

Design for a Reconfigurable Mass Timber Building System

Chuou Zhang

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Committee:

Tomás Méndez Echenagucia

Kimo Griggs

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Chuou Zhang

University of Washington

Abstract

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Chuou Zhang

Chair of the Supervisory Committee:

Tomás Méndez Echenagucia

Department of Architecture

Mass timber products like glulam and cross-laminated timber (CLT) can store / sequester carbon in building stocks for as long as the building components remain in use. For this carbon reduction to have a significant impact, mass timber products must not release the carbon emission back to the atmosphere in their end-of-life. The end-of-life options for wood products are often reduced to landfills, energy production, reprocess, and recycling facilities. Most buildings with mass timber components are not designed for their reuse or reconfiguration. This thesis is investigating mass timber building systems' design for reconfiguration, exploring joinery types, structural elements compositions, timber section areas, and steel connections. A qualitative research method is used to refine the joinery design in different aspects of buildings. This study proposed innovative joinery solutions that increase mass timber reliability and design specification for mass timber building systems. For the purposes of the prototype described in the thesis, a full-scale model was built to examine the constructability of the reconfigurable joinery.

Acknowledgments

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Keywords: Mass timber, End-of-life, Reconfiguration, Reusability, Design for
Deconstruction, Joinery Design

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Abbreviation

Life cycle assessment (LCA)

Environmental Product Declaration (EPD)

Computer numerical control (CNC)

United Nation Framework Convention on Climate Change(UNFCCC)

End-of-life (EOL)

Greenhouse gas (GHG)

1. Introduction

1.1 Wood Material in the AEC Industry

Building-material innovation appears as civilization advances; it is not driven by technology and knowledge, but by the requirements of society and civilization. Wood belongs to one of the oldest building materials among earth, rocks, and metal. Historically, timber was used to supplement the use of stone in 5,000BC. It has been used mainly in traditional folk architecture as structural and expressive materials. During the industrial revolution, innovative and better performance materials were discovered. A major decline in the use of wood as structural usage happened when concrete, steel, aluminum, plastic, and glass were introduced to the building construction industry in the second half of the 20th century.

Mass timber opened the market for high-rise timber buildings and the majority of timber construction remains residential (Cristescu et al, 2020). Mass timber like CLT and Glulam is gaining popularity in construction within North America (Udele et al, 2021). Manufacturing technology changes traditional use of wood by changing its physical properties and interlocking mechanisms. Modern technologically advanced wood processing using computer numerical control (CNC) changed material limitations and enabled complex geometry. Engineered wood products are manufactured to maximize the natural strength and stiffness characteristics of wood and designed to meet application-specific performance requirements (APA-the Engineered Wood Association, 2021). The ability to achieve structural strength for mid-rise and high-rise buildings.

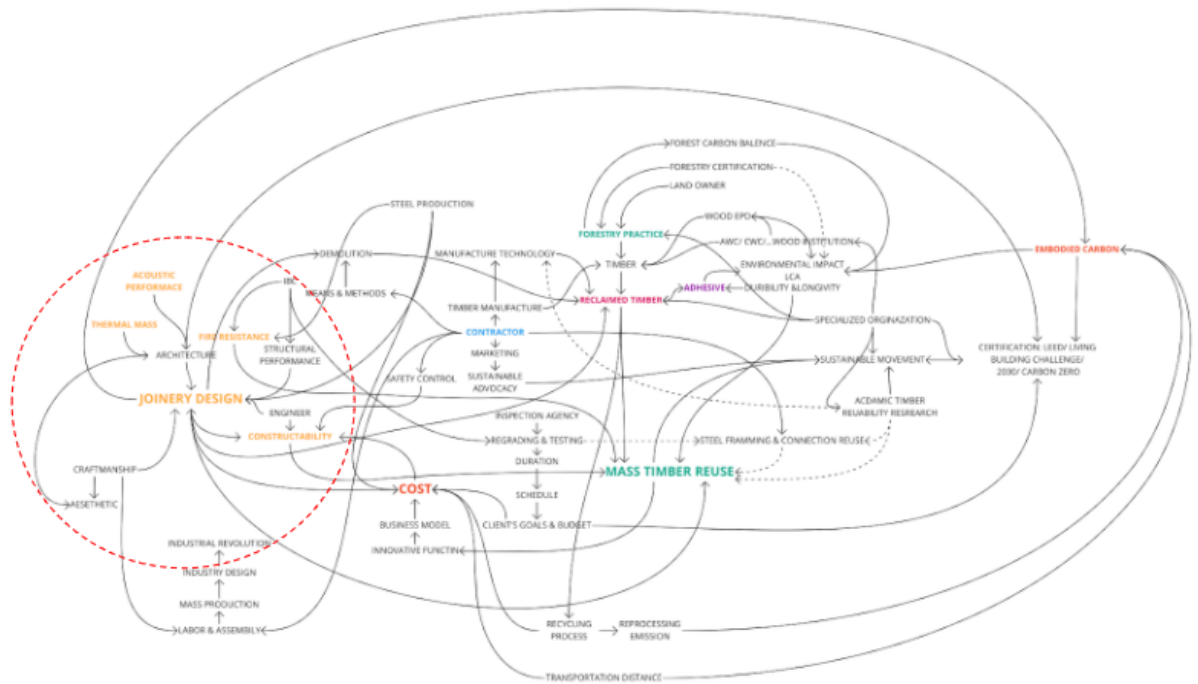
Mass timber received code acceptance in Europe in the early 2000s and was used in the low-to-mid-rise structure. A growing body of CLT research led to the North American market (Udele, et al, 2021). From 2018 to 2021, the International Code

Council approved 14 mass timber code changes, resulting in three new mass timber construction types with height limits varying from 9 to 18 stories. The height limits for mass timber and the extent of exposed timber will depend on the level of fire protection (ICC, 2021).

As the climate-smart solutions call for renewable resources, sustainable and low-carbon design has become a new criteria. Wood stands out among all other construction materials; apart from its physical resilience, its low carbon footprint plays an essential role.

In complexity theory, DeLanda suggested that there is no linear cause and effect, determining an outcome in the complex meshwork as a result of much different decision-making for the solutions (DeLanda, 2019). Mass timber reconfiguration design is situated in a dynamic relationship (Figure 1). This roadmap depicts the complex variances and subjects related to the thesis goals. Freier suggested in life-world and social science that new things don't fit into a category before a coherence package is formed (Freiere, P.,1972). In the subsection of complexity theory, DeLanda presents an assembly theory- sorting and cementing is a way to generate new things from existing networks. Though there are always contingencies with how things are connected. We can find patterns from how things come about and how things are accidentally connected. "Sorting and cementing" is a way of disassembling and reassembling variances which are used as a qualitative method in this thesis.

Figure 1. Roadmap of Design for Reconfigurable Mass Timber Building System in the AEC Industry Vision, demonstrating topics related to mass timber reconfiguration design.



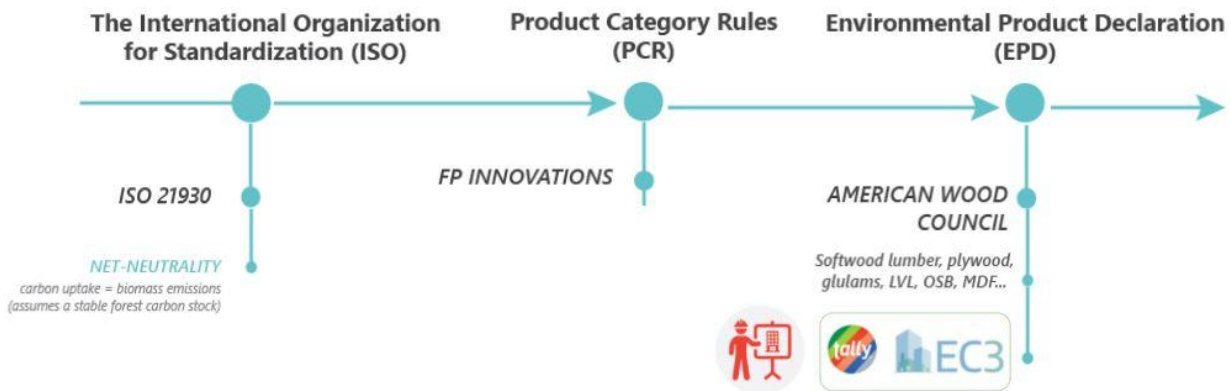
1.2 Wood is Carbon-Neutral

The International Organization for Standardization (ISO) 21930 requires a demonstration of forest sustainability to characterize carbon removals with a factor of -1 kg CO₂e/kg CO₂. Reports from United Nations Framework Convention on Climate Change (UNFCCC) provide annual net GHG Flux Estimates for different land use categories in Table 6-1 and indicate national increasing and/or neutral forest carbon stocks in recent years in the US and Canada. Thus, North American forests meet the conditions for the characterization of carbon neutral.

The ISO 21930 standard governs the product category rules (PCR), which is the framework for Environmental Product Declaration (EPD) used by the industry. Following

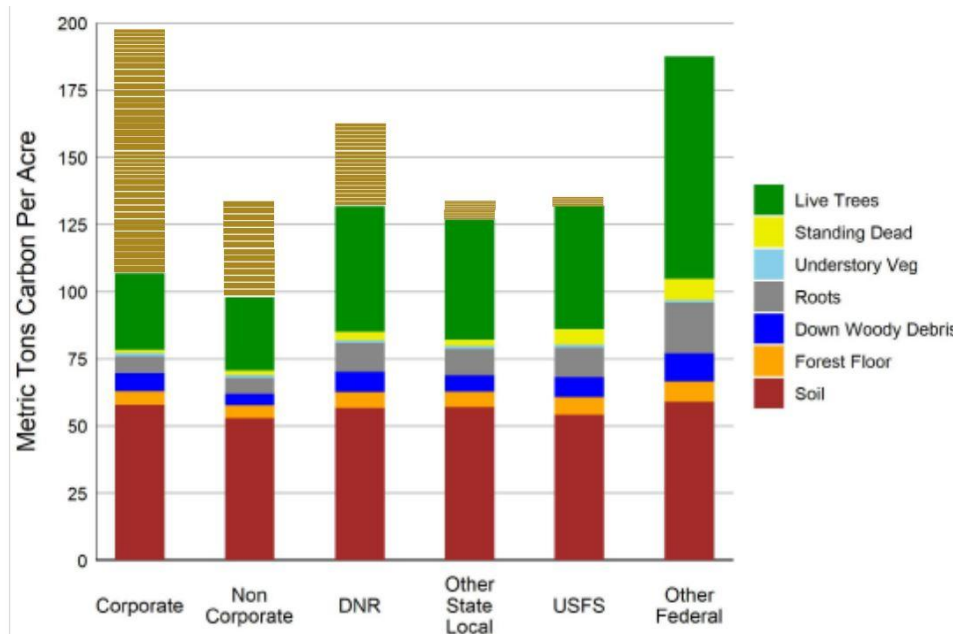
the carbon neutrality characteristic, the initial carbon sequestration in the wood product at the manufacturing gate is equal to the emission as the lumber product reaches the end of its service life in various disposal pathways.

Figure 2. The Trace of Carbon Net-Neutrality, Carbon Friendly Forestry, (2019).



The carbon-neutral assumption is based on stable carbon stock in the North American forest. Although not all forest performance is the same, among corporate forests, non-corporate forests, Department of Natural Resources (DNR), state forests, and USFS working forests (Figure 3), forest management should be taken into account when accounting for carbon sequestration at the landscape level. The way to evaluate forest performance is to look over forest carbon stock change over different forestry practices from various landowners. According to the United Nations Framework Convention on Climate Change (UNFCCC), the US forest is identified with stable or increasing forest carbon stocks (American wood council & Canadian wood council, 2020).

Figure 3. Carbon pool for the 2016 forest inventory, Ganguly (2020), including the wood products pool which is categorized by landowner types.



Wood can be more than net neutral if the forest is sustainably managed.

UpStream Carbon & the LCA Tool (*Dunn & Zhang, 2021*), developed around forest carbon, quantifies the carbon sequestration and builds upon the net neutrality assumptions. Various metrics impact wood LCA analysis: forest management and EOL LCA calculation across different scope/boundaries. To quantify carbon emission for wood reuse and design for deconstruction, having the capability to customize wood EOL drastically affects the quantity of carbon storage, compared to the current industry average standards LCA.

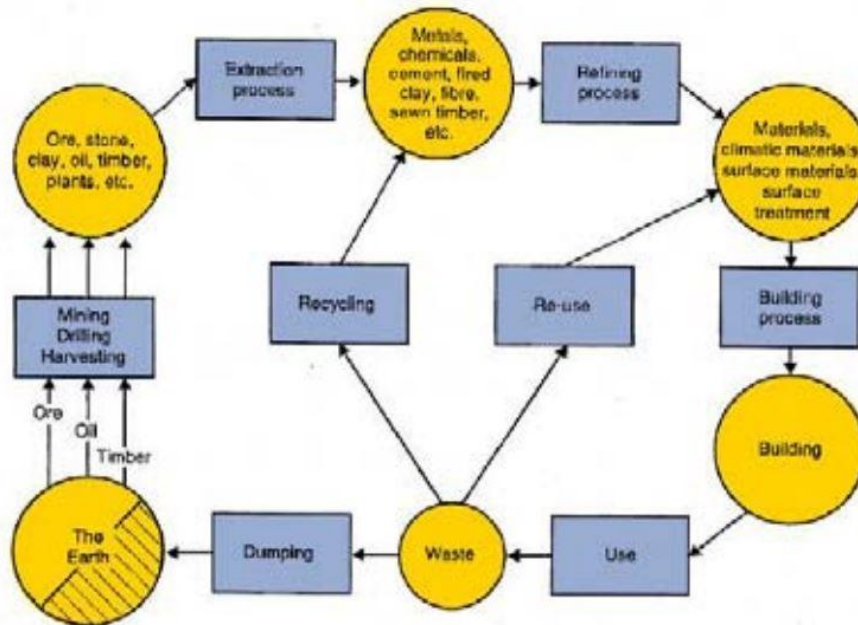
1.3 EOL Scenarios

Design for deconstruction (DfD) is a way to decrease embodied carbon, reuse building materials, or prepare a building for deconstruction (*Kanters, J., 2018*). *Akinade et al (2017)* identified five underlying factors for DfD that includes 'stringent legislation

and policy', 'deconstruction design process and competencies', 'design for material recovery', 'design for material reuse', and 'design for building flexibility.

