade do produto, reduzir os tempos de ciclo e aumentar a capacidade produtiva. Este artigo enfatiza a importância de alinhar os investimentos em automação com a configuração do sistema de produção para garantir eficiência e eficácia em todo o sistema. Os resultados deste estudo contribuem para o avanço da automação na fabricação de *mass timber*, apoiando a sustentabilidade e melhorando a eficiência da produção.

Palavras-chave: mass timber; construção industrializada; construção off-site; configuração de sistemas de produção de projetos; automação; robótica.

1. INTRODUCTION

Mass timber (MT) has gained prominence as a sustainable construction material used for structural systems in buildings. Its global adoption has been driven by advancements in materials science, building codes, growing awareness of its structural strength and environmental benefits, and innovations in manufacturing processes and digital tools. These developments have contributed to the expanding MT market (Comnick et al., 2022).

As interest in the use of automated manufacturing and fabrication equipment continues to grow in the construction industry (ABB, 2021), this study explores the opportunities for automating the fabrication of MT components, such as glulam columns and beams. A company's decision to invest in hardware and software tools must be aligned with the design of a production system that supports its business goals. Production system design is the process of determining the characteristics of a system for making products (P2SL, n.d.), considering both production goals and constraints. Deciding whether automation is the right strategy and if so, selecting the appropriate automation equipment is an integral part of this production system design process. A holistic approach allows for informed decision-making regarding automation investments, ensuring that technological solutions are not just implemented in isolation but contribute to improvements in productivity, quality, and overall system efficiency.

For clarity, manufacturing must be distinguished from fabrication in the context of MT. Manufacturing refers to the production of engineered wood products by bonding multiple layers of lumber boards with structural adhesives. In contrast, fabrication involves transforming these engineered wood products into structural elements, such as columns, beams, and floor panels. This paper focuses exclusively on the latter. The research question this study aims to answer is the following: **What are the opportunities to automate the fabrication of MT components?**

We begin this paper by defining MT systems, providing an overview of Industrialized Construction (IC) and its relevance to the MT supply chain. Next, we examine the role of automation in construction. Finally, we describe the fabrication process for MT components and propose ideas for automating steps of this fabrication process, while emphasizing the significance of designing production systems that efficiently and effectively meet both production demands and customer needs.

2. MASS TIMBER (MT) SYSTEMS

An earlier paper by Coelho et al. (2023) provided a background on MT systems. To summarize, MT can refer to several engineered wood products, such as Cross-Laminated Timber (CLT), Glue-Laminated Timber (Glulam or GLT), Nail-Laminated Timber (NLT), Dowel-Laminated Timber (DLT), Mass Plywood Panels (MPP), and Mass Plywood Lams (MPL), or a complete structural building system. In North America—where the authors have studied the MT supply chain in depth—manufactured MT products are typically shipped to other facilities for custom fabrication based on project-specific shop drawings. Custom-fabrication involves several steps, including machining, sealing or coating, hardware installation (structural connectors and fasteners), and fireproofing. These steps turn MT products into engineered-to-order structural components, such as columns, beams, floors, walls, stairs, and roofs. These components are then shipped to the construction site for final assembly, as illustrated in Figure 1.

Figure 1 – Multi-story MT structure under construction in Utah, United States

Source: Gardner News (2023).

The latest International Building Code (IBC), which serves as a baseline for state and local building regulations in the United States, was published in 2024 and allows MT structures up to 18 stories (ICC, 2024). In Brazil, the Associação Brasileira de Normas Técnicas (ABNT) introduced the first MT building code (NBR 7190-1:2022) in 2022, establishing the criteria and parameters for designing MT structures. This Brazilian code also addresses fire-resistance requirements and outlines quality control procedures for the manufacturing of MT products.

