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Production System Configurator for Mass Timber Supply and Construction

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ABSTRACT

Mass timber (MT) is a sustainable material increasingly used for both single- and multi-story buildings due to technological developments and evolving building codes. As demand increases, new MT supply systems are emerging. These systems include facilities where harvested timber is cut, glued, and made into materials subsequently shipped to other facilities where they are fabricated into structural components. These components are then shipped and erected on site. MT components demand fabrication and handling practices that differ significantly from those used in more typical construction systems involving precast concrete- or structural steel components. In this paper, we describe a supply system for MT and outline a discrete-event simulation model to characterize the features of that system. Currently, we have only a preliminary model. Then, we introduce principles from Lean Construction and Operations Science to illustrate how MT supply systems can be made “greener.” The objective is to build a configurator that integrates product- and process design, and that incorporates metrics pertaining to operational efficiency and the environmental sustainability potential of MT systems so that judicious trade-offs can be made.

INTRODUCTION

Mass timber (MT), short for “massive timber,” is a sustainable material increasingly used for structural systems in single- and multi-story buildings. Accordingly, the emerging MT supply chain is rapidly evolving due to the rising demand for MT products (Comnick et al. 2022) and competition among suppliers. With the adoption of this relatively new material, however, come management challenges related to storage, fabrication, and handling, that differ significantly from how common construction materials such as concrete and steel have been managed. If not addressed judiciously, these challenges can diminish the environmental benefits of MT construction. In this paper, we suggest that these challenges can be addressed through production system design, including the effective application of Industrialized Construction (IC) methods and the use of tools that help decision-makers make performance trade-offs.

This paper starts by defining what we mean by MT systems. Second, the paper presents a case study that provided data to describe the MT fabrication process and create a discrete-event

simulation (DES) model that illustrates the characteristics of this fabrication process. Third, it introduces Lean and Operations Science principles and methods that, along with related metrics, establish the basis for the development of a computer-based configurator to support the design of IC production systems.

MASS TIMBER SYSTEMS

MT encompasses various engineered wood products or structural building systems. These products are manufactured by compressing multiple layers of wood from harvested trees using glue, dowels, or nails, forming large elements such as Cross-Laminated Timber (CLT), Glue-Laminated Timber (Glulam), Nail-Laminated Timber (NLT), Dowel-Laminated Timber (DLT), Mass Plywood Panels (MPP), and Mass Plywood Lams (MPL). Once manufactured to various sizes, they are typically shipped to other facilities where they are custom-fabricated according to project-specific shop drawings. During fabrication, they are (1) cut to specified, tightly-toleranced sizes, (2) hollowed out to accommodate Mechanical, Electrical, Plumbing, and Fire Protection (MEPF) systems, (3) fireproofed, (4) fitted with connections, and (5) sealed with a protective coating. This process turns MT products into custom or Engineered-to-Order (ETO) building components, which are then shipped as a kit-of-parts for on-site assembly, where they serve load-bearing purposes (e.g., columns, beams, floors, walls, stairs, and roofs) (Coelho et al. 2023).

The introduction of “Type IV” construction in 2015 to specifically address heavy timber construction in the International Building Code (IBC)—which serves as the foundation for building codes across various states and local jurisdictions—played a crucial role in promoting the adoption of MT in the United States. The 2015 IBC allowed MT construction up to 5 stories for residential- or 6 stories for commercial occupancy. Just a few years later, the 2021 IBC included three new construction types (IV-A, IV-B, and IV-C), expanding the use of MT to buildings up to 18 stories for both commercial- and residential occupancies (Breneman et al. 2022). These code changes, alongside advancements in digital processes, workflows, tools, and equipment, spearheaded the evolution of MT supply chains in North America. As industry stakeholders acquire the necessary expertise to undertake MT projects, more manufacturers and fabricators are entering the market to meet the growing demand for MT products. As of March 2024, more than 2,100 multi-family, commercial, and institutional MT projects were either in progress or built in the US (WoodWorks 2024), with this number rapidly rising.

MT offers significant environmental advantages over other building materials. Its production requires less energy than concrete or steel, resulting in a lower carbon footprint (Hart et al. 2021). Additionally, wood’s inherent capacity for long-term carbon storage, known as carbon sequestration, provides another environmental benefit. Although MT has rightfully earned a reputation for environmental sustainability, its environmental impact, as with any other material, is tied to various phases throughout its life cycle. This includes harvesting, transportation, manufacturing, fabrication, installation, and potential end-of-life processes (e.g., reuse, recycling, or disposal). Beyond sustainability, MT offers other advantages, such as the aesthetic allure of exposed wood and the efficiency derived from IC, which can shorten construction timelines and reduce on-site labor requirements.