Design for reconfiguration provides design implementations in various building conditions with design guidelines. The reconfigurable design aims to manage material end-of-life responsibly to minimize raw material consumption. Architects and engineers play an important role in contributing design solutions to reduce materials damage and during building deconstruction and transform elements to other buildings.

Figure 4. Conventional Resource Flow Chart, Berge, B. (2009), indicating general material recycling flows from raw material extraction to manufacturing, building usage, and waste stream.



In the current construction industry, the linear view of material flows is deeply rooted in the consumerism culture. In *the Ecology of Building Materials*, Bjorn Berge illustrates this in a simple diagram: resources are extracted from the earth, refined and

manufactured into usable materials, assembled into buildings, and eventually returned to the earth via landfills when the buildings are remodeled or demolished. Dealing with the downstream, the “waste” is very close to our daily experience. We often categorize our waste into landfills, recycling, and compost. The real benefit of recycling and reuse is about closing the loop of resource use, reducing landfills. Design for reconfiguration is the fundamental method for reuse which creates a closed loop of material recycling.

Currently, there are various EOL measurement standardizations, including the American Wood Council Environmental Product Declaration in 2013 and 2020 Verizon (American Wood Council 2013 & 2020), Athena (Gloria et al, 2020), and Embodied Carbon in Construction Calculator (EC3, 2021) to quantify the carbon impact of wood EOL. Explicit design on wood material reconfiguration in the building sector has not yet been done. Facing climate challenges and carbon reduction goals 2030 Challenge (Architecture 2030, 2021), the demand for reclaimed wood products will rise due to the growing population and limited forest resources.

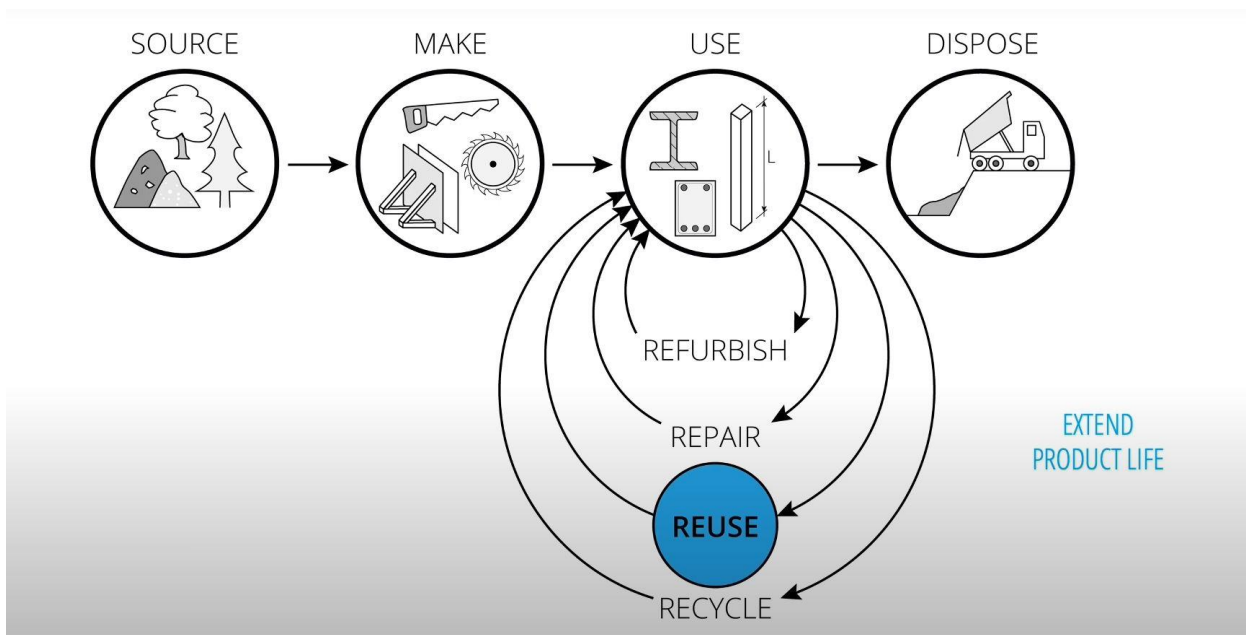
This research aims to reduce the cost to the environment of the construction industry by investing proper amounts of upfront carbon as well as using reusability as a cost reduction strategy for life-cycle costs. The environmental impact of the reclaimed components is prioritized. Measuring the cost of reprocessing is not in the scope of this thesis.

1.4 Material Reusability / Reconfiguration

In Galbreth's studies, reusability is considered an inferior feature of a product. Though, reusability/reconfigurability can be considered an innovative function in the products to appeal to the tastes of customers. A study investigated incorporating reusability into a product in two approaches: remanufacturing to original specifications and upgrading used items by replacing previous innovative components (Galbreth, 2021). Three product options are offered to the customers: a new product that includes

incremental innovations; upgraded products that are products with incremental innovation added from previous products; remanufactured products that are previously produced and have the same function as the original product without innovative features. Customers are the ones that make rational decisions and purchases that maximize their benefits. Galbreth's model uses reusability as the innovative function. The result shows the upgraded products that have the same functionality as the new, but reusable components are perceived to be of inferior quality which is also a common assumption in remanufacturing.

Figure 5. Component Reuse in Structural Design Contributes to the Circular Economy, Attisholz Areal, [Switzerland, fib. \(2021\)](#). Circular economy as a strategy for the reuse of building deconstruction material.



However, the transition from a linear to a circular economy is still at an early age (Bertino et al, 2021). Bertino et al suggested that business strategies need to adapt to sustainable improvement that can lead to a net reduction in the use of raw materials and

minimizing the waste to landfills. The study recognized “deconstruction” of building components as an important role for dismantlement selection in building circularity and evaluated deconstruction/reuse potential for constructive systems. A series of principles that need to be considered in the design phase are as follows (Figure 6): reduction of the building complexity, smart choice of material and building components, and access to deconstruction information.

Figure 6. Deconstruction Principles, Bertino et al (2018)

Categories	Principles
Reduction of building complexity	Minimize the number of components
	Minimize the number of component types
	Use of modular components
	Use of lightweight components
	Use of prefabricated elements
	Simplification of the connections
Smart choice of materials	Realization of accessible technical installations
	Use of reusable materials
	Use of eco-compatible materials
	Minimize the number of materials
	Minimize hazardous materials
Access to the deconstruction information	Minimize composite materials
	Technical drawings and pictures
	Database for the identification of components
	Instructions about reuse and recycling

Some issues exist in current mass timber practices that limit the material reusability and lower recovery rate, including composite slabs (Figure 7), unplanned screw holes (Figure 8), and joinery designs that are too specific (Figure 9). CLT floor panels are bound with concrete topping with metal mesh and rebar which make it difficult

to reassemble without damaging CLT panels. Documents of material construction and structural strength are critical for assembly and disassembly. Unplanned pilot holes or drills on-site leave unpredicted openings on timber that make it difficult to evaluate material strength after deconstruction. Standardized joinery designs are easy to be reapplied to other building designs. Unique architectural components can be attractive design features but limit reusability.

Figure 7. CLT-Concrete composite slab, Setragian & Kusuma, 2018.

Shear fins embedded in the CLT panels add difficulty to deconstruction.

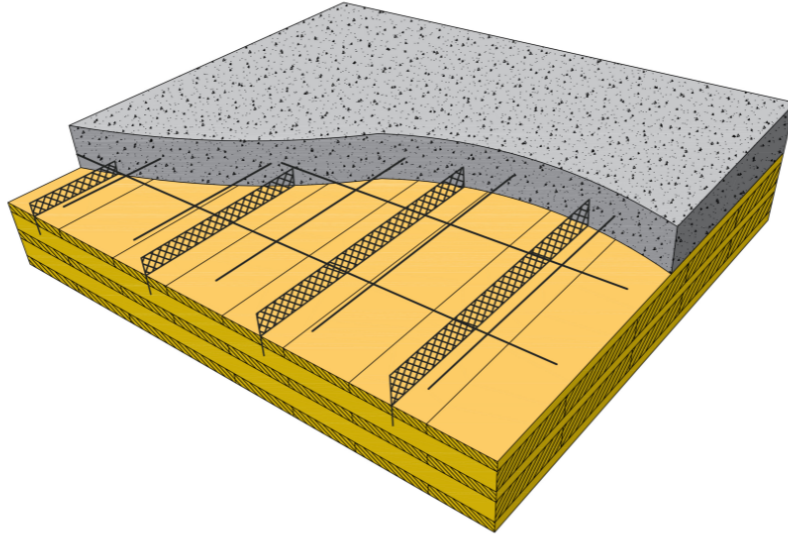


Figure 8. Unplanned screw holes, AppalachianWoods, 2021. Cuts and openings make timber lose structural integrity for reuse.



Figure 9. Tamedia Building timber only joinery prototype, Shigeru Ban Architects, image from World Architects, 2013. Unique geometry makes reconfiguration difficult.



1.5 Research Scope and Design Principles

1.5.1 Building Types

Considering CLT and Glulam are popular construction materials for low- and medium-rise construction (Lineham, et al., 2016), the focus of the thesis is based on their use as structural components. Regarding the current regulations and land zoning ordinances are unfavorable for new residential developments, Seattle City Council adopts new zoning that adds residential development capacity with Mandatory Housing Affordability (MHA) policy for new commercial and multi-family residential development, based on zoning building height range from low-rise to 95 feet (Seattle, 2019). Washington State Planning and Zoning in Code Cities incentivizes increased density

bonus for affordable housing (RCW 35A.63.300). Thus, the residential building type is suitable for this thesis scope.

1.5.2 Design Principles

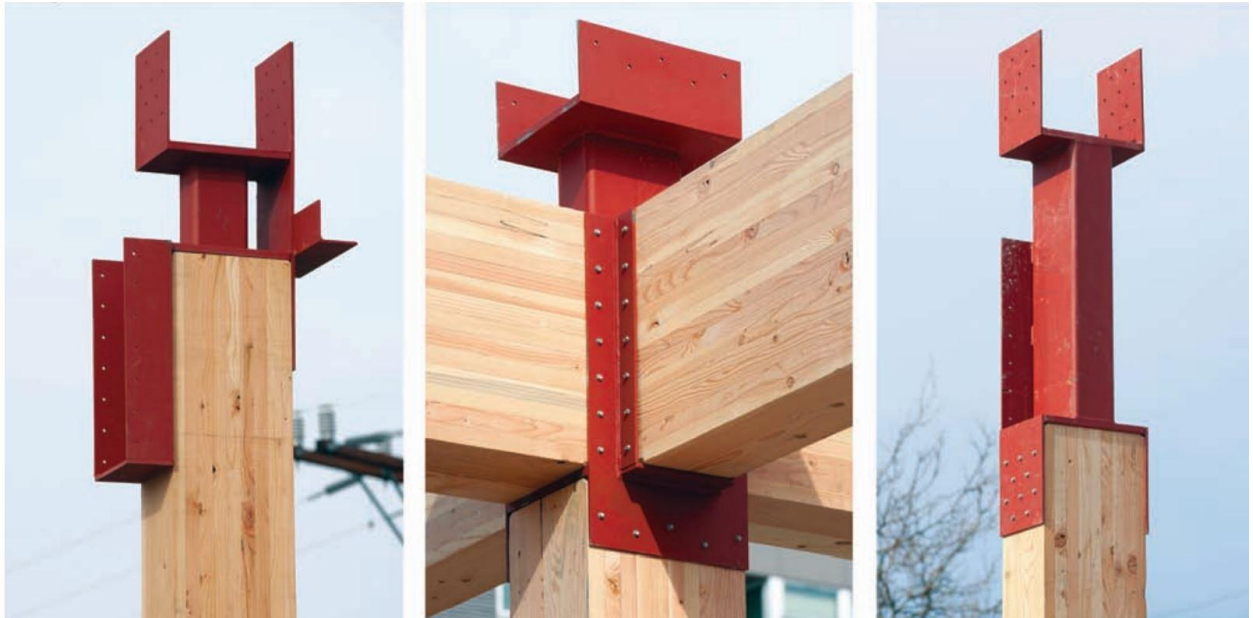
This thesis aims to conduct research on reconfiguration solutions for mass timber building systems. The design principle incorporates techniques that are efficient for modern building construction: design standardized joinery connections that can be reusable for general building construction, minimize direct bearing on timber grain, maximize the strength and efficiency of each connection, consider acoustic criteria and fire protection of the CLT floor panels connection, and explore optimal uses of materials.