Sustainability mandates, updates to building codes, and digital advancements have driven the global adoption of MT. MT offers significant environmental advantages over other building materials: its production requires less energy than concrete or steel, leading to a reduced carbon footprint (Hart et al., 2021), and wood has the inherent ability to store carbon long-term, a process known as carbon sequestration. Furthermore, the efficiency of prefabricated MT components shortens construction timelines and reduces on-site labor requirements.

3. INDUSTRIALIZED CONSTRUCTION (IC)

The industrialization of manufacturing, which began in the 1760s with the Industrial Revolution, marked a shift from handcrafted goods to machine-based production. This transformation enabled faster, cheaper, higher-quality, and larger-scale manufacturing processes. In 1913, Ford introduced the moving assembly line, enabling the mass production of automobiles. Decades later, Toyota refined high-volume manufacturing with the development of the Toyota Production System, focusing on eliminating waste in its processes while simultaneously increasing value delivery and improving customer satisfaction.

In contrast, the construction industry has been slower to adopt technology and mechanization, resulting in stagnant productivity growth (Barbosa et al., 2017). Several reasons contribute to this slow adoption: (1) the uniqueness of each construction project, (2) the nature of production moving from one location to another, (3) the divided authority (owner, designer, contractor, and other stakeholders) over the process of development and construction, and (4) market volatility (Warszawski and Sangrey, 1985). However, recent years have witnessed increased interest in innovation, technology, and consequently industrialization within the construction industry. This shift has been driven by stakeholders—including owners, developers, and contractors—who seek to become more competitive, deliver complex projects in less time, and address challenges such as ongoing construction labor shortages (Hovnanian et al., 2022).

In response, IC has emerged as a strategy that applies manufacturing principles and tools—both software and hardware—to improve project delivery. IC incorporates approaches such as Design for Manufacturing and Assembly (DfMA) and digital tools such as 3D modeling software to optimize the design of building components and systems for manufacturing, fabrication, and on-site assembly. These components are fabricated in controlled factory settings using Lean Production principles and the employment of mechanization and automation. Once fabricated, components are transported to the construction site, where they are assembled and integrated with other on-site or off-site fabricated components and systems to form the final built asset, such as a building.

The integration of IC and MT represents a shift in traditional project delivery, redefining existing supply chains and fostering new ones within the construction industry. Because large-scale components are produced off-site weeks or months in advance, substantial design efforts are required at the outset of the project delivery process. Key building systems—including structural, mechanical, electrical, plumbing, and fire protection—must be coordinated, integrated, and optimized early in the design phase. These upfront efforts are crucial to locking in key decisions that will affect the design and fabrication of MT components, ensuring an efficient workflow for off-site fabrication and on-site installation while minimizing downstream rework.

4. AUTOMATION IN CONSTRUCTION

The construction industry’s move toward industrialization can be significantly advanced through the adoption of mechanized equipment that facilitates the integration of automation technologies into the production of building components. Machines are particularly well-suited for physically intensive tasks that require speed, strength, and repetitive motions (Everett and Slocum, 1994). Construction work is inherently demanding, dangerous, and often repetitive, although the degree of repetition varies based on factors such as project type, design, and construction methods. These characteristics highlight the potential benefits of employing mechanization and automation in the fabrication of building components to replace labor-intensive tasks. These benefits include, among others, (1) faster fabrication, (2) higher quality, (3) greater precision, (4) better consistency, and (5) lower safety risks.

Although automation, particularly in the form of robotics, was first introduced in construction as early as the 1980s in Japan (Yoshida, 2006), its adoption in the industry remains limited today. Moreover, research into construction robotics has primarily focused on on-site applications (Tehrani et al., 2022). For instance, early studies explored ways to automate existing construction equipment or enhance its automation capabilities using technologies such as teleoperation, limit switching, numerical control, and microprocessors, which became increasingly accessible in the 1980s (Warszawski and Sangrey, 1985).