The nature of MT demands fabrication and handling practices that differ significantly from those used in other construction projects, such as those using precast concrete- or structural steel components. As is the case for concrete- or steel alternatives, the production of MT components is demand-driven rather than forecast-driven, with many components being designed, engineered, and fabricated to order. This contrasts with materials such as dimensional lumber used in light-frame timber construction, that are produced based on forecast demand resulting in made-to-stock

products. Furthermore, MT differs from concrete and steel in its sensitivity to weather conditions, as wood is particularly susceptible to moisture effects. Therefore, it is paramount to mitigate moisture-related risks associated with MT throughout its entire lifecycle, spanning manufacturing, fabrication, shipping, installation, and building operations.

CASE STUDY: PROJECT Y

The case study project presented in this paper is referred to as “Project Y,” a multi-story commercial building located in the state of Arkansas. The study involves describing the supply and installation of an ETO MT structural system for Project Y. “Company A” is a vertically integrated MT contractor based in the US, providing preconstruction, structural engineering, procurement, fabrication, and installation services for MT systems. For Project Y, Company A was responsible for supplying all the glulam columns and beams and installing the entire MT system on site, which includes CLT floor panels supplied by a third-party MT supplier.

MASS TIMBER PRODUCT DESIGN

Project Y features a post-and-beam MT structural system, in which glulam columns and beams form structural grids, with CLT panels spanning horizontally across these grids. Approximately 1,000 glulam pieces (columns and beams) were custom fabricated at Company A’s fabrication facility, located in the Southeast region of the US. These pieces were then transported approximately 1,500 km (900 mi) to Project Y’s site for erection and installation. All CLT panels were manufactured and cut to size by another MT supplier and shipped to site by that supplier.

Glulam is manufactured—typically by sawmills—by gluing and pressing timber lamellas together, with lamellas oriented parallel to one another. Manufactured glulam pieces are referred to as billets until they are fabricated into structural building components such as columns and beams. Company A received glulam billets at its fabrication facility for custom fabrication according to component specifications. Each MT component was structurally dimensioned and modeled using Building Information Modeling (BIM) software. The BIM supported the creation of fabrication drawings, later translated into files including the cutting paths to instruct Computer Numerical Control (CNC) machines on how to cut each component. CNC machines cut the glulam billets to specified dimensions in accordance with the industry product standard for structural glulam (ANSI A190.1-2022), ensuring compliance with allowable dimensional tolerances.

The MT components for Project Y vary in weight from 45 to 1,200 kg (100 to 2,650 lb) and in size from 0.8 to 9.1 m (2.7 to 30 ft) in length, 21.5 to 36.2 cm (8.5 to 14.3 in) in width, and 41.3 to 76.2 cm (16.3 to 30 in) in depth. Over 80% of Project Y’s pieces have the same 26 cm x 62 cm (10.3 in x 24.5 in) cross-section. This reflects the significant standardization efforts undertaken by the structural engineer to reduce design, manufacturing, fabrication, and assembly complexity (e.g., product standardization will reduce matching problems (Tommelein 2016)).

MT columns and beams are connected on site using L-shaped metal connectors (a.k.a. “hangers”), which are attached to each component at the fabrication facility after CNC processing. Most connectors for Project Y’s MT components are fastened with 24 fully threaded self-tapping wood screws, each over 20 cm (8 in) long, and most components use the same L-shaped connector, reaffirming the efforts to standardize product design to simplify the production system. Company A employees noted the simplicity of this fabrication job compared to previous projects, attributing it to the uniformity among MT components achieved through design standardization.

MASS TIMBER FABRICATION AND SUPPLY PROCESS DESIGN

The fabrication process of MT columns and beams described in this paper is based on field observations conducted by the first author, who visited Company A's fabrication facility twice (in July and October 2023). These visits provided insights into the processes of custom-fabricating MT components for Project Y. The author observed operations and interacted with Company A's employees working at the facility, who provided additional information and clarification upon request. This facility spans 7,000 m² (75,000 sq. ft.) and houses two 5-axis CNC machining centers from a world-class woodworking machinery manufacturer. Company A uses these CNC machines to cut and mill glulam billets that, upon completion of fabrication, become structural columns and beams. These are then transported to site for assembly as a kit-of-parts.