Modular construction includes the assembly and logistics aspect, which is done in proper coordination through planning, integration, and communication. Sachdev has proved that modular construction often exceeds local building specifications which ensures high safety quality and meets occupancy code requirements (Sachdev, 2018).

Wood is an anisotropic material, meaning it has different strength properties in different directions: longitudinal, tangential, and radial. Woodgrain acts like a bundle of drinking straws that is strong longitudinally (Showalter, 2016).

The optimal use of wood grain is beneficial for fire protection. In the Bullitt Center design, additional fire protection gained by the bucket connector (Figure 10) was installed so that the main girder bears directly on the timber column that supports them from below. In the event of a fire, beams remain in place even when steel buckets are weakened by heat. Each beam passing through the steel bucket connection retains three inches of material bearing directly on the column below (WW, 2013).

Figure 10. Bullitt Center steel buckets design, WoodWorks (2013)



Ultimately, assuming that proper connection for mass timber structural systems and preserving the length of columns and beams contributes to less waste in landfills, longer carbon-storing, and a more avoided burden.

Figure 11. Glulam Connection Billie Jean King Main Library. Left image taken from (Chan, B. 2020). Right image taken from (SOM 2020).

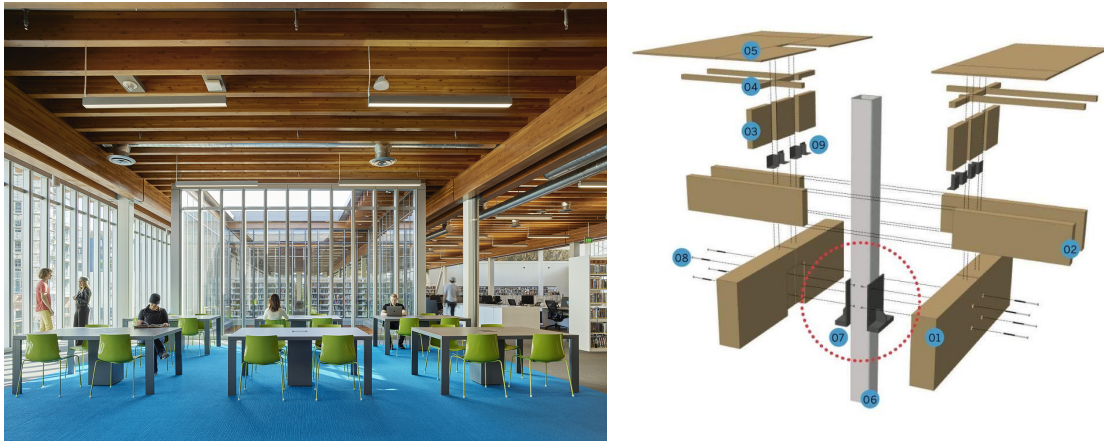
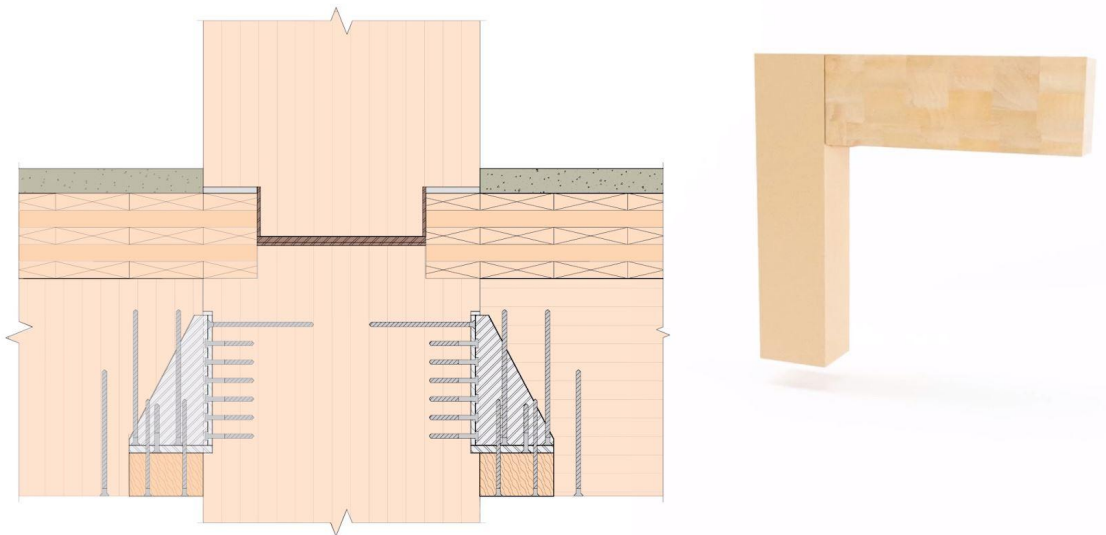


Figure 12. Hidden Steel Joinery Design, Ascent Building, (Thornton Tomasetti, 2021)



Chapter 2 will discuss the qualitative analysis and the reuse methods used in this thesis; Chapter 3 focuses on design details and reconfiguration of reused components in different building conditions; conclusions will be discussed in Chapter 4; future research and researchers that would promote reconfiguration application are discussed in Chapter 5.

2. Methodology

2.1 Qualitative Studies

The design of mass timber joinery involves more complex relationships that are beyond the building construction industry, like forestry practices, steel manufacturing, environmental impacts, cost evaluations, and adhesive use. So qualitative research is critical to identify how the thesis scope fits into the larger picture, and also zoom into the specific vision.

2.1.1 Structure Durability

Wood from the biological origin is at risk of decay upon the intrusion of moisture, leading to losses in physical and mechanical properties, and ultimately biological decay (Udele, et al., 2021). Thus, protecting wood from moisture content is important for preserving wood durability and performance, both in the current service life and extended service life. Chemical wood modification has been used to modify and improve its decay resistance. Although chemically modified timber (CMT) is more resistant to deterioration, wood decay fungi may grow through CMT without losing their capability to degrade unmodified wood (Emmerich, et al., 2021). Additional structural dimensions often are added during the design process given the collaboration between the architects and structural engineers. It is important for architects to understand the structural design process. Innovative developments are able to improve the structural performance for mass timber construction, including Interlocking Glued Solid Timber (IGST) presented by Patlakas et al.(2019).

2.1.2 Fire Resistance

When considering the use of mass timber as a primary structural material, it is critical to consider the combustibility of timber. Lineham et al. (2016) studied the fire behavior of exposed CLT. A charring rate is a key parameter for the calculation of fire resistance of timber structures and fire investigation (Martinka et al, 2018). Surface charring is caused by timber loss of acceptable sacrificial depth of the timber surface, which forms self-protection to insulate the underlying (cool) timber (Lineham, et al., 2016). Lineham et al. studied the advanced and rational guidance for fire resistance standards, like Eurocode 5, which is to determine the standard fire resistance based on the notional charring rate of timber element (EN, 2014). Bartlett et al. have previously presented different charring rates for timber under a range of different heat fluxes (Bartlett et al, 2015). The average charring rate of spruce and pine wood was calculated by Martinka et al. Mass timber had high fire resistance performance. A 5-ply CLT panel wall was tested to last 3 hours and 6 minutes which is far more than the two-hour rating from the building codes requirement (ThinkWood, 2020). Thus, charring layers and decisions around timber exposure need to be carefully considered according to the fire code and fire resistance specification.

2.1.3 Constructibility & Assembly

Ahmed, S. & Arocho, I. (2020) identified the existing major construction-related difficulties of mass timber buildings. The study showed that lack of experience in timber construction, poor coordination among the project parties, design-related difficulties and high cost of mass timber panels are the biggest barriers among the U.S. construction practitioners.

Like modular construction, mass timber components are prefabricated off-site (Shahtaheri et al., 2017). Since dimensional and geometric variability is more problematic than traditional construction methods, it requires designers to pay more

attention to construction precision tolerance. Design for reconfiguration needs to consider a comprehensive tolerance strategy that allows for flexibility during construction assembly and disassembly.

Cristescu et al.(2020) summarized novel design concepts for deconstruction and reuse that could be used in a modern timber building. The reuse potential depends on the scale of reclaimed components- large components are considered beneficial in terms of time, GHG emissions, and waste production. The report suggests that modular components, reversible connections, adaptability of the floor-plan and circular procurement are key factors. Demolition practices need to be considered in the design process to avoid damage to the components. Smith et al.(2017) investigate the added value of mass timber construction compared with traditional site built construction. It is proven that mass timber improves cost and schedule.

2.1.4 Fabrication and Schedule

As building systems become more sophisticated, it requires more advanced design collaboration and fabrication techniques. Documentation of the construction process and each component are key to design for disassembly. The extensive use of virtual design and construction (VDC) and building information modeling (BIM) are effective ways to facilitate a project delivery process (Fallahi et al., 2016) among owners, designers, manufacturers, and disassembly workers. Fallahi et al. identified the use of BIM and VDC in the UBC Tall Wood Building project as key factors for prefabrication and assembly of mass timber elements, envelope panels, mechanical elements, and design for prefabrication and assembly is a highly collaborative process that requires the presence of key decision-makers. Ahmed & Arocho (2021) showed that mass timber construction contributes 6.43% higher construction cost compared to concrete options which come from the high cost of engineered wood, timber installation and project staffing. On the other hand, The prefabricated mass timber structures can be erected in

a relatively shorter construction time than the conventional method. The schedule saving can be significant which occurs in indirect costs like administrative time, labor, equipment usage, etc (Procore), and direct costs from earlier occupancy (WoodWorks, 2019). The study identified potential schedule savings from less soil remediation and smaller foundations on site, faster erection with prefabricated mass timber elements and precise installation, faster enclosure time, faster MEP installation, and less finishes with exposed wood structure.

So the design for reconfiguration means thinking about building material beyond one building life span which requires more environmentally responsible considerations and future visions of the project from the decision-makers. It can achieve construction precision with the collaboration of multiple parties using VDC and BIM techniques, and possibly cost savings.

2.1.5 Aesthetics

Engineered wood products are considered an entirely new way of building for the 21st century, not only due to the cost and construction timeline saving, also the aesthetic characteristics given by the exposed structural wood (Jones, 2018). Exposed wood finishing offers warm design features, natural beauty (ThinkWood, 2021), and connection to human nature. Different mass timber joinery designs express different architectural expressions and languages. Design considerations around whether exposed or hidden joints present different results.

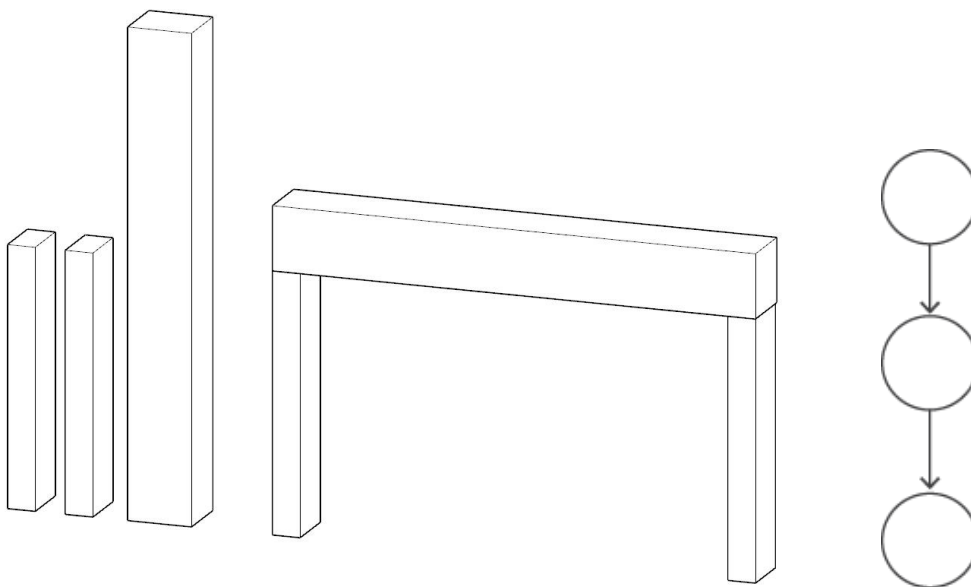
2.2 Reuse Methods

The thesis studied three ways of reuse methods: “one-to-one reuse”, “length reduction”, and “length preservation”.

2.2.1 One to One Reuse

The “one-to-one reuse” method (Figure 13) indicates the same components will be reused and using the same structural geometry. It is equivalent to moving the same structure to a different site. Similarly, a scaffolding system reuses the same parts and the same connections repeatedly. The assembly sequence remains the same as its original design. For example, old horse stables and barn have been recycled with the same building configuration in terms of materials and building systems (López, F. S., et al., 2013). The drawbacks of this system is that the reconfiguration flexibility is limited to a single design choice. This system is less capable to accept modifications and changes. To make sure the system is deconstructable, the elements are joined in the same way across their service life (from one building life span to the next).

