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INVESTIGATION OF THE SUPPLY CHAIN OF MASS TIMBER SYSTEMS

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ABSTRACT

How well production systems and their supply chains are designed, configured, and managed affects the delivery of construction projects. Industrialized Construction (IC) and mass timber present a shift from traditional project delivery: they are reshaping existing supply chains and creating new ones within the construction industry. The rapidly increasing number of mass timber projects in North America and the emergence of mass timber supply chains bring the need to study and seek ways to design and improve the production systems that deliver customer value by means of such projects. Accordingly, this paper presents an exploratory case study that describes the characteristics of the mass timber supply chain in North America and the major steps in the process of designing and delivering a mass timber structural system for a multi-story residential building. In addition, we present a list of recommendations for designing and delivering mass timber systems.

KEYWORDS

Mass timber, supply chain management, industrialized construction, off-site construction, production system design.

INTRODUCTION

The performance of construction projects—including mass timber projects—is tied to how well production systems and their supply chains are designed, configured, and managed. Being efficient on the jobsite is not enough. An integrated network of individuals and companies is key to ensuring that trade-offs are collaboratively evaluated, and optimal decisions are made during the design of products and processes. These in turn increase the likelihood of successfully delivering a project (i.e., providing the value that the customer expected). As O'Brien et al. (2008) point out, "it is difficult to address supply chain production improvements without also considering arrangements between organizations."

In the case of mass timber products and systems, due to the novelty of the material and the building codes that bring new design (not only product design but also process design) and use opportunities, the supply chains to deliver these products are still emerging and worthy of research. New businesses are emerging in many places, each one aiming to provide value for a part of the supply chain. Additionally, automated manufacturing equipment is becoming less expensive and increasingly versatile, which is encouraging companies to contemplate entering the Industrialized Construction (IC) and off-site fabrication world (ABB 2021) as they identify opportunities to deliver projects more economically, efficiently, and effectively.

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The opportunity for this study comes from three directions: (1) the rapidly increasing number of mass timber projects in North America (WoodWorks 2023), (2) the emergence of mass timber supply chains, and (3) the use of automated manufacturing equipment becoming more widespread in construction. Furthermore, given the lack of publications on how to design and manage the production systems to deliver projects (including mass timber projects) using IC, we see the need to study and seek ways to design and improve the production systems that will deliver customer value by means of such projects. These systems will be enabled by companies that use manufacturing principles, methods, and tools and strive to lower costs, shorten lead times, and increase quality.

Exploring the current state of the mass timber supply chain and the process of designing and delivering a mass timber structural system for a multi-story building is essential for formulating recommendations that will improve the efficiency and effectiveness of the mass timber industry. As part of ongoing research, this paper aims to answer the following questions: (1) What are the characteristics of the mass timber supply chain? and (2) What is the process of designing and delivering a mass timber structural system for a multi-story building? In response, we (1) introduce mass timber as a family of engineered wood products and as a structural building system, (2) present the reasons for its increase in use in the North American building industry, (3) describe some mass timber products used in building construction, (4) report on the emergence of the mass timber supply chain in North America, (5) explore the association of mass timber with IC, (6) describe the delivery process of a mass timber structural system for a multi-story building, and (7) provide a list of recommendations for designing and delivering mass timber structural systems.

SUPPLY CHAIN MANAGEMENT IN CONSTRUCTION

A supply chain is a network of entities involved in the design, production, and delivery of products to customers. Supply chain management (SCM) is “the practice of a group of companies working collaboratively in a linked chain of interrelated processes designed to best satisfy end-customer needs while rewarding all members of the chain” (Tommelein et al. 2003). Companies need to decide, for example, either individually or collectively, what products to make, where to make them, and how to make them, and what products to purchase, where to purchase them, and from whom to purchase them.