For Project Y, the MT manufacturer delivered all glulam billets to Company A over the course of 3.5 months, totaling 40 truckloads. Each load comprised about 25 billets. Ideally, billets are delivered to the facility, fabricated, and delivered to site in the same sequence as they are to be installed on site. Billets come individually wrapped to keep them clean and protect them against moisture, debris, and scratches during storage and transportation. Each one is labeled with manufacturer details, including size (length, width, and depth), layup combination (or structural grade), project name, weight, volume, date, incoming truck number, piece ID, and QR code. Upon arrival, a forklift unloads billets from the truck and stores them indoors while still wrapped.

Before processing these billets on CNC machines, a Company A label is affixed to each billet, including piece ID, project name, and outgoing truck number. This labeling step indicates that the billet has been designated to become a specific beam or column, ensuring matching dimensions, fire rating, species, structural grade, etc., and prioritized in the CNC production queue. Next, a worker removes the protective wrap from the billet and a forklift operator transports it to the designated CNC machine. Once on the CNC loading table, a CNC operator measures the billet dimensions to ensure conformance to specified dimensional tolerances. With the matching billet CNC file loaded into the CNC console, the operator initiates the machining process.

The CNC machine grips and pulls the billet to execute all cuts and notches as outlined in the CNC file. Upon completion, the CNC machine moves the custom-cut glulam component to the CNC unloading table, where an operator measures and verifies its dimensions and notches. These notches serve as designated positions for installing metal connectors, a process also carried out at Company A's facility, or for placing other structural MT members on site, as is the case with purlin beams. Components that do not meet the specified dimensional tolerances undergo repairs in the hand fabrication area. In such instances, the CNC operator affixes a piece of tape to the component, indicating where and what needs to be done to ensure the component can meet the specifications. This information is also recorded in an online spreadsheet.

Next, the glulam component is transported from the CNC unloading table to the hand fabrication area, where it is placed on sawhorses. Here, fabrication workers address any required repairs to cuts and notches using several hand- and power tools to ensure all dimensions align with the specifications. The component is then coated with a clear protective undercoat to guard against UV degradation and moisture absorption. Although the glulam manufacturer seals all billets prior to delivering them to Company A, Company A reseals the pieces at least at all cuts (or entirely if requested by the project owner). Additionally, the pieces can receive finish coats if the owner desires a certain tone color and a more polished appearance, although this is uncommon. Once the sealant has dried to the touch, workers install metal hardware by driving screws into the wood according to specifications outlined in fabrication drawings. These drawings detail the type and position of connectors and fasteners for each glulam component.

Subsequently, the finished piece is transported to a designated area in the facility where components are stored prior to inspection. Various criteria are verified during inspection: (1) physical integrity: whether the piece is free of any delamination or cracking; (2) dimensions: length, width, and depth; (3) metal connectors: quantity, type, position, and whether they should be recessed or flush with the surface of the glulam piece; and (4) metal fasteners: quantity, type, distance between screws, and whether they are fully screwed into the wood. If all criteria are met, the inspector affixes a piece of green tape on the component, indicating that it has passed inspection. In case of any concerns, the inspector affixes a piece of red tape and communicates the issue(s) to a manager. Repairs are often feasible, although the inspector may decide it is necessary to issue a Request for Information (RFI) before proceeding. In such instances, the component remains stored until Company A receives a response from the Engineer of Record detailing the correct repair procedure. If no RFI is required, the component can be promptly repaired. Although uncommon, some components may be irreparable and are either disposed of or repurposed for non-structural use. After passing inspection, components are transported to a designated area, separate from the hand fabrication and inspection areas, where a worker wraps each piece individually with heavy-duty plastic in preparation for shipping. Next, the wrapped components are moved to an outdoor storage area prior to shipment. For Project Y, approximately 25 glulam pieces are loaded onto each truck for shipment.

DISCRETE-EVENT SIMULATION MODEL OF FABRICATION OF MASS TIMBER COMPONENTS

Computer simulations allow for the study of new process designs or can imitate real-world processes in various fields of study, including construction and manufacturing, to help understand system behaviors. Using simulation for operations research offers advantages over experimenting with real-world setups, as it is cost-effective and does not disrupt real-world systems. DES is a method that “concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time” (Law and Kelton 1991). It has been used in construction, e.g., by Ioannou and Martinez (1996) to compare alternative construction methods, Tommelein (1998) to simulate pull-driven scheduling for pipe-pool installation, Altaf et al. (2018) to develop, along with Radio-Frequency Identification (RFID) data, a production planning and control system for a panelized home production facility, and Hasan et al. (2019) to study the off-site fabrication of steel bridge girders.