Warszawski and Sangrey (1985) attributed the limited interest in industrializing construction processes (e.g., through mechanization and automation) to several inherent characteristics of the industry: (1) bespoke nature of projects, (2) transient nature of production sites, (3) fragmented authority among stakeholders (owners, designers, and contractors), (4) rugged environments, and (5) market volatility. They argued that the advancement of construction robotics would depend on the prefabrication of components into assemblies for easier installation and the development of task-specific robots. Now, four decades later, their vision is gradually materializing as the construction industry increasingly embraces the transition from traditional practices to IC.

Given the unique characteristics of construction, tailored strategies for implementing mechanization and automation in construction must be developed, drawing insights from manufacturing, which has demonstrated substantial progress in improving quality, efficiency, and productivity. IC integrates digitally-driven manufacturing principles and tools with off-site, assembly-based production. This controlled, factory-like environment facilitates the observation, analysis, and refinement of production processes, including the adoption of mechanization and automation. Unlike traditional construction sites, where workers move to various locations to perform work, off-site IC enables products to travel along an assembly line. Tehrani et al. (2022) identified IC as the optimal context for applying robotics in off-site, assembly-based construction. IC makes construction more manufacturing-like and potentially offers greater opportunities than those pursued in studies on construction robotics focused on on-site applications.

In the realm of MT, the fabrication of engineered-to-order components is already a leading example of digital innovation in construction. Computer numerical control (CNC) machines are widely used for subtractive manufacturing tasks such as cutting, milling, and drilling (Eversmann et al., 2017). Recent studies (e.g., Eversmann et al., 2017; Krieg and Lang, 2019) have explored the application of robotics in the fabrication of MT components. Robots have the potential to replace CNC machines by offering greater flexibility, or take over manual tasks in current production processes. Both possibilities are explored in this study.

5. FABRICATION OF MASS TIMBER COMPONENTS

The fabrication process of MT components described in this section is based on field observations conducted by the first author in 2023 at Company A’s fabrication facility in the United States. A more detailed description of this process, including a discrete-event simulation model, is provided by Coelho et al. (2024). Nevertheless, to familiarize readers with this process, an overview of the fabrication of MT columns and beams is presented below.

As this description reflects the operations observed at Company A, it may not fully represent practices at other MT fabrication facilities in the United States or elsewhere. However, since the final product—an MT column or beam—must meet consistent performance standards regardless of where it is fabricated, the general steps involved in transforming MT billets into structural components are likely similar across different facilities. In this context, glulam “billets” are glulam pieces that are fabricated into structural elements, e.g., glulam columns or beams. While this paper specifically focuses on the fabrication of glulam components, the ideas, principles, and approaches discussed may also apply, with minor adjustments, to the fabrication of other MT products, such as CLT panels.

Glulam billets undergo the following fabrication steps on the assembly line:

(1) Tagging and Queuing: each billet is tagged and matched to a specific column or beam by a unique ID, then placed in the production queue.

(2) Unwrapping: when a billet's turn in the queue arrives and a CNC machine becomes available, the billet is unwrapped and transferred to the CNC machine's loading table.

(3) Dimensional Verification (Pre-CNC): a CNC operator measures the billet (width, depth, and length) to confirm it meets specified dimensional tolerances.

(4) CNC Machining: the billet is machined according to CNC files derived from shop drawings. This step includes all necessary cuts, penetrations (service holes), and notches, slots, or grooves required for the later installation of metal hardware (step 7). In the case described in Coelho et al. (2024), pre-drilling was not part of the machining process. After this step, glulam components are referred to as "columns" or "beams" rather than "billets."

(5) Dimensional Verification (Post-CNC): once machining is complete, all dimensions of the glulam component—including width, depth, and length, and now all cuts, penetrations, notches, slots, and grooves—are measured on the CNC unloading table.

(6) Sealing or Coating: the glulam component is sealed with a protective undercoat or an alternative sealant, depending on the requirements.

(7) Hardware Installation: metal hardware (connectors and fasteners) is attached to the glulam component. All fasteners are drilled in during this step.