The importance of managing supply chains comes from the potential that developing relationships, integrating processes, increasing transparency and alignment, and focusing on customer needs can enable organizations to gain an economic advantage over their competitors. SCM—a term used more widely since the 1980s (Ashcroft 2021)—originated in the manufacturing industry (Vrijhoef and Koskela 2000) and evolved significantly in the 20th century. A substantial advancement in SCM came from Just-in-Time (JIT) production, one of the pillars of the Toyota Production System (TPS) (Liker and Meier 2006). JIT production is concerned with providing only the necessary quantity of items to each process in an assembly sequence, only when needed. The principles of the Lean production philosophy that constitute the TPS inspired the conceptualization of Lean Construction in the 1990s. The study of construction supply chains, which is a more recent phenomenon than the study of manufacturing supply chains, is closely related to the emergence of Lean Construction. Both adopt a systemic view of production systems.

Construction supply chains have been studied by several authors including Vrijhoef and Koskela (2000), who presented four roles for SCM, Arbulu and Tommelein (2002), who studied the supply of pipe supports used in power plants, Akel et al. (2001), who studied practices of parametric product design, vertical integration, and Lean construction in a pre-engineered metal building company, and Souza and Koskela (2013), who proposed a set of contextualized practices for improving construction SCM. Construction supply chains are arguably among the most complex supply chains to study and manage due to several factors, including (1) the temporary nature of projects, (2) the large number of stakeholders, (3) the wide variety of products and services, (4) the need for customization of products (e.g., Engineered-to-Order or ETO products) (5) long lead times, (6) disruptions caused by the existence of global supply chains, (7) regulations, codes, and standards, and (8) market volatility. Additionally, built assets—the finished products of these construction supply chains—are not only unique products (or prototypes) but they also require capital-intensive investment. These factors all have contributed to the existing fragmentation of construction supply chains. This fragmented nature has culminated in a business with low-profit margins, high risk, and a huge amount of waste—not only material (physical) waste but also waste from inefficient processes. Although a focus of construction management research has been on improving on-site processes, the uptake of off-site construction and IC means that a broader view of the design and aspects of supply chains is needed. Accordingly, and given the growing number of mass timber projects, this paper focuses on studying the supply chain of mass timber.

STRUCTURAL WOOD BUILDING SYSTEMS

In North America, wood structural materials have been used mainly in the construction of single-family homes and low-rise residential, commercial, and industrial buildings. Light-frame wood construction is the predominant structural wood building system in North America. It has dominated the North American housing market (both single- and multi-family) since the latter part of the 20^{th} century and is also widely used in low-rise commercial and light industrial applications (Ross 2021). The vast number of builders with experience in light-frame wood construction and the relatively low cost and off-the-shelf availability of the materials (e.g., lumber, plywood, and fasteners) and tools used in this type of construction have contributed to its predominance in North America.

Other types of structural wood building systems such as post-frame, log, and heavy timber construction have also been used for decades in North America. In the early 1990s, cross-laminated timber (CLT) was invented in Europe and began to define a new family of engineered wood products known as mass timber. The use of CLT increased significantly in Europe in the early 2000s, driven by the green building movement and the increased efficiencies achieved with the fabrication and installation of CLT (Karacabeyli and Douglas 2013, p. 1). Other mass timber products include products that have existed for decades such as glued-laminated timber (glulam or GLT), nail-laminated timber (NLT), and others developed more recently, such as dowel-laminated timber (DLT), mass plywood panel (MPP), and mass plywood lam (MPL).

MASS TIMBER CONSTRUCTION

The term "mass timber" (with "mass" referring to "massive") refers to a family of engineered wood products (or structural building systems) that are made of multiple compressed solid layers of wood joined together with glue, dowels, or nails, forming large solid wood elements such as CLT, glulam, NLT, DLT, MPP, or MPL. These products are manufactured (additive manufacturing) to various sizes and later processed or fabricated (subtractive manufacturing), usually off-site and according to a set of fabrication shop drawings. In the fabrication process, mass timber elements are cut to size, hollowed to make openings for penetrations to allow for the passage of Mechanical, Electrical, Plumbing, and Fire Protection (MEPF) elements, receive fire protection and connections, and are sealed. This turns mass timber elements into custom (ETO) building components. These components are then delivered to a jobsite as a kit of parts to be assembled. They are generally used for load-bearing purposes (e.g., columns, beams, floors, walls, stairs, and roofs) but can also function as an interior finish material (e.g., walls).