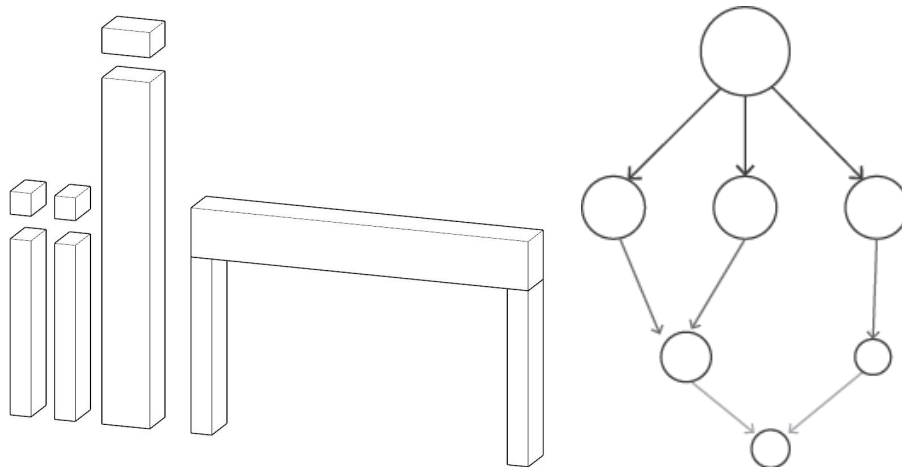
Figure 13. One-to-one reuse method. The left figure displays the same pieces will be reused from one building life span to the next. The graph on the right shows that the reconfigurability is highly limited due to the system’s simpleness.



2.2.2 Flexible Reuse Component with Length Reduction (LR) Method

The “length reduction” method (Figure 14) follows rules that remove defects and holes on the ends before reclamation. In the reclaiming process, the ends of columns and beams with screw holes and openings would be chopped off. So the total length would be reduced each time the materials are reclaimed. Compared to the one-to-one method, more reconfiguration potentials are shown in this method as the length is reduced according to design iterations. The advantage of the LR method is that it provides easy application, and the reclamation process can be applied to a wide variety of materials. The disadvantages are that the reconfigurability is limited as the material becomes shorter and shorter. Eventually the material becomes unusably short and must exit the reuse cycle.

Figure 14. Length reduction (LR) reuse method. The figure on the left displays the ends of materials being removed for reconfiguration for its service life in the next building. The right graph displays a initial increase in potential reconfiguration choice, followed by a reduction when members become too short.

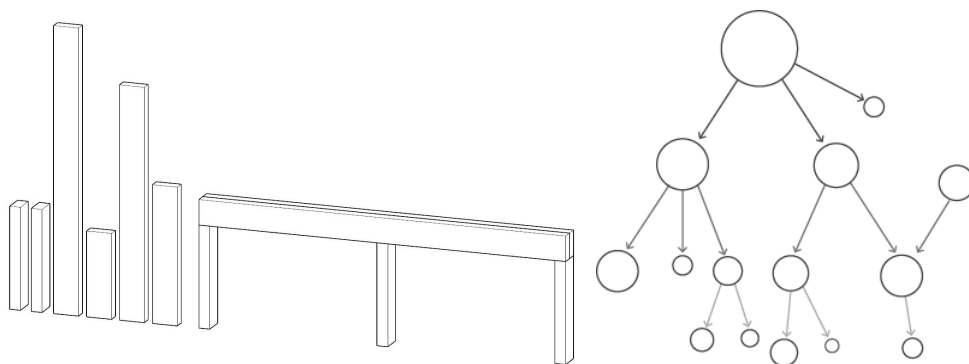


2.2.3 Flexible Reuse with Length Preservation (LP) Method

The “length preservation” method (Figure 15) is inspired by the previous design principles and the two reuse methods. To preserve the material length and provide reuse flexibility, the beam will start with a longer span and two half-widths, and the joinery design will preserve the column height and not create openings on the column. This is shown in the left side of figure 14. For instance, if a beam has a span of S and height of H in one-to-one and/or LR systems above, the LP system would have a span of $2S$ and height of H . The LP system would split the $2S$ beam section in half with a vertical cut to form two beams with span S , like what’s shown in the lower right diagram in figure 15.

One benefit of using the LP system is that it provides greater design flexibility and reconfiguration for different lengths and section iterations in later reuse in different buildings (as shown in the right diagram in figure 15). Another benefit is that the column height is preserved without cutting off the ends. Overall, the LP system keeps the best of each component without losing materials.

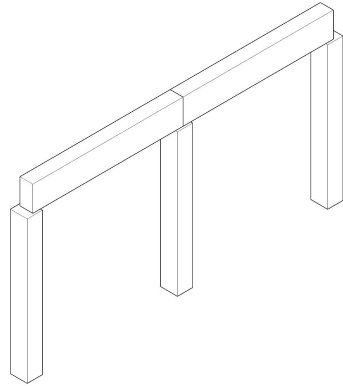
Figure 15. Length preservation (LP) Reuse Method. The left figure shows that the LP system starts with a longer span and provides various beam lengths for reconfiguration with the same column height across the board. The right graphy shows that the number of potential configuration options increases.



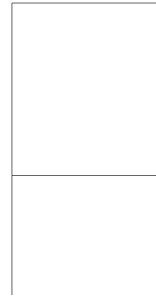
Comparing the timber portion of the three reuse methods (Figure 16), the LP method utilizes two half-width beams instead of one large beam and spans two bays within the same building grid as the one-to-one and LR methods.

Figure 17 demonstrates the material reuse life cycle process. The one-to-one reuse components are limited to the same design and do not provide configuration flexibility. The LR system has more reconfiguration potential but limits the design possibilities, options will be reduced. The main innovation in the LP system is to preserve the best of each component without losing materials, in the means of an investment of upfront carbon cost (timber and steel joinery) to increase carbon storage and avoid burden (Gaudreault, C.,2020).

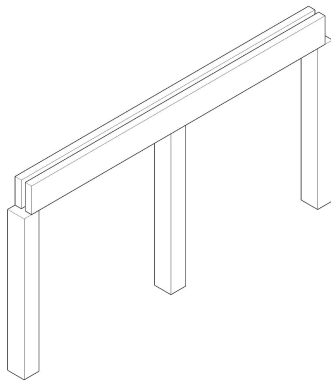
Figure 16. one-to-one, LR, and LP reuse method comparisons. (a) the beam span and column configuration for the one-to-one and LR systems. (b) the beam section for the one-to-one and LR systems. (c) the longer beam span and same column height configuration for the LP system. (d) the double beam section for the LP system.



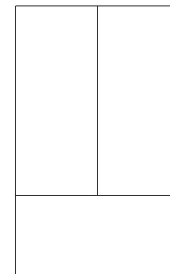
(a)



(b)

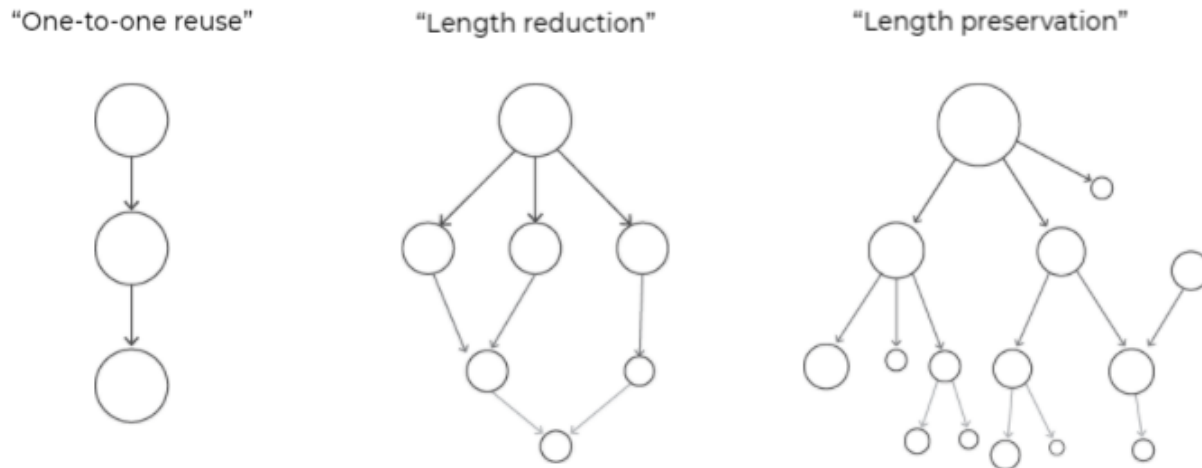


(c)



(d)

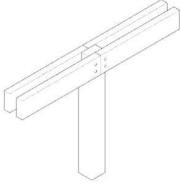
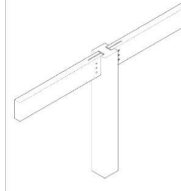
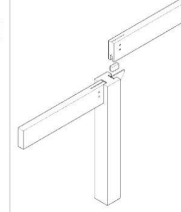
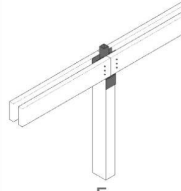
Figure 17. Three reuse methods evolvement process comparisons



2.2.4 Joinery Types

The thesis evaluated various timber connections from current practices and summarizes the differences in table 1. In category A, for the all-wood scenario, the beam connection uses wood dowel, but it is limited to a one-way span. In category B, for the scenario that has wood with a plywood insert, the dowel connects to beam instead of column, like in category A. Categories C and D are both composed of wood beams and steel knife plates, and have a two-way span capacity. The difference between categories C and D is that the steel is exposed in C and designed to be hidden in D. Category E is a more comprehensive steel connector that neither cuts into the wood columns nor slides into wood beams. Out of all options, design E fulfills most criteria mentioned in the previous design principles. This will be further developed in the next chapter.

Table 1. Timber joinery categories from current practices.

	 A.	 B.	 C.	 D.	 E.
Wood	✓	✓			
Steel			✓	✓	✓
Knife plate		✓	✓	✓	✓
Post cap/stirrup					✓
Concealed steel				✓	
One-way beam	✓	✓	✓	✓	✓
Two-way beam			✓	✓	
Corner condition			✓	✓	✓

3. Design

3.1 Flexible Reuse with Length Preservation (LP) Method

The LP method allows beams to start with a longer span and two smaller sections which largely increases design flexibility for the next building's life. This chapter further develops the LP method to be applied in various building conditions such as primary beam system, secondary beam system, corner conditions, envelope connections, and connections to concrete podiums.

3.1.1 Design and Details

For the primary beam (Figure 18), the steel joint connects the double beams to the glulam columns. The bottom steel cap and bottom stirrup hold on to the glulam columns using through bolts. The beam section is doubled with a longer span which does not stop at every column (as explained in the LP system). Through bolts also hold the double beams together. The double beam provides greater reconfiguration potential and preserves column height which reduces material loss during reclamation. Vertical load is transferred from steel joints to the column. Direct bearing on cross-grain is prevented. CLT floor slabs are resting on primary beams as part of the diaphragm to resist shear. Although CLT has directionality, in some seismic zones, we still need the secondary beams for the lateral system.

In the primary beam schematic design (Figure 19 & 20), through bolts are used for all connections, instead of lag bolts. This requires pre-drilling bolt holes on steel and mass timber. Depending on the width of the gap between the horizontal double steel plates, additional wood blocks can be added for structural and fire-proofing purposes (Figure 24). To achieve more shear force, split rings are installed between the CLT floor slab and double beams.

Looking at the steel joints individually (Figure 20), each one is composed of three separate parts to largely provide reuse flexibility, connected through inner and outer pipes, fastened together with bolts. For example, if the columns are different sizes in the next life, it can be switched to a bigger or a smaller steel cap in the standardized system.