The rationale for using DES was to model the impact of various types of variability on production system performance. The DES model presented herein was built with Simio software (Academic Edition, v. 15.254.33325). A Simio model requires at least four objects from the standard library to run, namely: (1) entity: an element that flows through the system, in our model, entities represent glulam billets, batches of MT components ready to be shipped, and trucks; (2) source: an object that generates entities, in our model, it generates glulam billets that are delivered to the fabrication facility according to a delivery schedule; (3) server: a means to model a capacity-constrained processing location, in our model, several servers represent different steps taking place in the fabrication facility as described previously; and (4) sink: a means to destroy entities that have finished processing in the model, in our model, it represents the depository of fabricated glulam columns and beams that have been delivered to Project Y’s site.

The first author developed the model using collected data to understand and articulate the fabrication of MT components. Information input into the simulation model included: (1) delivery schedule of glulam billets to the fabrication facility; (2) quantity of glulam billets to be fabricated; (3) sequence of fabrication steps; (4) duration of fabrication steps; (5) fabrication resource

constraints, including: (a) work schedule (days and hours worked), (b) number of available CNC machines, (c) number and role of fabrication workers; and (6) shipping schedule of fabricated glulam components to Project Y's site. This model illustrates IC component fabrication. The authors are currently conducting research to develop a framework for a configurator to support production system design for IC components and to identify metrics for supporting performance trade-offs when deciding on these systems' design characteristics. Additional details about this configurator are provided in the next section.

The fabrication sequence in the simulation model includes the following steps (numbers correspond to the Simio objects in Figure 1): (1) a "Source" object generates the arrival of glulam billets to the fabrication facility, with 40 deliveries scheduled between June and October 2023; (2) upon arrival, glulam billets are identified and tagged, and then unwrapped when a CNC machine is available; (3) billets are placed on a CNC loading table, measured by a worker before CNC processing, and again measured on the CNC unloading table after processing; (4) 90% of MT components are moved to the hand fabrication area for sealing; (5) the remaining 10% require some sort of repair before sealing; (6) sealant curing time; (7) metal hardware (connectors and fasteners) is installed; (8) components are moved to a separate area for inspection; (9) components are wrapped and prepared for shipment; (10) a "Combiner" object groups components in batches ranging from 22 to 30 pieces; (11) components are shipped to the project site, with 40 shipments scheduled between July and November 2023; (12) a "Sink" object marks the arrival of MT components at the construction site, where they are installed.

The simulation includes two dedicated CNC machines for processing glulam billets. Other resources incorporated in the model are: (1) two "logistics" workers responsible for tagging, unwrapping, and wrapping MT components; (2) four "fabrication" workers responsible for repairing, sealing, and installing hardware; and (3) one "inspection" worker responsible for inspecting the MT components after hardware installation. In the real-world facility, two forklifts transport MT components between different areas, namely the areas for: (1) tagging and unwrapping, (2) CNCs, (3) hand fabrication, (4) inspection, (5) wrapping, and (6) final storage. For simplicity of the simulation model, forklifts were not explicitly modeled at this time. Instead, processing times of specific servers were adjusted to account for transportation.

For now, the model acts like a push-based production system, in which work is released based on a forecast (possibly derived from a schedule) and irrespectively of whether the downstream customer (subsequent workstation or final customer) is ready to process it. In such systems, inventory (raw materials, Work-in-Process or WIP, and finished goods) accumulates between workstations. In contrast, pull-based systems regulate the amount of WIP to avoid overproduction (Hopp and Spearman 2004).

The simulation (illustrated in Figure 1) revealed that the fabrication facility, operating 5 days per week for 8 hours each day, had ample production capacity to fulfill Project Y's demand. The maximum observed throughput was 27 glulam pieces per day, and this number was not constrained by the CNC machines, indicating they were not the system's bottleneck. However, in many instances, throughput dropped to between 5 and 10 pieces per day due to variability in the supply of billets, occasionally resulting in material shortages. The real-world customer demand (Takt) average was roughly 13 pieces per day. Deliveries to the project site were scheduled to start during the 3rd week of fabrication, providing Company A with a 2-week window to build up an inventory of finished MT components.