Although timber framing is not a new concept, it was the invention of CLT that now enables the construction of taller wood structures. Successful fire tests supported the inclusion of mass timber as a structural material into the 2015 IBC (ICC 2015), allowing mass timber buildings up to 6 stories (commercial projects) or 5 stories (residential projects) and about 26 m (85 ft.) in height. This spearheaded the development and construction of hundreds of mass timber projects in the United States (US). The most recent IBC (ICC 2021) went even further, introducing three new construction types that allow mass timber buildings of even taller heights, more stories above grade (up to 18 stories), and greater allowable areas.

Sustainability has been a major driver for the use of mass timber. Compared to alternative materials such as steel or concrete, the benefits of mass timber construction are significant, both in embodied carbon reduction because it requires much less energy to produce and in the long-term storing of carbon in the wood (carbon sequestration). That being said, mass timber products are only as sustainable as the process used to harvest, transport, and manufacture them, which explains why embodied carbon data can vary between different mass timber manufacturers. Nevertheless, mass timber construction also offers other benefits such as aesthetics and efficiency gained through off-site fabrication, which can accelerate construction (resulting in schedule savings) and reduce on-site labor.

The mass timber movement in North America has been fueled by more manufacturers entering the market, architects, engineers, and builders acquiring expertise in the design and construction of mass timber, and the advancement of digital processes, workflows, tools, and equipment. This has given rise to mass timber being now considered one of the most suitable building materials or systems for IC and off-site prefabrication. Mass timber systems are also included in the Modern Methods of Construction (MMC) framework (MHCLG 2019).

Because mass timber is a relatively new system, oftentimes owners and designers will compare it to alternative structural systems to decide on the most appropriate one. Therefore, we suggest using a sound decision-making system like Choosing by Advantages (CBA). CBA is a system that considers value expressed by means of advantages of alternatives relative to one another, and makes comparisons based on those advantages, without considering money (cost or price) until after attributes of alternatives have been evaluated based on factors and criteria (Suhr 1999). Examples of CBA applications in the AEC industry were presented by Parrish and Tommelein (2009) and Arroyo et al. (2012, 2013). Factors that can be used with the CBA system to compare mass timber construction to other types of construction include but are not limited to (1) building type, (2) building height, (3) building and floor areas, (4) fire resistance, (5) structural strength, (6) sustainability, (7) aesthetics, (8) material availability and lead time, (9) site logistics, (10) on-site work and schedule, (11) off-site work and schedule, (12) material sizes, (13) tolerance management, (14) industry knowledge, (15) insurance availability (e.g., builder's risk and property), (16) integration with other building systems, (17) transportation and logistics, (18) use of technology during design and fabrication, and (19) material durability.

Next, we provide a categorization of some of the most used mass timber products in North America with their usual applications and dimensions. Knowing what products are offered and what they can be used for is fundamental when studying SCM and designing production systems because different products may require different processes and resources.

GLUED-LAMINATED TIMBER (Glulam)

Glulam is a wood element composed of lumber boards that are joined end-to-end and bonded by means of structural adhesive. The grain of the laminations runs parallel with the length of a glulam. Glulam elements are commonly used as beams and columns. They can be straight or curved and are stress-rated. They are available in four appearance classifications: (1) framing, (2) industrial, (3) architectural or commercial, and (4) premium. Glulam elements fabricated in North America are typically between 7.5 cm (3 in.) to more than 50 cm (20 in.) wide, 10 cm (4 in.) to more than 150 cm (60 in.) deep, and up to 18 m (60 ft.) long.

CROSS-LAMINATED TIMBER (CLT)

CLT is a large-scale solid, straight, and rectangular wood panel that consists of an odd number (usually three, five, seven, or nine) of layered lumber boards stacked in alternating directions, bonded by means of structural adhesive, and pressed. CLT panels can be used as load-bearing elements and applications include floors, walls, and roofs. Panels fabricated in North America are typically up to 3.6 m (12 ft.) wide, up to 18 m (60 ft.) long, and up to 32 cm (12.5 in.) thick.