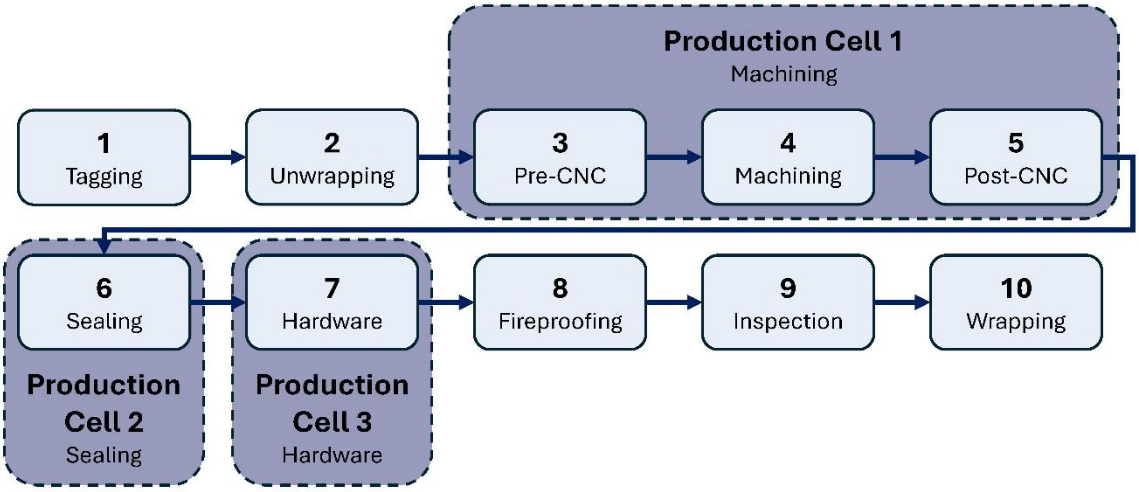
(8) Fireproofing: firestop sealant or tape is applied to designated areas of the glulam component to meet required fire-resistance ratings.

(9) Inspection: the finished component is inspected by the engineer of record, who is responsible for the design of the MT system.

(10) Wrapping: the finished component is wrapped and prepared for shipping.

Figure 2 illustrates the sequence of fabrication steps along with proposed automated production cells, which are discussed in more detail in Section 6.

Figure 2 – MT fabrication steps and proposed production cells



Source: authors.

6. AUTOMATION IN MASS TIMBER FABRICATION

Building on this ongoing research, the study presented in this paper has two objectives: (1) to evaluate the feasibility of employing robotic arms as an alternative to CNC machines for machining MT components, and (2) to identify additional fabrication steps that could benefit from automation, either through robotic arms or other automated equipment tailored to meet the specific needs of the MT fabrication process.

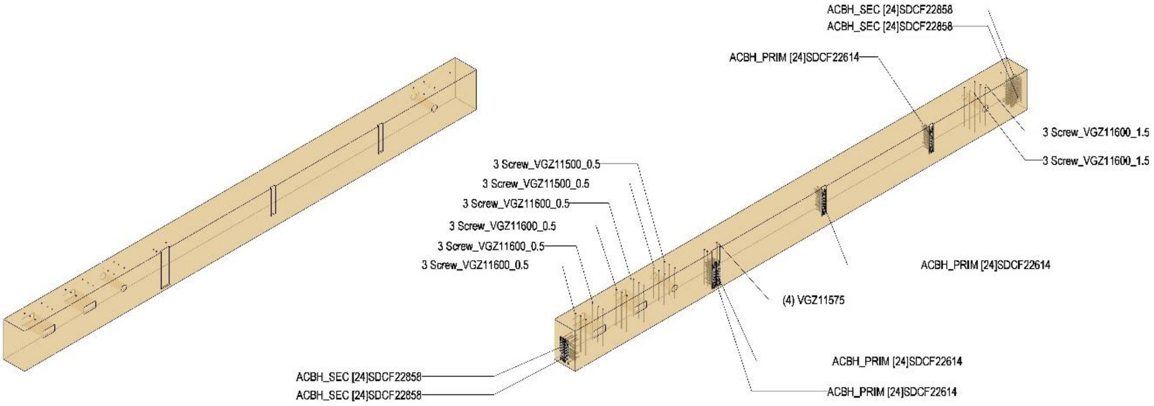
Decisions about automation investments (e.g., whether to purchase equipment and what type of equipment to purchase) must consider the production system's overall configuration to ensure efficiency and effectiveness in producing what customers want. A production system consists of multiple production units, each encompassing one or more process steps, and ultimately delivers a product—in this case, a MT structural component. Rather than optimizing individual production units in isolation, efforts should prioritize addressing the system's bottleneck—production unit with the lowest throughput (longest cycle time) of all production units in a system (P2SL, n.d.). Continuous improvement of the bottleneck can be achieved by improving means and methods, reallocating resources (e.g., equipment and labor), or redesigning the production system to redistribute work from the bottleneck to other production units with available capacity. Once the bottleneck shifts, attention can then shift to the new one.