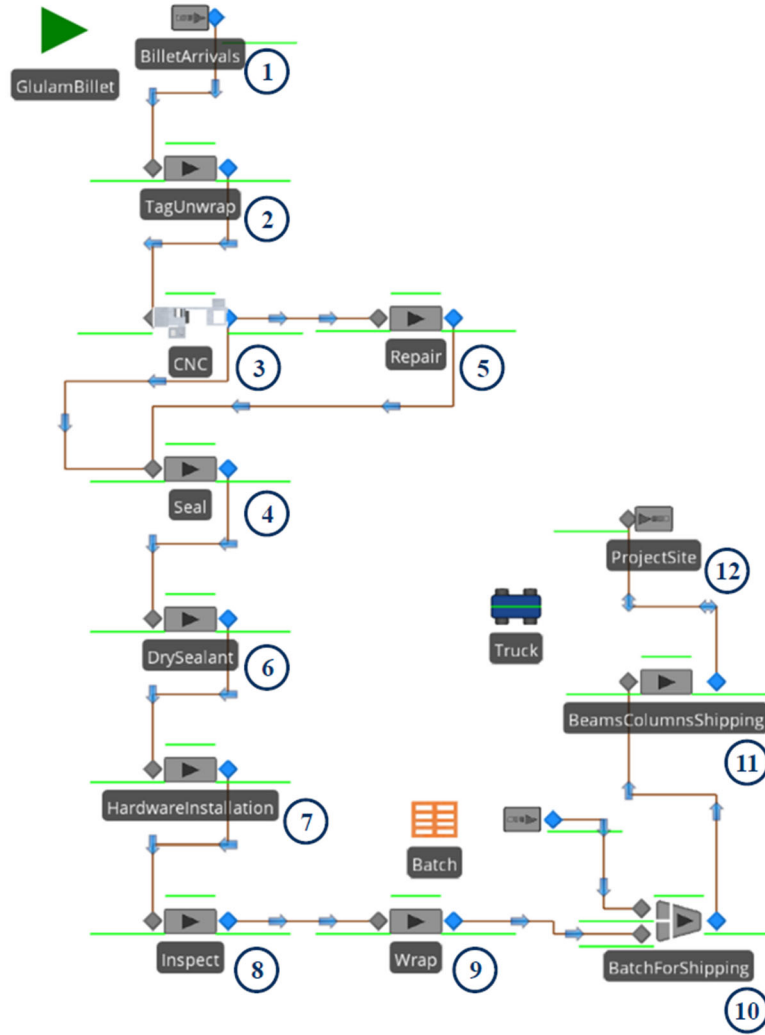


Figure 1. Discrete-event simulation model of mass timber fabrication.

Process simulation can guide production capacity planning for new factories or assess whether existing ones need to modify their capacity in some way. Increasing capacity does not necessarily require more resources. It can be achieved by reducing waste (i.e., defects, inventory, overprocessing, waiting, motion, transportation, and overproduction), thereby increasing throughput (e.g., Mao et al. 2023). Furthermore, Lean and Operations Science (Hopp and Spearman 2008) principles and methods can improve operational efficiency and environmental sustainability. The application of these principles not only makes processes “greener” as fewer resources are needed to produce the same amount of output, but also minimizes lead times and makes businesses less vulnerable to competitors who can charge lower prices for similar products.

PRODUCTION SYSTEM CONFIGURATOR

Fabricating building components in a factory setting offers numerous advantages over traditional on-site construction, including (1) improved production workflow, (2) improved product quality, (3) reduced variability, and therefore increased predictability and efficiency, (4) shorter delivery times, and (5) lower construction costs. Integrating Lean and Operations Science principles (e.g., Ballard and Arbulu 2002, Yu et al. 2013) such as standardized work, takt time, pull production,

continuous flow, mistakeproofing, built-in quality, and continuous improvement, with well-defined IC business models enhances these advantages. IC can also offer environmental sustainability advantages compared to traditional construction, such as reduced material waste, lower energy consumption, and less embodied carbon (Wilson 2019). Furthermore, companies across several industries are increasingly positioning their product offerings in the market based on the environmental sustainability credentials of both the company and their products (Hoffman 2018). To realize these advantages and succeed in the market, IC companies must establish clear business models to inform, among other aspects, the configuration of production systems (supply) to satisfy customers' needs (demand). Nevertheless, identifying target customers and defining product offerings is not only about meeting customers' needs. It is, fundamentally, about business profitability and meeting other must- and want criteria defined by the business to ensure its long-term success. Long-term success hinges on a consistent pipeline of projects and the ability to (re)configure production systems dynamically to efficiently deliver projects.