MASS PLYWOOD PANEL (MPP) AND MASS PLYWOOD LAM (MPL)

MPP and MPL consist of multiple layers of 2.5 cm (1 in.) thick lamellas joined together, with each lamella constructed of multiple layers of thin veneer that are glued and pressed together (Freres Engineered Wood 2023). Lamellas are stacked in alternating directions in an MPP (like CLT) while they are stacked end to end in an MPL (like glulam). MPP is certified as a CLT panel and can be used in identical applications. MPL elements can be used as beams and columns, like glulam elements. MPP fabricated in North America are typically up to 3.6 m (12 ft.) wide, up to 14.6 m (48 ft.) long, and up to 30.5 cm (12 in.) thick. MPL are typically up to 61 cm (24 in.) wide, up to 121 cm (47.5 in.) deep, and up to 14.6 m (48 ft.) long.

MASS TIMBER SUPPLY CHAIN IN NORTH AMERICA

CLT panels combined with glulam beams and columns were used in 2012 as a structural system for the first time in North America (Structurlam 2019). The high-volume manufacturing of mass timber products requires the use of specialized equipment to, for example, apply adhesive between lumber boards and press the lumber boards together. For this reason, even though the US and Canada have a long-established lumber industry, the mass timber supply chain is still young and relatively small but is rapidly growing.

The Pacific Northwest region of the US and the Canadian province of British Columbia are home to forests that provide softwood of good quality (e.g., spruce, pine, fir, and Douglas fir) to manufacture mass timber products. Not surprisingly, this region houses not only the largest number of mass timber suppliers but also the largest number of mass timber projects in North America. Some of these suppliers focus on the manufacturing of Fabricated-to-Order (FTO) mass timber products. FTO products are those "put together from parts that are already designed, but as-of-yet have to be made, so as to meet the specifics of a customer request" (P2SL 2023). In the case of FTO products, a customer provides a list of mass timber products with their exact quantities and sizes, and the supplier (manufacturer) manufactures them to size, without having to redesign or engineer these parts. Other suppliers focus on the fabrication of ETO mass timber products. ETO products are those for which design and engineering are done in response to a specific order from a customer, and the product is then made according to those design specifications (P2SL 2023). In the case of ETO products, a customer provides, e.g., structural- or architectural drawings and the supplier (fabricator) needs to create fabrication shop drawings so that all openings and connections can be included according to those drawings.

Some mass timber products have been manufactured and used for decades in North America. For example, the first glulam structures were erected in the US in the 1930s, although the first American manufacturing standard was published only in 1963 (APA 2023). Significant advances have been achieved during this time, particularly with respect to the adhesives used to join lumber boards during the manufacturing of glulam.

Other products, such as CLT, MPP, and MPL have come onto the market much more recently. The first manufacturer of CLT based in the US was SmartLam in 2012 (SmartLam 2012); this was followed by other manufacturers that opened factories and began producing CLT panels a few years later. Among this group, arguably the most notable one was Katerra, the now infamous vertically integrated off-site construction company founded in 2015 and shut down in 2021 after filing for bankruptcy. Katerra opened a state-of-the-art CLT and glulam factory in 2019 in Spokane Valley, WA, with the largest capacity at the time and still today to produce CLT in North America (Wohlfeil 2021). This factory has since been purchased by another company and is now back in operation (Dalheim 2021).

MPP and MPL are newcomers to the family of mass timber products. They were developed and launched in 2018 and 2020, respectively, by Freres Lumber and are alternatives to CLT and glulam, respectively. Instead of using lumber boards as with CLT and glulam, MPP and MPL are produced by combining thin layers of veneer, which allows more wood to be used out of a log compared to sawn lumber. However, the manufacturing process for MPP and MPL is more energy intensive than that of CLT and glulam (Atkins 2018). At this time, MPP and MPL commercialized in the North American market—not considering the subtractive manufacturing process that turns them into custom (ETO) building components—are offered at a slightly lower price than CLT and glulam.

INDUSTRIALIZED CONSTRUCTION (IC) AND MASS TIMBER

The industrialization of manufacturing—the evolution from creating goods by hand to using machines to produce them faster, cheaper, with better quality, and in larger quantities—took place in the 1760s with the Industrial Revolution. Manufacturing has continued to evolve ever since. Ford introduced the moving assembly line to mass produce automobiles in 1913 and Toyota developed the TPS decades later, focusing on eliminating waste in its production processes and improving customer satisfaction. The construction industry, however, has lagged behind most other sectors in the adoption of technology and mechanization, which has consequently stalled productivity growth (Barbosa et al. 2017).