In alignment with Lean Production principles of waste elimination and lead time reduction, this study analyzed potential bottlenecks in the MT fabrication process and explored how automation could improve the overall flow and efficiency of the production system. The proposed concept envisions the MT fabrication system comprising several production cells, each integrating machines and workers responsible for one or multiple process steps. In order to define these production cells, we identified the fabrication steps with the longest cycle times in the process described in Section 5, supplemented by insights from the authors' extensive experience in automation, manufacturing, and wood processing.

A glulam beam was selected for this study to determine the characteristics of these cells. This beam, in this paper referred to as "Beam A," is one of over 1,200 glulam components comprising the structure of a building ("Building B") located in the state of Tennessee, United States. In discussions among the authors, it was agreed that Beam A was a suitable case study due to its design complexity, which correlates to some extent to fabrication complexity. It was assumed that Beam A would likely require more time to fabricate compared to the average beam used in Building B.

Figure 3 illustrates Beam A, which measures 869 cm (28.5 ft) in length, 40 cm (15.8 in.) in width, and 66 cm (26 in.) in height, and has a weight of 1,340 kg (2,955 lb). It features eight metal connectors, each secured with 24 fully threaded structural screws, totaling 192 screws. These screws are either 15.9 cm (6.3 in.) or 21.9 cm (8.6 in.) long. Additionally, 28 fully threaded structural screws, ranging from 50 cm (19.7 in.) to 60 cm (23.6 in.) in length, are installed for structural reinforcement, bringing the total number of screws in Beam A to 220.