However, determining production capacity for MT- or other IC factories is challenging due to the volatility of the construction market, characterized by demand variability. IC companies often grapple with limited control over project timelines, which are influenced by external factors such as permitting, financing, economic uncertainties, design and schedule changes, customer decisions, and unpredictable on-site progress. This variability makes it difficult to schedule jobs sequentially in a factory, affecting the fit-for-purpose degree of production capacity utilization. This raises the question: How can manufacturers ensure somewhat consistent demand for their products so that they can confidently design their production systems? Potential strategies include, for example, building and maintaining long-term partnerships with suppliers and clients, diversifying product offerings, and enabling production flexibility. These can assist in establishing a pipeline of projects to mitigate, to some extent, the challenge posed by demand variability.

Amid the rise of IC (e.g., Jemili et al. 2024), companies must decide whether to invest in fabrication facilities to produce IC components and how to achieve their desired return on investment (ROI). In view of this, and as part of ongoing research, we are developing a novel software tool—an “IC configurator”—to support the design of production systems for MT and other IC components. This tool would assist companies in making informed trade-offs to align process design with production goals and product design. Although generic configurators exist for manufacturing systems (e.g., Dassault DELMIA, Siemens Tecnomatix Plant Simulation, and Rockwell Arena), customization is needed to address the (1) differences between manufacturing and construction, (2) application of Lean and Operations Science in IC settings, and (3) specific requirements of the production of IC components.

This IC configurator would enable users to iteratively configure and adapt their production systems over time, considering factors such as (1) product design, (2) process design, (3) factory layout and capabilities, (4) logistics, (5) availability and capability of technological tools (software and hardware), (6) demand rates, (7) material lead times, (8) availability and capability of labor and equipment, (9) environmental sustainability, and (10) desired ROI. The configurator would provide several related metrics to gauge performance of alternative production system scenarios and help users make informed performance trade-offs that support strategic business goals. Our research also focuses on identifying and developing such metrics. These trade-offs would influence production system design characteristics provided by the configurator, such as (1) workstation configurations, (2) process flows, (3) cycle times, (4) WIP, (5) throughput, (6) equipment selection, (7) labor requirements, (8) material inventory levels, (9) resources' consumption (e.g., water and energy), and (10) production costs. Users could then adjust these characteristics to create

new production system scenarios and analyze their impact on trade-offs, ensuring production systems can be fine-tuned to meet both production capacity demands and desired ROI.

For example, if initial parameters input into the configurator indicate that required material inventory levels to meet demand rates are not achievable due to increased costs conflicting with the desired ROI, users could adjust demand rates or material lead times and analyze their impact on throughput and ROI. Similarly, if producing a product is not financially- or operationally feasible, the configurator would explore changes to product- and process design, allowing users to see the impact thereof on various performance metrics and make informed trade-offs. Additionally, a real-time monitoring system (e.g., Altaf et al. 2015) to track performance of physical production systems and identify bottlenecks and production issues would be included in this configurator. This would enable continuous improvement and adaptation of these production systems over time.

Finally, the configurator recommendations—taking into account trade-offs made by users—would inform decision-makers on IC investment alternatives and how to (re)design their production systems. As mentioned, research to further describe the characteristics and functionalities of this configurator is ongoing and will be reported in future publications.

CONCLUSIONS

This paper described the MT fabrication process and outlined a DES model to illustrate it. As the demand for MT construction grows, the configuration of production systems to supply MT (and other IC systems) plays a pivotal role in achieving long-term business success and environmental sustainability. IC can be a strategic approach to ensure more effective, efficient, and sustainable project delivery. Accordingly, our ongoing research aims to integrate product- and process design to help decision-makers make judicious trade-offs when (re)designing production systems.

We acknowledge the limitations of this study that could be addressed in future research. Our DES model was developed based on observations from a single fabrication facility and a single project. Future studies could compare the MT fabrication job described in this paper with other MT fabrication jobs involving more intricate product designs. Additionally, they could compare the MT production system described in this paper with other IC production systems.

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