Various often-mentioned reasons explain why the construction industry has been traditionally slow at developing and using new technologies, and thus has not progressed at the same pace as other industries. Some of these reasons are (1) the uniqueness of every project, (2) the nature of production moving from one location to another, (3) the divided authority (owner, designer, contractor, etc.) over the process of development and construction, and (4) market volatility (Warszawski and Sangrey 1985). In recent years, however, the construction industry has increased its appetite for innovation, technology, and consequently industrialization. This is a result of owners, developers, contractors, and other players striving to become more competitive, deliver complex projects in less time, and overcome challenges such as the current construction labor shortage (Hovnanian et al. 2022).

In this context, IC has emerged as a means to leverage high-volume manufacturing principles and tools (both software and hardware) for optimizing the delivery of construction projects. Building systems and their components are designed using, for example, Design for Manufacturing and Assembly (DfMA) principles and employing digital tools, such as 3D modeling software. The fabrication of building components takes place at a location other than a project site ("off-site"), in a controlled environment (i.e., a manufacturing or factory setting). It can use Lean production principles (e.g., from the TPS) and employ mechanization or automation. The systems and components are then delivered to a jobsite, where they are assembled—i.e., connected to other parts that were either built on-site or also fabricated off-site—to create a built asset (building), which is the final product of the construction process.

Arguably the best-known IC framework at this time is the MMC definition framework, created in 2019 by the UK Government's Ministry of Housing, Communities & Local Government (MHCLG 2019). This framework presents seven MMC categories in total, of which five are off-site. Mass timber as a structural building system is part of category 3 (pre-manufacturing of non-systemized structural components), standing out as one of the most promising MMC today because of its (1) environmental benefits over alternative materials such as concrete and steel, (2) suitability for off-site automated prefabrication, and (3) easy and rapid on-site assembly.

IC and mass timber present a shift from traditional project delivery and are reshaping existing supply chains and creating new ones within the construction industry. Since large elements are fabricated off-site months or weeks before they are installed on a jobsite, intensive design efforts are required upfront. These efforts are to coordinate, integrate, and optimize structural, MEPF, and other building systems to guarantee that all key design decisions are locked in early on, before the fabrication of mass timber components begins. This ensures off-site fabrication and on-site assembly can proceed seamlessly, reducing or eliminating downstream rework.

CASE STUDY: DELIVERING A MASS TIMBER SYSTEM FOR A MULTI-STORY RESIDENTIAL BUILDING

The exploratory case study presented in this section describes the delivery process from design to installation of an ETO mass timber structural system for a multi-story affordable housing project in the US. The data for this study was collected through various unstructured and semi-structured interviews and from project documents such as construction and shop drawings and project schedules. This paper presents the initial findings of this ongoing research.

Project X herein studied is currently being delivered under a design-build contract, in which the owner signs a single contract with a general contractor who is also responsible for the design of the project. The general contractor on this project worked together with a design firm and an engineering firm to develop the architectural and structural design of the project. They also hired multiple specialty contractors to deliver the project, including Company A which was responsible for the entire mass timber scope. Company A is a vertically integrated mass timber contractor based in the US, providing design, engineering, off-site fabrication, and on-site installation services. Company A has an in-house design and engineering team and owns a fabrication facility with Computer Numerical Control (CNC) machines that are used to process FTO mass timber products (manufactured by third-party suppliers) into custom ETO mass timber components such as beams, columns, floor panels, and stairs.

For Project X, Company A's design team started to work with the architect from the beginning of the design phase. Their early involvement was crucial in the decision-making of several design, procurement, fabrication, transportation, and installation aspects of Project X's mass timber system. Designing a mass timber building requires early coordination between designers, builders, fabricators, and suppliers because mass timber components are not only long-lead items but are also fabricated off-site weeks or months before they are installed on-site. A benefit of mass timber construction is the speed at which the structure can be erected, which can shorten the project schedule, but for that to be realized it is critical that little to no rework on the mass timber components is needed after they are delivered to a jobsite.

