Creating Flexibility from Rigidity:

A New Way of Looking at the Mass Timber Panel

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Abstract

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Using mass timber panels in the built environment in any capacity requires offsite prefabrication and frequently involves preassembly in a factory. On site construction and assembly is then much faster, cleaner, quieter, and less labor intensive. Yet this prefabrication can frequently remove 20% to 40% of the overall panel, which leaves a vast quantity of waste material. While treating that material purely as waste would negate much of the carbon sequestration benefit from using mass timber in the first place, prohibiting its creation would prohibit the widespread adoption of the material. This paper discusses why that waste exists to begin with and investigates the possible avenues for using that material. The aim of this thesis is to look at mass timber panels from a different perspective—one that treats them as a flexible product ripe for creativity. Innovative solutions for using small format mass timber are demonstrated with a computational design script in a case study that creates parametric relationships between envelope features and other project components. Future work on both waste reduction and changing the narrative around using mass timber panels is discussed.

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Introduction

Building materials of all types have advanced significantly since they were first introduced. While originally used in simple, flat foundations, concrete is now regularly poured in all kinds of curved manifestations. There is undoubtedly some advanced engineering that goes into the formwork and reinforcement for these kinds of pours, but domes, spheres, and undulating surfaces are all possible. All manner of structural component has been either poured in place on the jobsite or been made in a factory before shipment for installation. Concrete can now be specified in color, strength, texture, thickness, and more.

Steel has a similar story. While originally used in the built environment as a skeleton structure, its use is now much more widespread. Steel rebar reinforces almost every modern concrete pour. Cross sections in limitless combinations of dimensions are used in beams and columns. And those cross sections can now be bent into angular formations or rolled into arcs of specified radius and used as architectural elements. Steel plate adorns interior and exterior walls. Various alloys have been created to provide different aesthetics and strengths.

Wood, too, has changed its shape in the built environment. Although timber's first use in construction was quite close to its form in nature—a round log—that has changed greatly over the years. Logs were squared into timbers, and then timbers were sawn first by hand and then by machine into boards. Near the end of the 19^{th} century, timber mills began peeling logs circumferentially to create veneers. Those veneers were then laminated into plywood, which quickly became and has remained ubiquitous—particularly in residential construction. Plywood is just one example of a group of products known as sheet goods; oriented strand board (OSB), medium-density fiberboard (MDF) and particleboard are also wood fiber-based sheet goods. More recently than the advent of dimensional lumber and plywood has come a new category of wood products know as Mass Timber. These are considerably more technically advanced than other wood products and have brought a revival to the timber industry.

The use, application, and formulations of all materials in and for the built environment continues to be a hotbed of innovation. As the conversation around climate change intensifies and as materials get more and more expensive, much of that innovation concerns minimizing the embodied carbon of materials or improving the efficiency of their use. Several companies are working on “green” concrete, wherein some portion of the cement—which is very energy intensive to produce—is replaced by an unwanted byproduct of another industrial operation, such as fly ash from coal powerplants or slag from steel plants. New steel alloys are under development that would allow the downsizing of structural members while maintaining the same strength properties, thereby decreasing the embodied carbon per structural unit. The timber industry has also seen a good deal of innovation in recent decades, but with a different carbon conversation.

As its name implies, mass timber is a collection of massive timber-based products that came about in the late 20^{th} century in Europe and have gained global traction in recent decades. These products have some variation but are generally large laminations of either dimensional lumber or veneers and are used in structural capacities like columns and beams as well as in panel applications like floor plates and walls. Mass timber is very interesting for several reasons, chief among them its carbon capture benefits. As opposed to materials like concrete and steel that have high embodied carbon—their production actively adds carbon dioxide to the atmosphere—timber products are almost always carbon sinks. Carbon is pulled out of the atmosphere as trees grow and is then kept stored in the wood unless the timber is burned or allowed to decay in places such as landfills. To be sure, a good deal of energy is still required to process trees into commercially viable timber products: trees are harvested in forests, trucked to timber mills, sawn, kiln dried, and frequently laminated before they are ready to be used. Yet the embodied carbon of a mass timber building is still much lower than that of the concrete required to build a functionally equivalent building, and concrete has none of the carbon storage benefit that mass timber does.