Figure 18. Primary beam system design

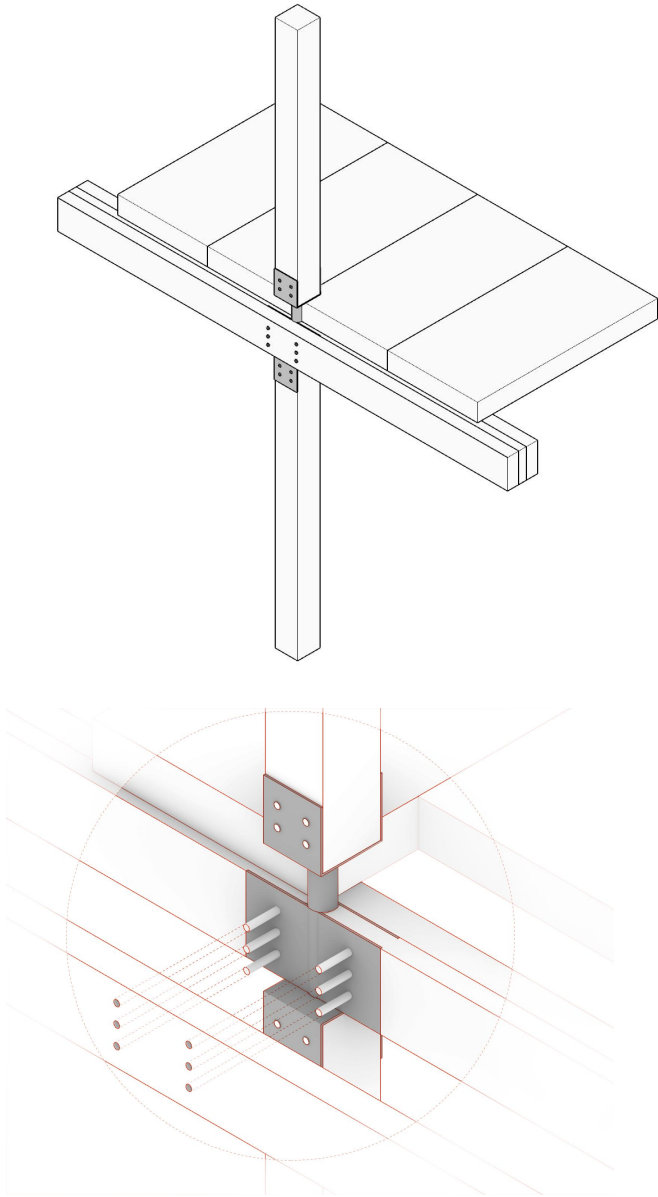


Figure 19. Primary beam axon details

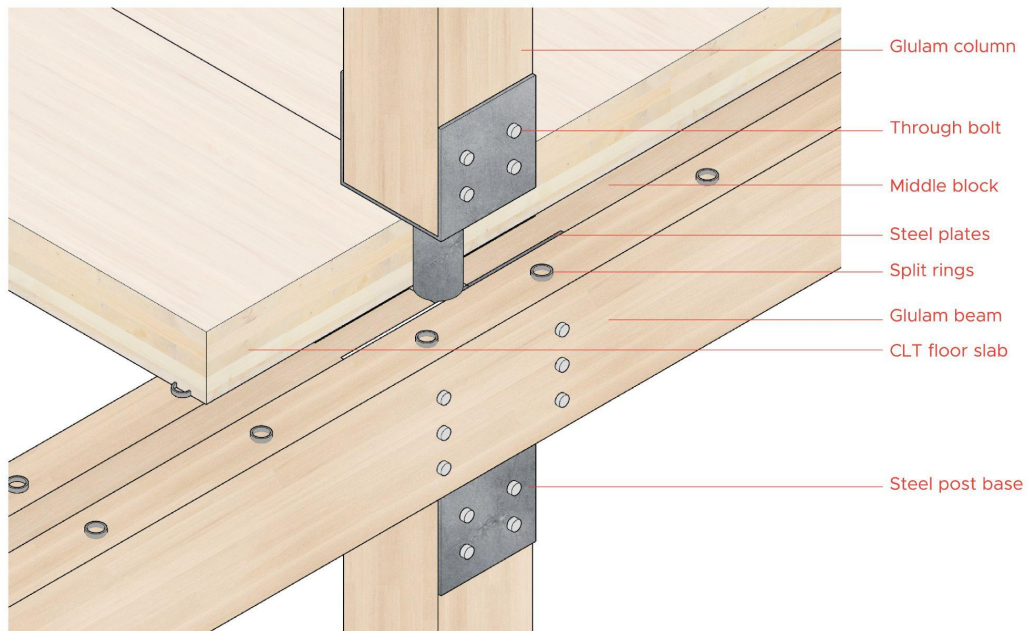
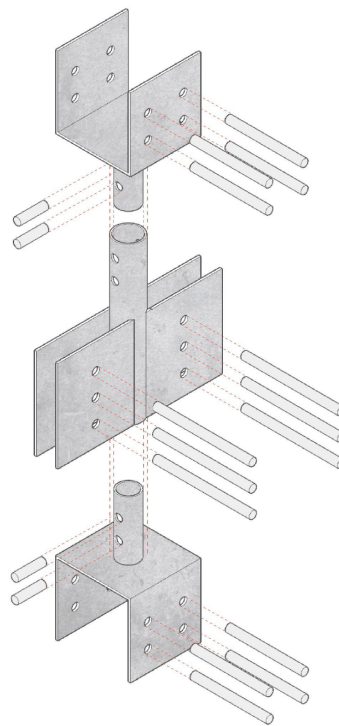


Figure 20. Primary beam design details



There are two design options for attaching secondary beams (Figure 21). Figure 22 shows the use of 2 L-shaped steel plates with through bolts running through the

secondary beam. The second one, shown in Figure 23, is to use a T-shaped plate in the middle of 2 half-width secondary beams. Both options are aligned with the primary bolt location.

Figure 21. Secondary beam design

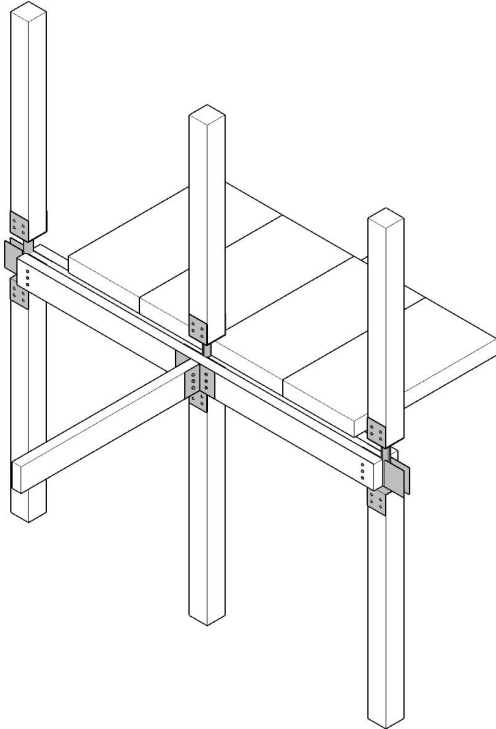


Figure 22. L-shape plate secondary beam connection

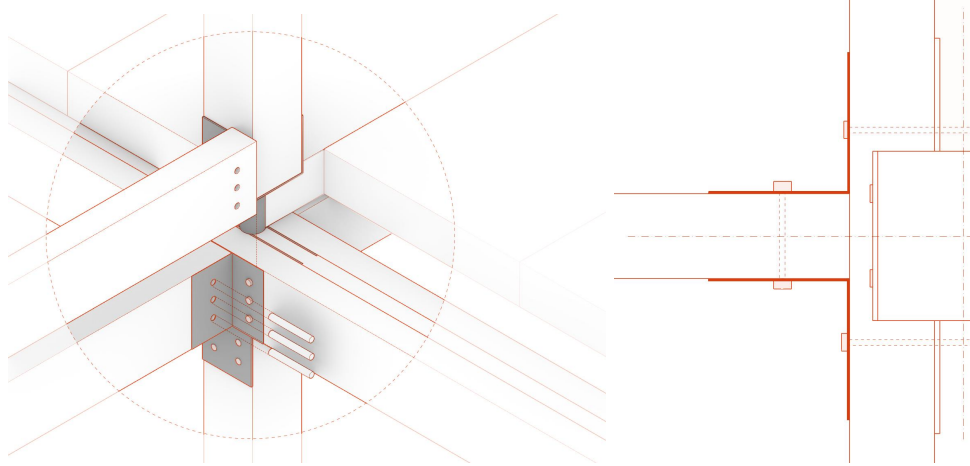
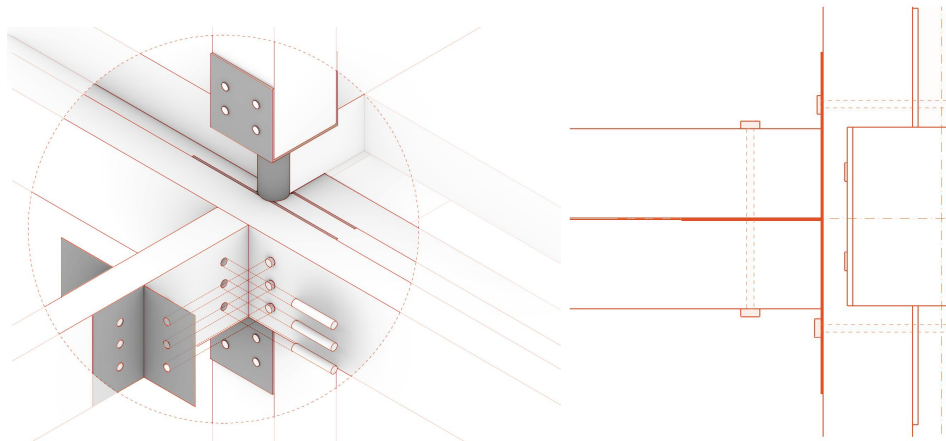


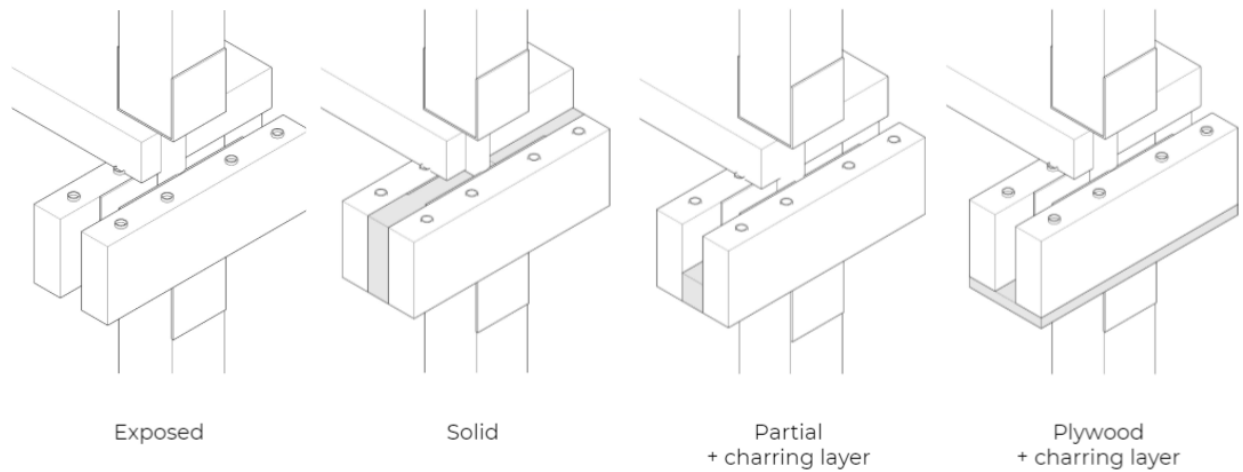
Figure 23. T-shape plate secondary beam connection



There are also fire considerations (Figure 24) regarding the additional wood block in the middle of the double beam. If the middle block is left empty, more areas will be exposed to fire.

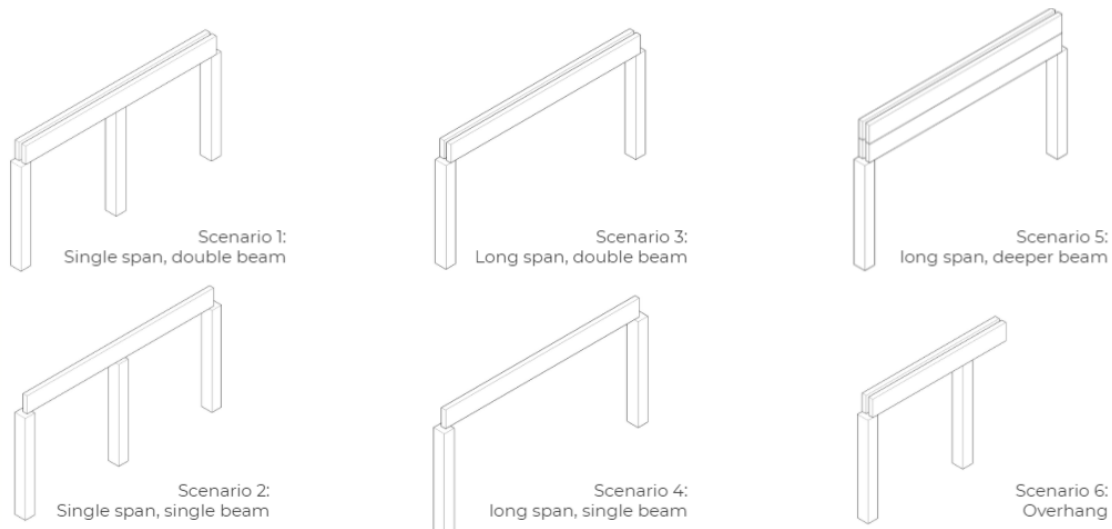
The gap can be filled with timber to achieve higher fire resistance. Buildings with other fire coding requirements can also choose to use particle wood blocks or plywood on the ceiling with considerations of a charring layer dimension to adapt to your flexible designs.

Figure 24. Fire resistance design strategy



The LP reuse method provides high reconfiguration potential. The glulam beam's span and beam section can be modified according to different design criteria and building load. Figure 25 demonstrates six reconfiguration variations with the same column height condition. In scenario 1, the same components with the connectors can be reused under the similar load requirement and column span. Scenario 2 can be utilized when there is less building load as it only uses a single beam. Scenario 3 allows for a longer span as the middle column is removed, but it also requires less building load. Scenario 4 is similar to scenario 3, but allows for even less building load with a long span. In scenario 5, the primary beams can be stacked for a larger building load to achieve a long span with additional required timber connections. In scenario 6, the steel joints, bolt holes, and column length can remain the same while the primary beam can be modified to achieve an overhang.