Figure 3 – Beam A

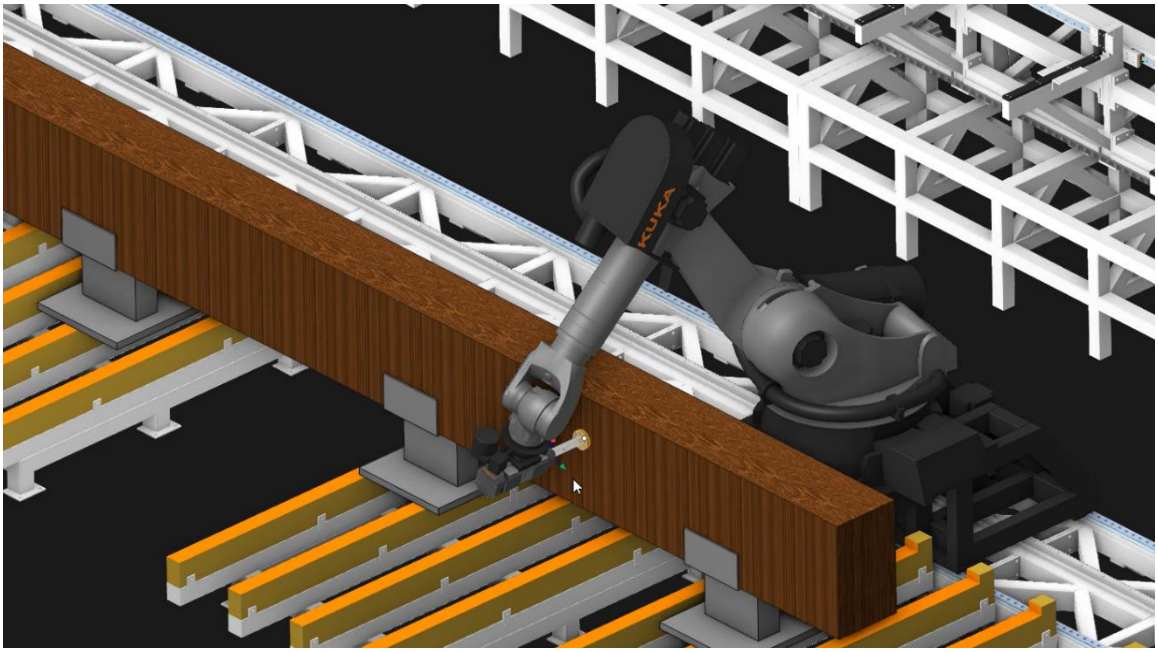


Source: Timberlab.

The three proposed production cells (Figure 2) are: (1) Machining; (2) Sealing; and (3) Hardware. This production system configuration represents one of many potential arrangements, as these production cells can be structured in various ways. In particular, Production Cell 3 poses significant challenges for automation due to the dexterity required for the process and the lack of readily available automated solutions. Nevertheless, we present a potential solution in this paper. Alternatively, improvements in machining precision and refinements to the current manual hardware installation process could reduce cycle times without automation.

Production Cell 1 (Machining) includes an intuitive vision system with integrated laser sensors, a multi-axis robotic arm mounted on a linear track for extended reach (Figure 4), and a fixed table. The MT component is placed on the fixed table and secured in place with clamps. Next, the vision system pre-processes the component by capturing images and measurements of the glulam billet and comparing them to the digital model to determine any necessary adjustments (e.g., depth or angle of cuts). Then, the robotic arm executes all required cuts, penetrations (service holes), and notches, slots, or grooves based on a digital file. It also pre-drills holes for fasteners. Finally, the vision system inspects the finished part to ensure compliance with dimensional tolerance specifications.

Figure 4 – Simulation of a robotic arm on a linear track machining a glulam billet



Source: authors.

Production Cell 2 (Sealing) includes a pass-through spraying machine with infeed and outfeed roller conveyors. The MT component is placed on the infeed conveyor and automatically moved through the machine. Sensors detect the component’s cross section to adjust the position of the spraying head and drying device accordingly. As the component moves through the machine, its surface is sprayed with the desired protective undercoat, paint, or stain. Finally, the machine blow-dries the surface of the component.

Production Cell 3 (Hardware) includes a multi-axis robotic arm mounted on a linear track for extended reach. The robotic arm, equipped with a multi-function head (Figure 5), operates next to a storage area for all metal hardware. A human operator selects and places the connectors and fasteners onto a feed conveyor. The robotic arm then picks up, grips, and precisely positions each connector on the MT component before drilling the fasteners to secure it in place.

Figure 5 – Example of multi-function head for robotic arm

Source: Zimmer Group (2025).

Table 1 presents characteristics, approximate production cycle times for Beam A, and approximate equipment costs for these production cells. These figures were derived from industry experts, including authors of this paper and others, as well as computer simulations and technical data from equipment manufacturers. Although these estimates are preliminary and need to be refined, they are considered sufficient for the objectives of this paper. All cells were designed to achieve a minimum throughput rate of two units per hour, similar to the current fabrication process described in Section 5. Production scenarios with higher throughput demands could benefit from additional automated cells, further automation of other fabrication steps, and overall process improvements to all fabrication steps.