Project X uses a post and beam structural system consisting of glulam columns and beams creating structural grids and CLT panels spanning horizontally across these grids. Most of the glulam and CLT elements in the building are exposed. Exposed MPP stairs complement the mass timber system. Steel-braced frames are used as the system to resist lateral forces, while the mass timber structure sits on top of a concrete foundation. Company A provided design and on-site installation services for the following ETO components of the mass timber system: (1) CLT floor panels, (2) glulam columns, (3) glulam beams, and (4) MPP stairs. Additionally, Company A procured FTO glulam and MPP, custom-fabricated (2), (3), and (4) at their own fabrication facility, and then delivered these elements to the jobsite, located around 170 miles from the fabrication facility. (1) were both manufactured and custom-fabricated by a third-party supplier, stored by Company A at their facility, and later delivered to the jobsite. Figure 1 depicts the major steps of delivering Project X's mass timber system, with emphasis on the design, engineering, and procurement phase.

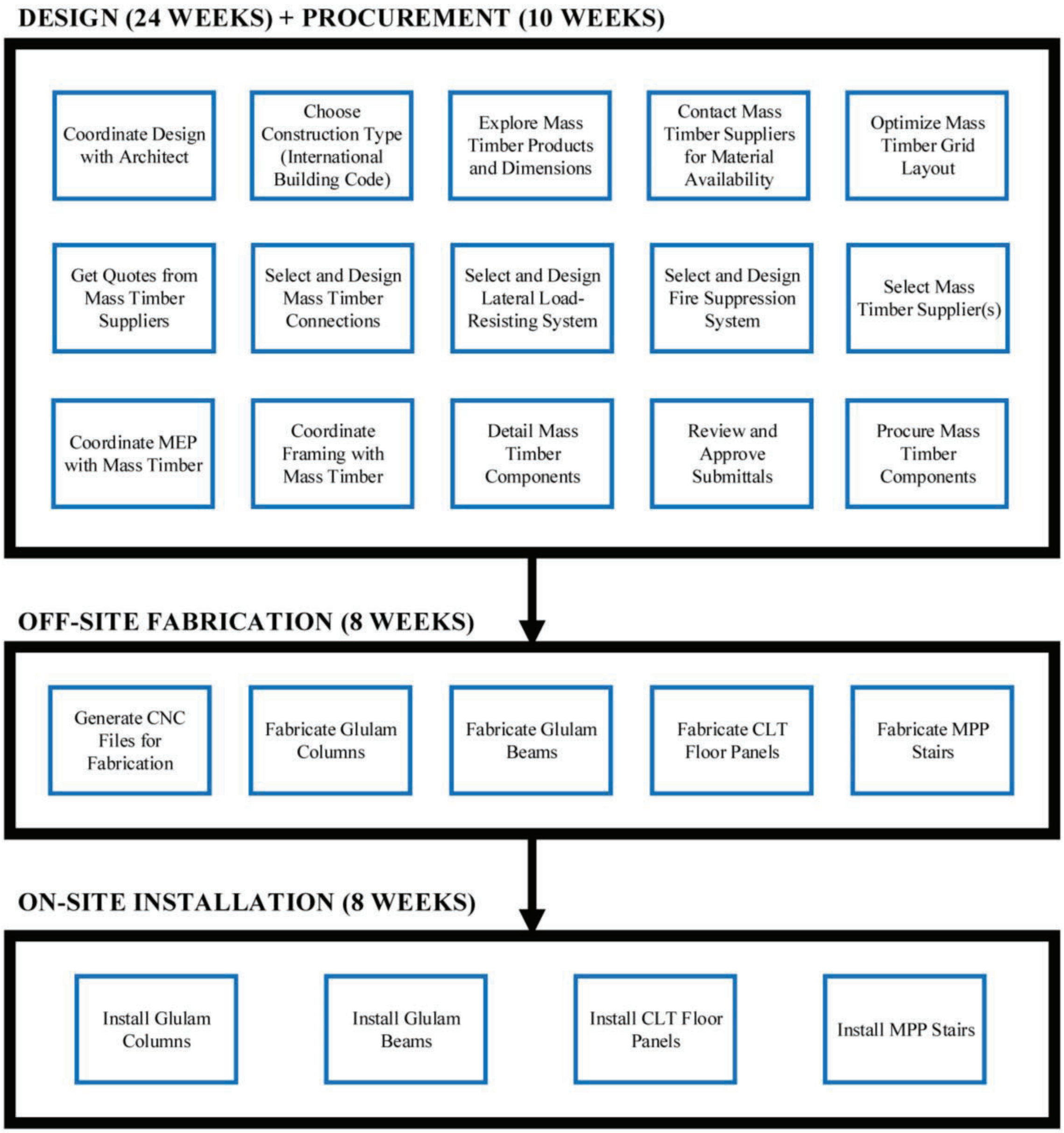

Figure 1: Delivery Process of Project X's Mass Timber System

The design process is iterative and non-linear. Over the years, Company A has developed relationships with several architects who design mass timber structures. For Project X, Company A got involved with both the project owner and the project architect early on. Collaboratively they were able to evaluate and make design trade-offs to develop an optimal mass timber system that achieved the project goals and kept it within budget. Initial considerations included design and constructability constraints, occupancy and construction type, and project goals. After these initial considerations were understood, a conceptual design was developed, defining key project characteristics such as the number of floors, building height, building and floor areas, fire resistance ratings, and allowable exposure of mass timber. Next, Company A began to seek out potential mass timber suppliers located in North America. All suppliers for Project X were located within a 400-mile radius of the project site.

For Project X—as is the case with any multi-story mass timber building—one of the most important design decisions concerned the size of the CLT floor panels, in particular their widths.

Overall, manufacturers offer panels with the same typical thicknesses (3-, 5-, 7-, or 9-ply), but varied widths and lengths. Different manufacturers also produce CLT from different wood species, which affects the appearance of the panels (this aspect is particularly relevant when the panels are left exposed on at least one side in buildings), and have different lead times, which can severely limit the number of companies that can supply CLT panels to a project. Choosing a CLT panel supplier early in the design