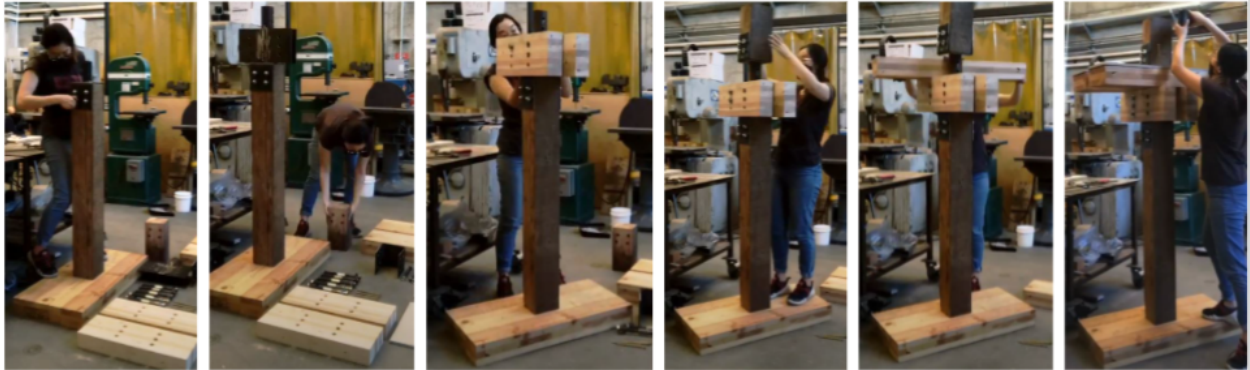
Figure 25. Reused Components Reconfiguration Scenarios



3.1.2 Prototyping and Lessons Learned

As part of design development, the author built a full-size prototype (Figure 26) to further examine the ease of assembly, disassembly process, and feasibility of the connections. It was built following the design as expressed in digital Rhino 3D model. The prototype is composed of a section of CLT floor, a mass timber post, and a double-beam, spanning 2 feet by 4 feet. It includes the primary elements and steel connections: the CLT panel floor assembly, glulam columns, glulam beams, acoustic mat, and stainless steel fasteners. All of the components were fabricated by the author and her advisors.

Figure 26. Assembling and Disassembling Process. All Components were Built in the Fabrication Lab of the Architecture Department at the University of Washington. The figure shows the process of assembling and disassembling a sample of the mass timber building system utilizing the LP reuse system.



Materials were collected from a variety of sources, including reclaimed 2 x 4 and solid lumber, used CLT panels, reclaimed sheet metal, threaded rods, and fasteners (Figure 27). All parts were fabricated in the University of Washington Fabrication Lab at the College of Built Environments. In the reclaiming process, the author encountered various fabrication issues. Reclaimed materials require special equipment and techniques to deal with unexpected material conditions, such as a larger and stronger saw blade to be able to cut through lumber with nails embedded in it.

Different fastener choices and combinations were explored to achieve flexible designs (Figure 28). The fasteners can either be visible or countersunk into the glulam beams. Coupling nuts are located between the glulam beam connecting bolts and nuts on the outside, which provides room for adjustment during assembly and disassembly.

Overall, the prototype examined the constructibility of the LP reuse system. The design has the potential to be scaled into larger building modules. However, it should be noted that structural testing needs to be done to testify to the structural strength of

materials after receiving the building load. The size of each fastener was determined by the dimension of the glulam beams and columns. Value engineering and specifications are needed for design development.

Figure 27. Prototype using reclaimed materials and fabrication process. All Wood was Planed, Cut, or Glued, and Sanded; Steel was Cut, Drilled, Welded, Sanded, and Bended using equipment under Fabrication Lab Supervision.

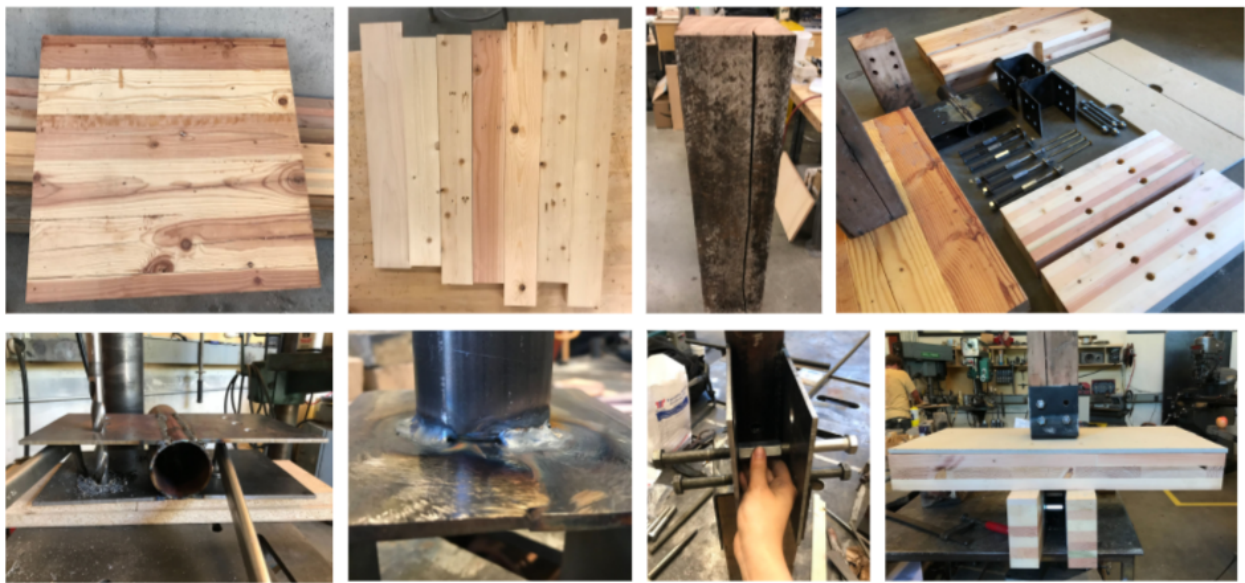


Figure 28. Fastener Choices for Glulam Beams. (from left to right): hex nuts, threaded rod with washers; hex tap bolt with washers or serrated hex flange screws; flat head Slotted/Phillips machine screws



Figure 29. Fastener Choices for Column Cap and Stirrup. Upper left: hex nuts on both sides with a threaded rod in the middle. upper right: hex bolt with a hex nut on the other side. lower left: hex cap nuts on both sides with thread rod. lower right: flat head Slotted/Phillips machine screws with a hex nut on the other side.



3.2 Application in Different Building Conditions

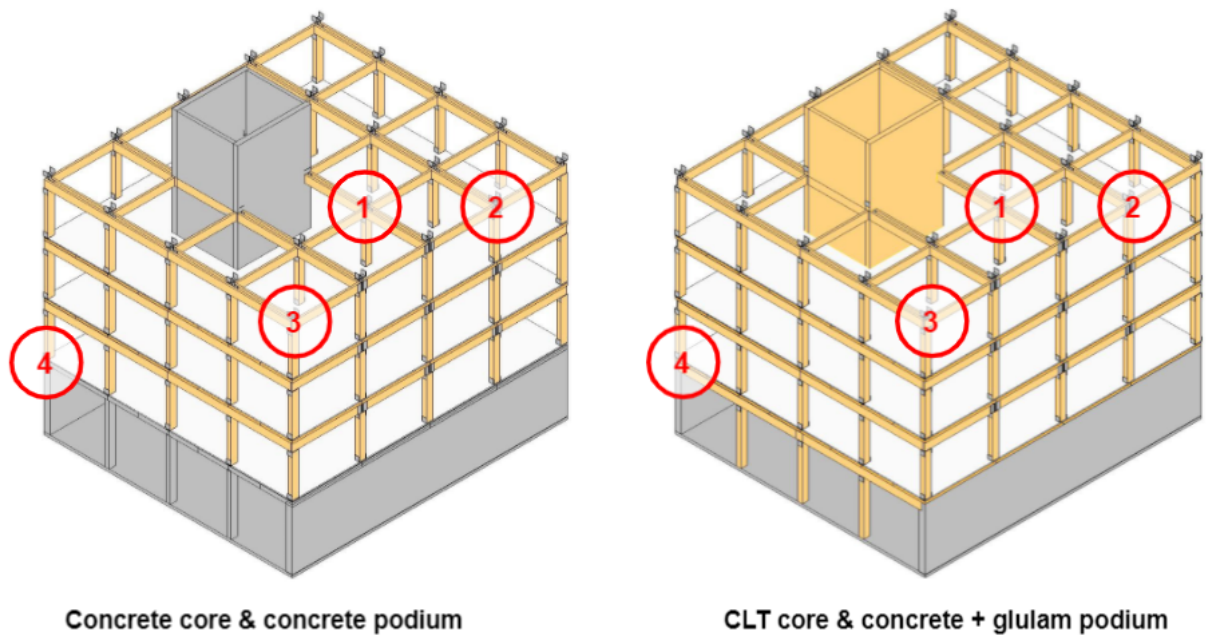
3.2.1 Joinery Conditions

This section demonstrates the joinery designs that can be applied to common mass timber building systems with a concrete core and/or CLT core. Different building conditions (Figure 30) includes:

- 1) Typical beam-to-column conditions
- 2) Beam-to-building-envelope conditions
- 3) Beam-to-beam corner conditions
- 4) Column-to-concrete podium conditions

The following CLT detail drawings reference the CLT Handbook by Karacabeyli, E & Douglas, B. (2013)

Figure 30. Joinery Design in 4 General Building Conditions



The typical beam-to-column condition (Figure 31) is a pure mass timber solution without a concrete topping. High acoustic performance and thermal stability solutions should be considered to mitigate any concrete usage. Based on the studies in the earlier chapters, composite slabs binding structure makes it difficult to detach the CLT floor from the concrete portion. The section (Figure 31) shows the double beams, glulam column, CLT slab with a drop ceiling which leaves room to run MEP based on design specifications. An acoustic mat is installed on top of the CLT floor to prevent sound transmission (see CLT soundproofing details in Karacabeyli, E & Douglas, B. (2013)). Although the size of wood members is based on building load and bay size, the decision around whether to expose or conceal the wood per code requirement also determines the sizing.

Figure 32 and Figure 33 demonstrate the connections to the curtain wall and exterior wall using the LP reuse method.

Figure 31. 1) Typical Beam-to-Column Joinery Condition

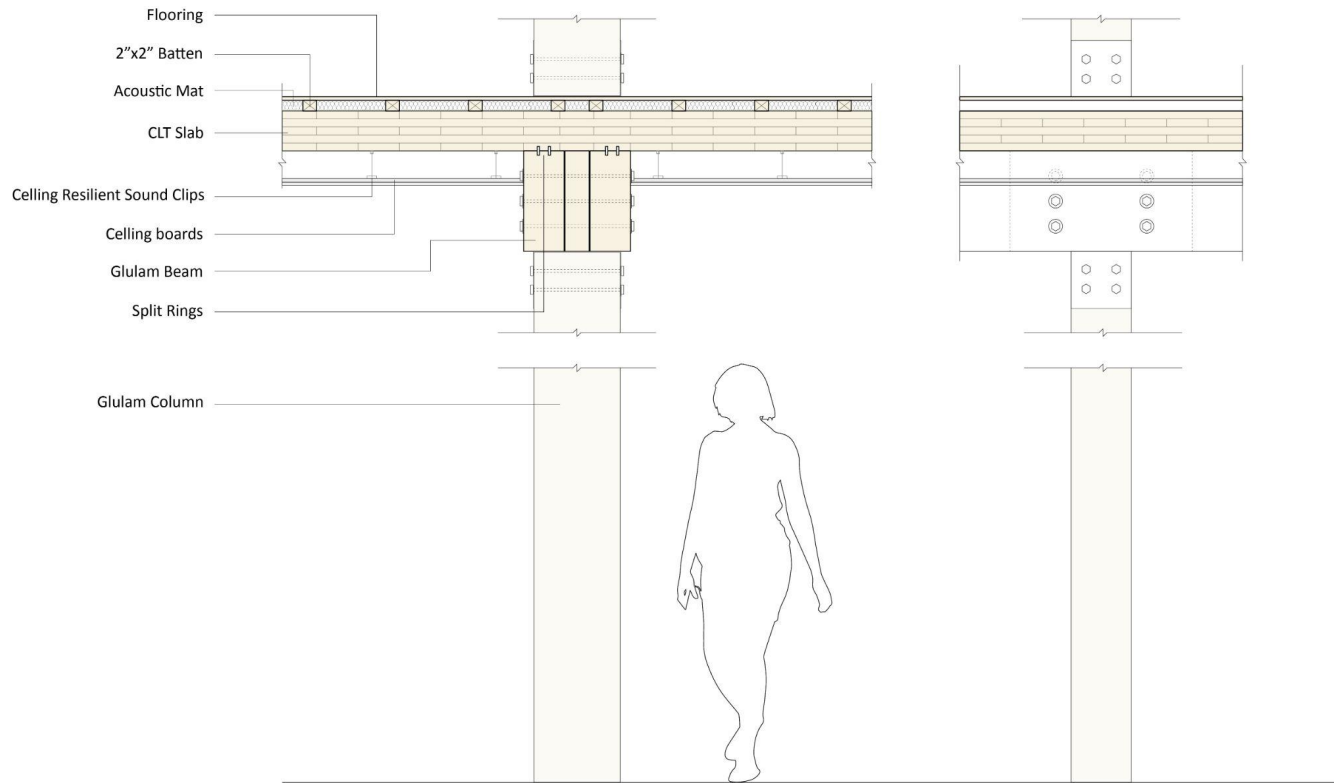


Figure 32. 2.1) Curtain Wall Details that demonstrates the curtain wall connection to glulam beams and CLT floor panels. Curtain wall channels are mounted on glulam beams. It is a conceptual design suggestion for the LP system.