These three production cell configurations serve as a starting point for designing a production system for fabricating MT components. Various alternative configurations are possible and were explored among the authors, and we intend to continue this collaboration and present some of these alternatives along with corresponding simulation models in future publications. This will allow for a comparison of different production system configurations to identify the most optimal options for different production scenarios, considering performance metrics such as cycle time, work-in-process (WIP) inventory, throughput, and production costs.

Table 1 – Production cell characteristics

Production cell	Automated solution	Approximate cycle time	Approximate equipment cost
1: Machining	Robotic arm on linear track + vision system with laser sensors	30 min	$500,000
2: Sealing	Pass-through spraying machine with roller conveyors	10 min	$150,000
3: Hardware	Robotic arm on linear track with multi-function head	20 min	$500,000

Source: authors.

7. DISCUSSION

The relationship between design- and production complexity is a key consideration in MT fabrication. Design complexity is influenced by factors such as component geometry and dimensions, the number of connectors and fasteners, and required finish quality. Production complexity, in turn, is influenced by factors such as the number and capabilities of machines and tools, labor skill requirements, cycle times, and process variability. Designing a production system to accommodate certain products—and designing products that align with production system capabilities—is a two-way process.

Lean Production adopts a system-based approach, focusing on improving overall production performance by eliminating waste across the entire system rather than merely optimizing individual workstations, or introducing advanced machinery that may not yield system-wide production gains. Addressing bottlenecks is essential, as reducing cycle time at the slowest workstation leads to the most significant system throughput gains. However, identifying bottlenecks and opportunities for improvement requires analyzing the current state by observing production, collecting production data, and evaluating production metrics. These metrics can then inform whether automation is feasible or necessary. While technology and automation can contribute to improving production performance, they are seldom the sole solution. Krafcik (1988) noted that “high technology is not often the solution to poor manufacturing performance if the technology is employed without a suitable production management policy.” Thus, a system-based approach is essential to ensure that automation efforts will increase system efficiency and throughput, rather than improve performance only at isolated workstations.

That said, automation can help mitigate production complexity. While human workers must perform numerous elemental motions in MT fabrication, robotic systems—due to their dexterity and flexibility—can simplify production by reducing manual interventions. However, for automation to be effectively implemented, certain product characteristics must be standardized to ensure compatibility across multiple product families, and robots must be configured to perform tasks with minimal motion waste. Standardization does not necessarily imply a total lack of customization. Mass customization is an approach that allows for a degree of design flexibility while keeping production costs and delivery times within acceptable limits (Conte et al., 2024). Although mass customization still requires adaptable automation—systems capable of handling a variety of products without extensive reprogramming or retooling—it does not require redesigning the production system for every new project or product variant.

Selecting the appropriate product or product family is crucial when designing production systems. For simplification, we focused on analyzing a single component with a relatively high degree of design complexity within Building B’s family of MT components. However, if this component is a one-off or represents only a small fraction of the total number of components, it may not be the most appropriate choice for designing this production system. Instead, identifying commonalities across multiple products may provide a more suitable foundation for the production system design process.

8. CONCLUSION

This paper explored opportunities for automating the fabrication of MT components in response to increasing demand, driven by sustainability benefits, advancements in building codes, and technological innovations. To meet this growing demand, efficient and effective production systems are essential. To that effect, and adopting a system-based approach, we proposed a production system for MT fabrication, identifying key fabrication steps that could benefit from automation, including machining, sealing or coating, and hardware installation. Through an analysis of three proposed production cells, we described automated solutions—such as vision systems with laser sensors, robotic arms, and other machinery—that can alleviate production bottlenecks, reduce cycle times, and improve throughput.

As part of our ongoing research, we continue to explore additional automation solutions for MT fabrication. We will build on the findings of this paper by evaluating various automation technologies based on their performance across different production scenarios. Additionally, we will compare proposed automation strategies to current practices to assess their impact on production metrics. As the construction industry increasingly embraces automation, this research provides insights into optimizing production systems for the fabrication of MT components, enhancing sustainability and efficiency.

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