Mass timber is rapidly gaining popularity amongst architects and developers around the world, and particularly in areas where timber is abundant. It is beautiful, lightweight, faster to construct, climate friendly to produce, and paired with modern forestry practices can be a sustainable material. Yet it is not without challenges. Mass timber brings with it a scheme of manufacturing and fabrication that is new and unfamiliar to many designers, developers, and contractors. Building codes have had to change rapidly to allow for its use and no current mass timber project is without lengthy code discussions. As such, mass timber can be considered in its infancy as a modern, intelligent building product. This thesis aims to bring a new perspective to mass timber that will hopefully allow for it to be treated with more flexibility and less of the rigidity that comes to mind when thinking about massive pieces of wood. Of particular focus will be the mass timber panel products.

This paper will be divided into five main sections. First, an overview of mass timber will dive into the history of the material, describe its different forms, and present various environmental considerations. Mass timber construction will then be examined, including the tradeoffs to consider and the material streams involved. Next will be an investigation into how to allow for mass customization of mass timber, with particular attention on using the material with maximum efficiency while allowing for greater flexibility. A case study of these concepts in practice will then be examined. This paper will end with a discussion of next steps in mass timber manufacturing and some thoughts on where the industry is headed. Many topics are covered in the following pages, but the main research question pursued and therefore to keep in mind is the following:

- How can digital fabrication and parametric design tools be leveraged to make designing for mass timber more materially efficient while simultaneously providing more flexibility with the material?

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1. Mass Timber Overview

Mass Timber was invented in the 1990's in Germany and Austria. By the early 2000's it had begun to show up in single and multi-family residential projects in Europe, and it first appeared in the International Building Code in 2015. As a subcategory of Engineered Wood Products (EWP), the Mass Timber heading encompasses many different products. These include glue laminated beams (Glulams), laminated veneer lumber (LVL), and a subset of panelized materials. This last category is comprised of nail laminated, dowel laminated, and glue laminated products. The most common panel products are cross-laminated timber (CLT) and a nascent product known as the mass plywood panel (MPP).

Although mass timber has existed for over three decades, its popularity in the United States is much more recent, with the first few mass timber buildings arriving only about a decade ago. That said, local building codes around the country—particularly in the Northwest—and the International Building Code (IBC) are being challenged to allow the use of mass timber in taller and taller buildings. In 2021 the IBC was changed to include “Type IV” buildings—those made from mass timber—in various height designations: Type IV-C up to nine stories, Type IV-B up to twelve stories, and Type IV-A up to eighteen stories.

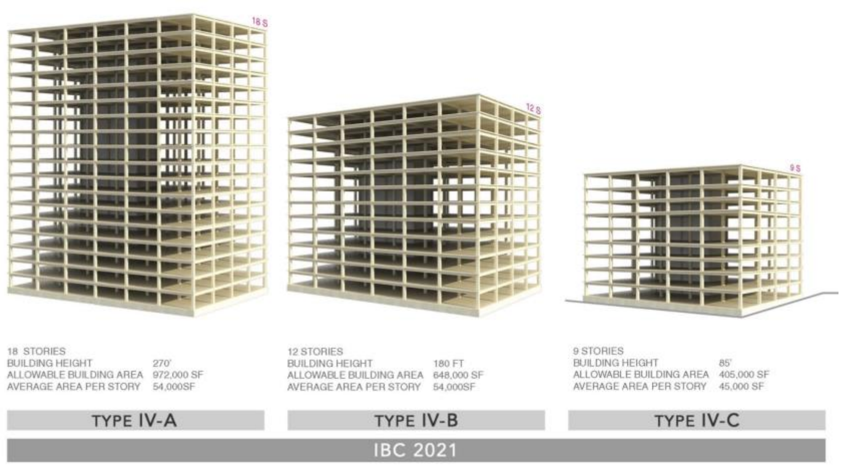


Figure 1: (Atelier Jones)

While currently marginally more expensive, mass timber is a lightweight, sustainable, and beautiful building material. Developers and investors are attracted to mass timber's embodied carbon benefits as well as the speed with which a mass timber building can be constructed due to the factory-based fabrication and pre-assembly that is inherent in its use. Mass timber is regularly employed today as large structural components of buildings in the form of beams and columns. These are straightforward uses of the material in that a square or rectangular section simply needs to be manufactured to length and dropped in place just as steel and concrete beams and columns are currently used. Strength properties are easy to calculate, and replacement of the materials used for decades in a one-to-one fashion is relatively straightforward. Many projects already exist with timber skeletons or substructures that still utilize poured in place steel-reinforced concrete as floor plates. These fall into the category of hybrid-timber structures.