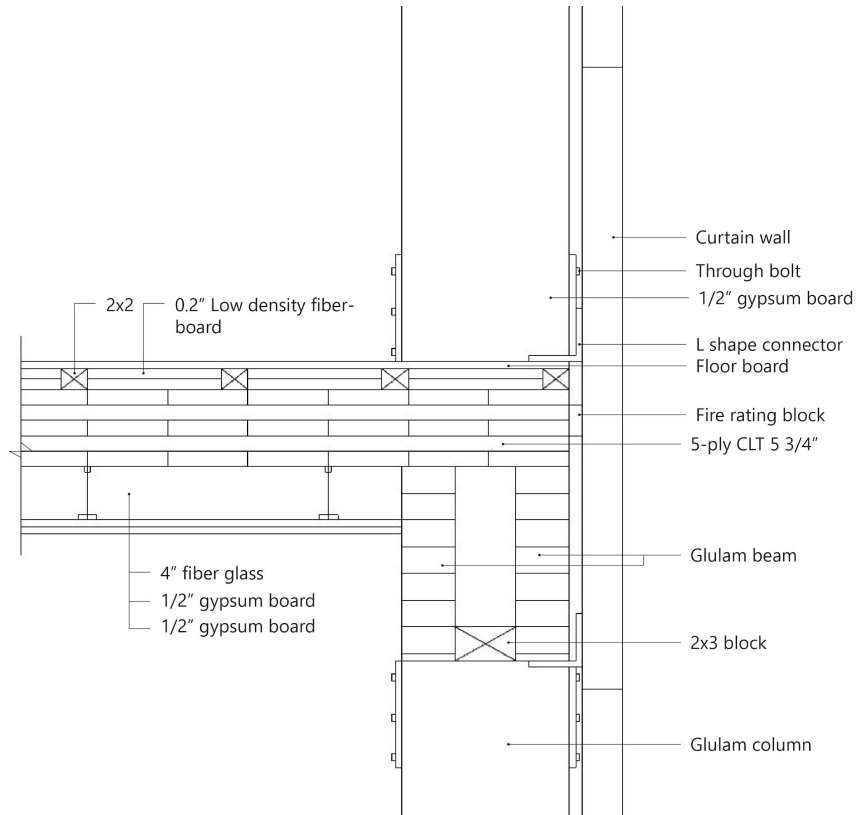


Figure 33. 2.2) Exterior Wall Details, which demonstrates the exterior wall connection to CLT wall panels. Exterior wall / cladding is mounted on the CLT wall with an air and vapor barrier and insulation reference the CLT handbook. It is a conceptual design suggestion for the LP system.

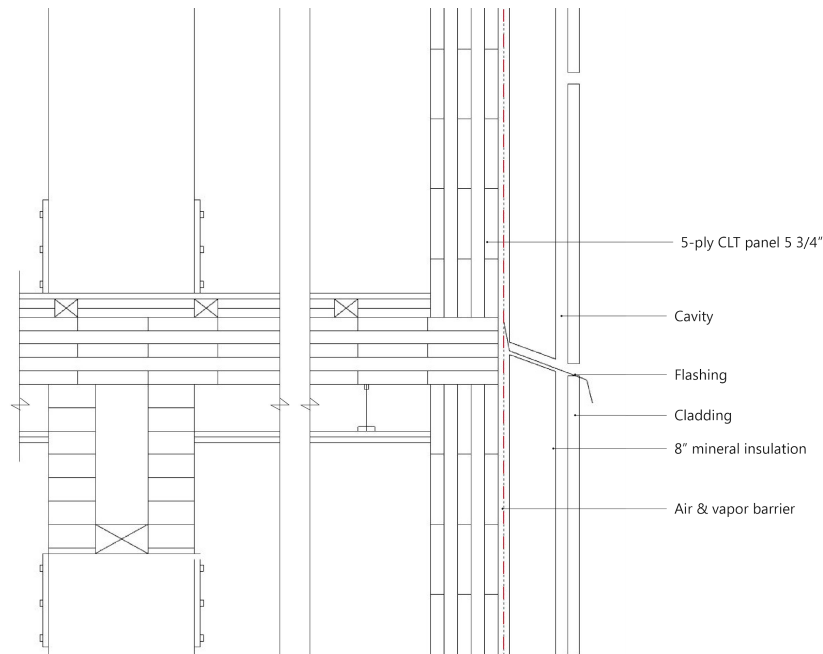
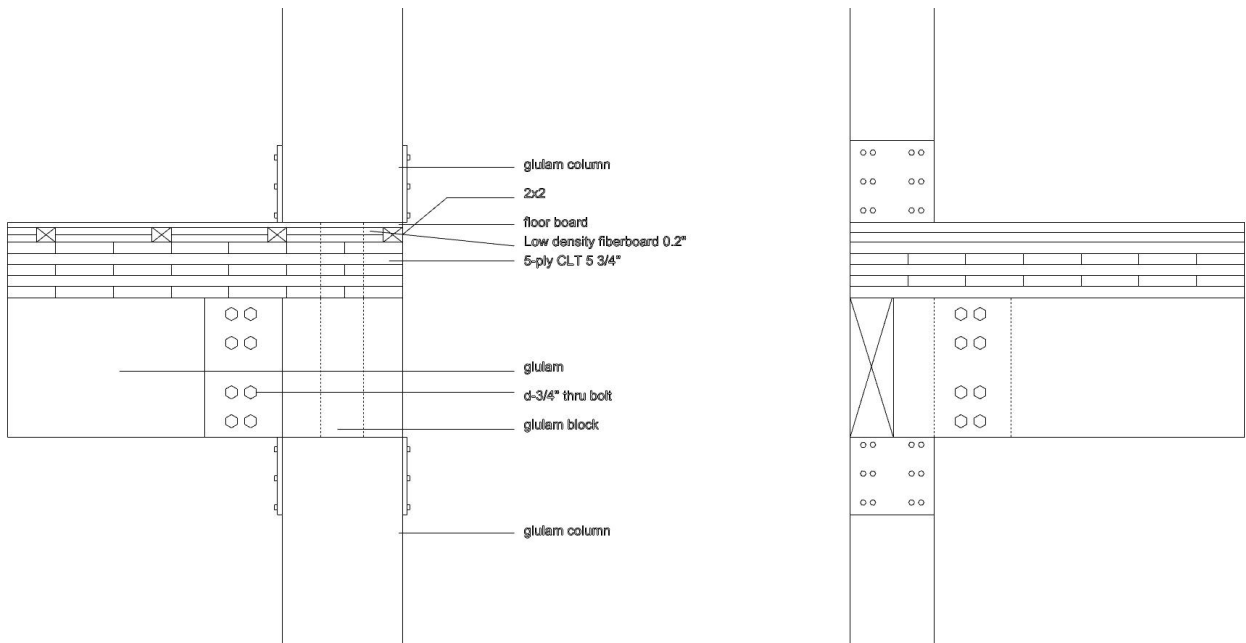


Figure 34 illustrates the glulam beams' connection in facade conditions, such as building edges and corners. The glulam beam is oriented so that it's flush with the building's exterior wall for ease of installation. The glulam column connection remains the same as it is in the typical condition.

Figure 34. 3) Corner Conditions



To connect with the cast-in-place concrete foundation, the glulam columns are installed in place when the column stirrups are cast (Figure 35) in concrete. Glulam beams will be bolted to steel brackets with knife plates in the middle due to the structural provision (Figure 37). For connections with precast concrete, the column stirrups are bolted (Figure 36) in the precast concrete foundation.

Figure 35. 4.1) Cast-in-place Concrete Floor Details

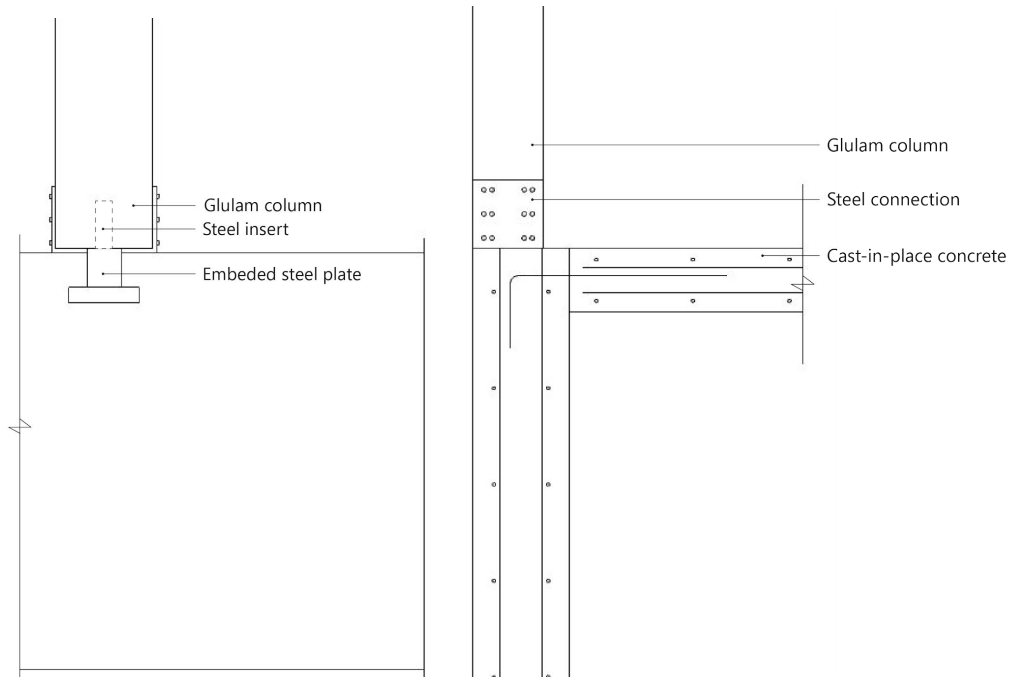


Figure 36. 4.2) Precast Concrete Details

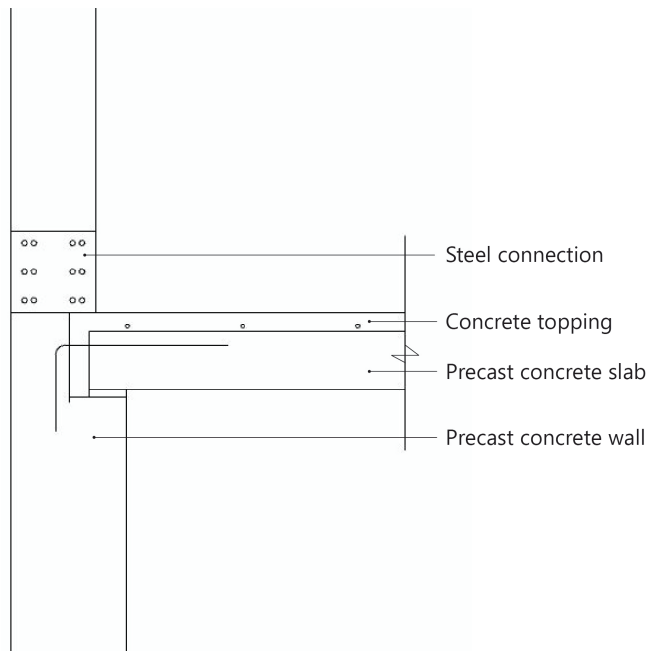
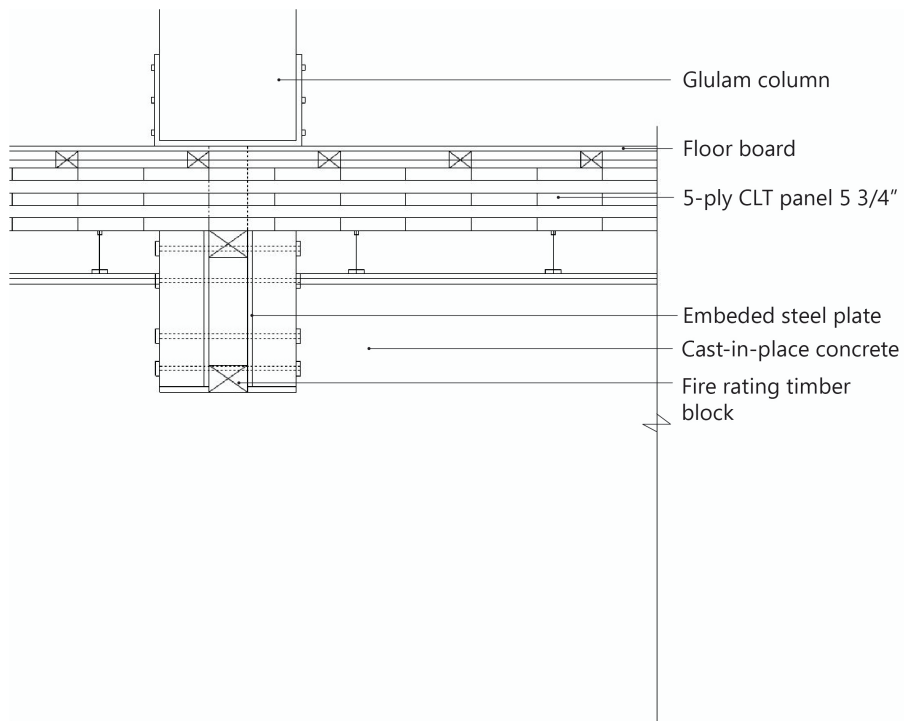
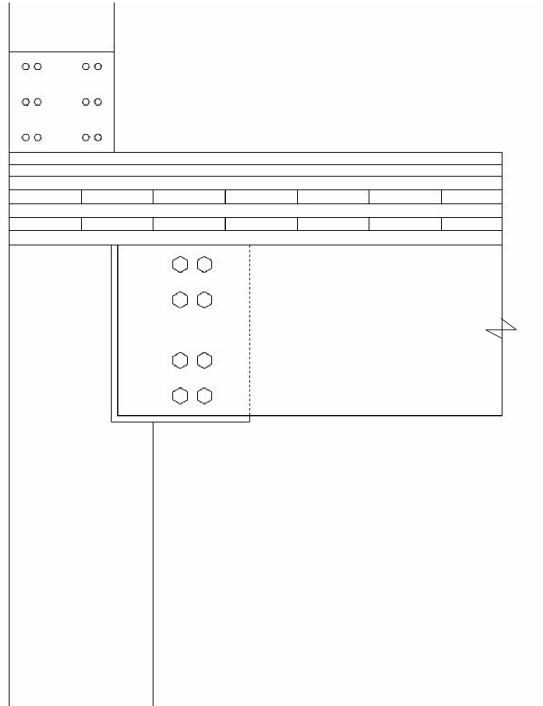


Figure 37. 4.3) Cast-in-Place Concrete with Glulam Beams. Upper: side view; Lower: section view.