phase is critical because it determines what panel sizes can be used, which in turn defines the building's structural grid layout. Determining the size of CLT panels is particularly crucial because it involves three trade-offs: (1) the transportation of panels from the factory to the jobsite, (2) the number and type of surface spline joints (that are used to connect CLT panels together), and (3) the number of crane picks on the jobsite (less is better). The maximum legal load width in the US is 2.6 m (8.5 ft.), although some manufacturers can provide panels up to 3.6 m (12 ft.) wide, which could potentially reduce (2) and (3). Although most of the CLT panels used on Project X are 2.6 m (8.5 ft.) wide or narrower, some are wider than 2.6 m. The transport of oversize loads usually requires permits and can be done only during certain hours of the day (depending on local rules), which increases the cost of transportation. Determining the size of glulam columns and beams, although also important, is not so much of a constraint as it is with CLT panels. It mostly revolves around finding the most economical solution, i.e., the minimum depths and widths (lengths are determined based on CLT panel sizes) that satisfy all structural requirements, and working with suppliers that can provide those glulam elements.

One design goal of Project X, an affordable housing project that was to benefit from both a reduced project cost and accelerated installation of the mass timber system on-site, was to eliminate or reduce the number of steel connections (e.g., to connect beams to columns). Company A worked with the design team to develop a wood-to-wood mortise and tenon connection to that end. Another design goal was to have as much exposed mass timber as possible inside the residential units. To achieve that, most of the overhead MEPF systems are routed above the hallway ceilings and then distributed to each unit, so that the units could have, for the most part, fully exposed CLT ceilings.

Although Company A has an in-house engineering team that designed and engineered the entire Project X's mass timber system, Project X still had an outside structural engineer of record responsible for the engineering of the project. This engineer of record was also tasked with designing some of the structural non-mass timber components of Project X, including the concrete foundation. After the mass timber system and other related systems (e.g., lateral-load resisting, MEPF, framing) were designed and integrated, the engineer of record reviewed and signed the structural drawings. These drawings were then used to create fabrication shop drawings, where each mass timber component is individually modeled in Building Information Modeling (BIM) software. Then, files were generated to feed the CNC machines. These files describe paths for CNC machines, instructing them on how to perform the tasks required to fabricate the custom mass timber components.