3.2.2 Buildings Reconfigurations

This thesis studied the reconfigurability of the LP system by designing different building reconfigurations all using the existing materials of the Brock Commons Tallwood

House (Figure 37). In other words, if the Brook Commons have been built with the LP system, what other configurations could be possible using its columns and beams It is an 18-story mass timber residential building with a concrete podium, glulam columns, and CLT floor slabs. The following assumptions are made through remodeling the base scenarios using the LP reuse system.

Figure 37. Brock Commons Tallwood House, Brudder. (2020) is used the recently completed student residence building in August 2017 at the University of British Columbia (UBC) in Vancouver as a base scenario for the reconfiguration study.

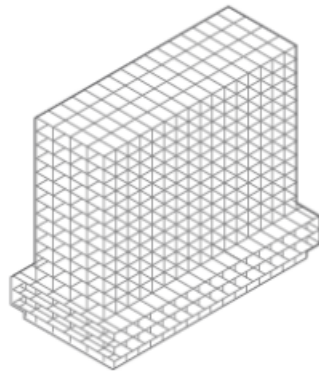
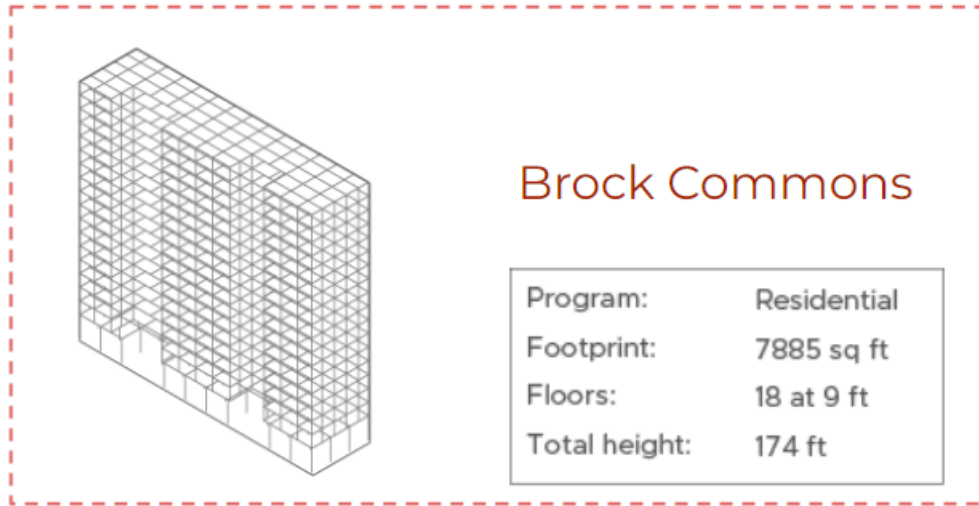


The conceptual reconfiguration designs A, B, C, D, E, F, G, and H (Figure 38) kept the same floor height, various bay sizes, different building footprints, and different total heights. The buildings range from a 4-story warehouse to a 26-story office building.

For some buildings scenarios like B, D, E, F, and G, there are leftover materials from the base scenarios, for some cases like A, C, G, and H, new columns and beams need to be added.

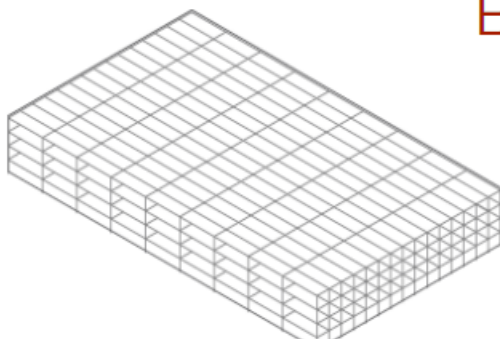
For example, the base scenario could be turned into a four-story warehouse. In terms of design criteria, the warehouse has less roof load, so in some locations Scenario 3 can be used (figure 39). According to design calculations and a rough estimate, there are leftover materials after constructing the structural component of the warehouse.

Figure 38. The second life of Reused-timber in different building reconfiguration which is developed based on the assumption of the use of the LP system in the base scenario. Details are shown in the diagrams.



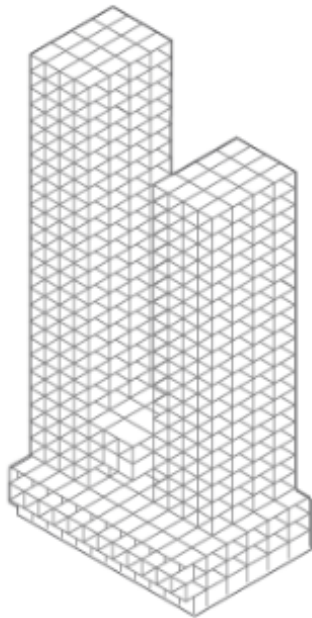
A

Program:	Office	
Footprint:	12567sq ft	
Floors:	14 at 9 ft	
Total height:	126 ft	
Materials	Leftover	New
Primary beams:	45	0
Secondary beams:	0	299
Columns	0	58
CLT	0	97



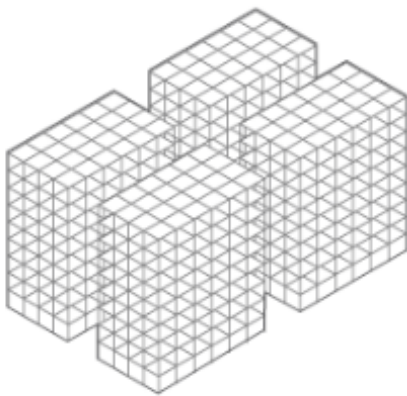
B

Program:	Warehouses	
Footprint:	33131 sq ft	
Floors:	4 at 9 ft	
Total height:	136 ft	
Materials	Leftover	New
Primary beams:	72	0
Secondary beams:	498	0
Columns	728	0
CLT	0	0



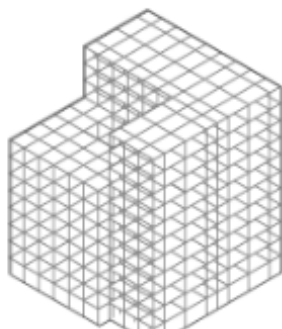
C

Program:	Office	
Footprint:	8835 sq ft	
Floors:	24 at 9 ft	
Total height:	216 ft	
Materials	Leftover	New
Primary beams:	262	0
Secondary beams:	0	20
Columns	39	0
CLT	152	0



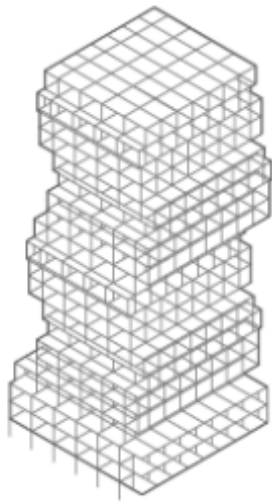
D

Program:	Office	
Footprint:	9872 sq ft	
Floors:	9 at 9 ft	
Total height:	81 ft	
Materials	Leftover	New
Primary beams:	106	0
Secondary beams:	8	0
Columns	103	0
CLT	200	0



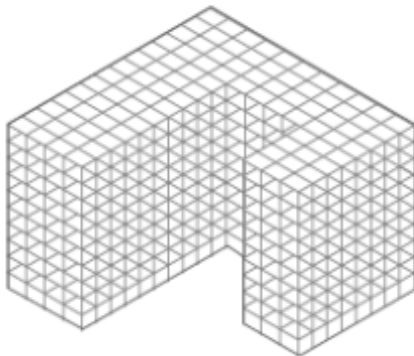
E

Program:	Office	
Footprint:	7300 sq ft	
Floors:	11 at 9 ft	
Total height:	99 ft	
Materials	Leftover	New
Primary beams:	210	0
Secondary beams:	130	0
Columns	321	0
CLT	25	0



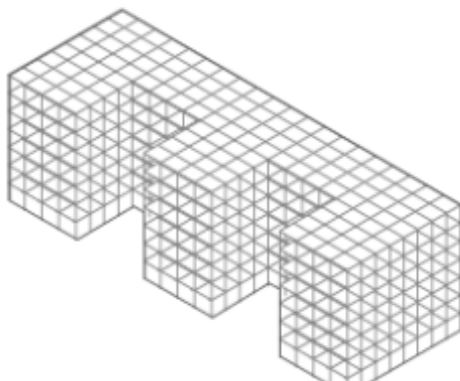
F

Program:	Office	
Footprint:	5890 sq ft	
Floors:	19 at 9 ft	
Total height:	171 ft	
Materials	Leftover	New
Primary beams:	183	0
Secondary beams:	90	0
Columns	299	0
CLT	399	0



G

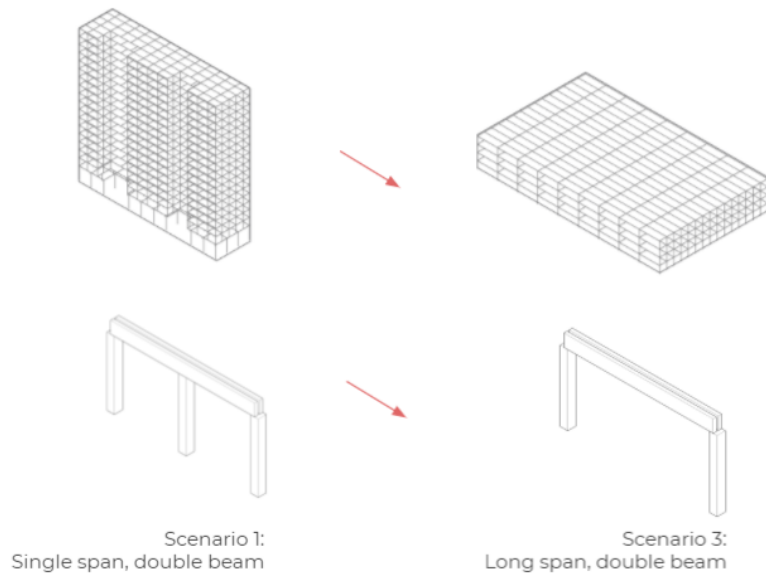
Program:	Residential	
Footprint:	10771 sq ft	
Floors:	11 at 9 ft	
Total height:	99ft	
Materials	Leftover	New
Primary beams:	0	25
Secondary beams:	103	0
Columns	68	0
CLT	25	0



H

Program:	Residential	
Footprint:	10684 sq ft	
Floors:	7 at 9 ft	
Total height:	63 ft	
Materials	Leftover	New
Primary beams:	0	26
Secondary beams:	18	0
Columns	106	0
CLT	34	0

Figure 39. Component reconfiguration comparisons



Program:	Warehouses	
Footprint:	33131 sq ft	
Floors:	4 at 9 ft	
Total height:	136 ft	
Materials	Leftover	New
Primary beams:	72	0
Secondary beams:	498	0
Columns	728	0
CLT	0	0

4. Conclusions and Future Research

Through this thesis, the mass timber building system reconfiguration design strategies are explored. The flexible reuse with length preservation (LP) design guidelines is effective for mass timber building reconfiguration. The major driver of the LP reuse method is to preserve the material and increase reuse and reconfiguration flexibility during and/or after deconstruction. The prototype examined the constructibility and the potential to be applied in building practice.

This thesis examined the schematic joinery design of the residential building with mass timber structural system. Various joinery was designed for different building conditions. The Brock Commons Tallwood House building reconfiguration studies further examined the potential of the LP reuse system to be applied to other buildings.

The prototype in this thesis was only tested for constructability and might not prove to be structurally sound, but it provides a starting point to further analyze the structural strength and durability in design for reconfiguration in future research.

The LP method with various building conditions such as the primary beam system, the secondary beam system, corner conditions, envelope connections, and connections to concrete podiums, set a foundation for comprehensive reconfiguration scenarios in the next building service use.

This thesis posed various questions which were associated with future investigation. The LP reuse method intends to reduce the usage of concrete, but that also reduces the thermal and acoustic performance. We need to seek alternative solutions for thermal performance and acoustic performance to be compatible with the mass timber system.

Since the mass timber structure relies on steel structure for lateral system, we need to investigate reusable steel design. In terms of material technology, we need to ensure the mass timber components and the adhesive are durable enough that they can serve multiple buildings.

All the components need to be well documented with essential structural strength and connection type information embedded in each components. The research cannot be isolated from fabrication practitioner and needs to be incorporated into their business operations. It helps broaden the cascading use of reclaimed material.

Sustainability continues to be a focus for the built environment. Proper methods to quantify the carbon impact of the reuse material are critical. Though there is increasing interest in product reuse initiative and sustainable practice within academia, actions and border application are needed from the AEC industry to execute sustainability and reusability to their business model and financial evaluations to bridge the gap.

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