Finally, after fabrication, the mass timber components were stored at Company A's fabrication facility and later delivered to the Project X jobsite when it was ready for installation. Due to space constraints on the Project X jobsite, the deliveries were JIT with all pieces being erected and put in place the same day they were delivered. Installation of all the pieces took around 8 weeks.

DISCUSSION

As new materials and products are developed and come to the market, new supply chains are formed, or existing ones are reshaped. In the case of mass timber, the supply chains to deliver these products are still emerging and worthy of research due to the growing demand for this product. Consequently, new theory and knowledge ought to be developed so that these supply chains can evolve and mature, and people can think about how to design production systems for the efficient and effective delivery of mass timber buildings.

Delivering such buildings poses new challenges when compared to delivering, for example, concrete or steel buildings. Wood requires more careful handling, storing, and transporting—for example, if a piece of mass timber is not properly stored and its moisture content is higher than ideal, it may not meet the specified tolerance requirements. Upfront design coordination is a must to ensure that all components and systems fabricated off-site not only fit together when they are brought to the jobsite but also fit with what is built on-site. Company A identified an opportunity to integrate multiple phases (design, fabrication, and installation) of the delivery process of mass timber systems and, as a result, provide their clients—owners, architects, and general contractors—with a "one-stop shop." A challenge for Company A comes from having to keep capacity across all their teams (design, fabrication, and installation) balanced (i.e., to keep all teams busy), although this has not yet been a significant issue. Demand for mass timber projects is high and increasing in the US construction market. Not many companies operate in this market space or offer the same level of vertically integrated services as Company A does, but this may change in the future as competitors seek to enter this growing market. Another challenge is that because the number of CLT suppliers in North America is still small and the current demand for the product is high, Company A does not have much bargaining power over its upstream suppliers.

From the exploratory case study presented in this paper, we present several general recommendations for teams designing or delivering mass timber systems: (1) communicate with the project owner to understand the project timeline so that it can be aligned with mass timber lead times, as they can vary from 4-6 weeks (if sourced nationally) to 3-6 months (if sourced internationally), (2) integrate design, fabrication, and installation by having the design team coordinating with the fabrication and installation teams so that all fabrication and installation constraints can be understood early enough to reduce design iterations and facilitate fabrication and installation, (3) before locking in the grid layout and consequently the panel layout of a building, find out what products and sizes mass timber manufacturers offer and then design accordingly to optimize the use of CLT panels since it accounts for most of the volume (70 to 85%) of mass timber in a multi-story building, (4) standardize by reducing the number of unique mass timber connections to speed up and reduce complexity in design (less detailing), fabrication, and installation, (5) evaluate ways to reduce the number of MEPF penetrations through floors and beams by, for example, strategically using corridors (with soffits) and shafts to distribute MEPF systems, and (6) verify and reconcile the tolerance of mass timber components with other off-site and on-site building components during design of the mass timber system.

CONCLUSION

The aim of this paper was twofold: (1) to describe the characteristics of the mass timber supply chain and (2) to describe the process of designing and delivering a mass timber structural system for a multi-story building. To achieve (1), we presented mass timber construction as an MMC, a number of mass timber products and their respective applications, and how the mass timber supply chain has developed in North America. To achieve (2), we presented an exploratory case study, described the major steps in designing and delivering a mass timber structural system for a multi-story residential building, and presented a list of recommendations for designing and delivering mass timber systems.

Some future research ideas stem from the limitations of this exploratory case study. This paper provides only a general view of the delivery process of a mass timber system. Additional research is needed to develop more detailed process maps (e.g., value stream maps), focusing, for example, on other phases (e.g., fabrication) of the mass timber delivery process to identify additional opportunities for improvement. Furthermore, research is needed to study other types of mass timber projects (e.g., commercial- or educational projects) and compare their characteristics with the (residential) case study presented in this paper. In addition, future research could also investigate opportunities to use other IC building systems that in conjunction with mass timber can accelerate the delivery of construction projects.

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