Panel products are used as floor plates either alone or with a layer of concrete poured over the top for a durable wear surface and added strength. Panels can be cut to size and features for mechanical, electrical, and plumbing are frequently added in a factory before shipment to the jobsite. The two most common panel products, CLT and MPP, have similar strength characteristics but are manufactured in different ways. CLT starts out as timbers milled very similarly to the two-by material found in all lumber yards across the United States, the only difference being that corners aren't softened with a radius but are instead left as sharp. These timbers are then finger jointed and glued together to create a continuous board that can be cut to the exact length and width of panel being manufactured. Timbers are stacked lengthwise and then crosswise in repetition, with glue being applied between timbers in the same layer (edge-glued) and between layers of timbers (face-glued), before entering a press that applies pressure from the top, bottom, and all four edges until the lamination is set. A minimum of three layers is in every CLT panel, with most manufacturers producing panels in 3, 5, and 7 ply thicknesses. These roughly equate to 4", 7", and 10" in thickness, respectively. Press capabilities differ from one manufacturer to the next, but as an example: a major

CLT supplier in British Columbia, Kalesnikoff, produces panels up to 11.5’ in width and up to 60’ long.

MPP is a much newer product than CLT, with production starting in 2017, and is produced exclusively by Freres Lumber in Lyons, Oregon. Unlike the sawn timber in CLT, the feedstock for MPP is one-inch-thick laminated veneer lumber (LVL) which in turn is made from individually peeled veneers. LVL sheets eight feet long by four feet wide are joined on their short ends with a low angle scarf joint to create a continuous sheet of four-foot-wide LVL. This material is then cut to length and stacked in alternating directions from one layer to the next before lamination. Glue is only applied on the faces between layers, not between the narrow edges within individual layers. Panels are produced in nominal widths of 8, 10, and 12 feet, up to 48 feet in length, and in thicknesses of 2”-24” on 1” increments. As well as alternating direction of plies from one layer to the next, the 1” thick LVL plies also have cross laminations internally.

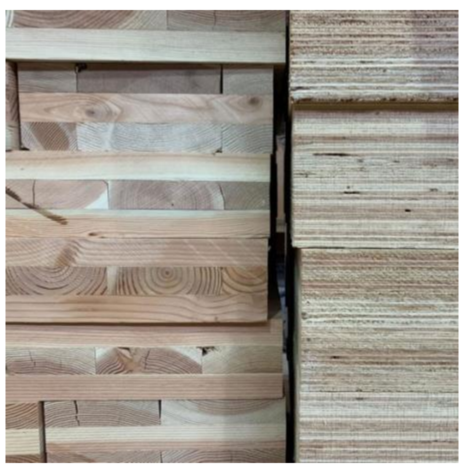


Figure 2: CLT vs. MPP (Freres)

Mass timber buildings are generally warm and inviting spaces. These spaces tend to have biophilic elements that make inhabitants comfortable and are liked for the way they look, feel, and smell. Most people have a gut feeling that a mass timber building is better for the environment than a functionally equivalent building built from reinforced concrete, but it is helpful to put data to the sentiment. Two main environmental conversations generally come to the fore with mass timber construction, the first being: what is the environmental impact of a mass timber building in comparison to a concrete building? A 2017 study compared two functionally equivalent buildings constructed side by side in Trondheim, Norway, one a reinforced concrete building and the other a mass timber building. For the product stage of the building materials, Life Cycle Analysis (LCA) stages A1-A3, the mass timber building produced 25% less greenhouse gas (GHG) emissions than the reinforced concrete building (Eliassen 2019). In LCA stage B6, the operational energy use, the mass timber building also fared better than its neighbor. However, in the transport of product to the jobsite, stage A4, the mass timber building had almost double the GHG emissions. This is due to mass timber's comparative novelty to concrete and steel in that there are many fewer manufacturers of the material and therefore the shipment to the jobsite is frequently a greater distance. Data from another study in China in 2021 showed similar results. Again, two functionally equivalent potential buildings were compared, one built from reinforced concrete and the other from mass timber. LCA stages A1-A5 were lumped together, and the mass timber building was projected to have a 25% less Global Warming Potential (GWP) (Chen, C. 2021). What is of note here is due to a shortage in China, most of the lumber was projected to ship from a European timber mill to the CLT facility in China, some 20,000km by various modes of transportation, and the timber building still performed better averaged across all stages A1-A5 than its reinforced concrete counterpart. The study made sure to note that in the United States, timber travels on average 250km from sawmill to CLT manufacturing facility. The graphic below is from an article discussing the demand for mass timber vs. the locations of lumber mills and manufacturing facilities (Brandt et al., 2021). Manufacturing facilities are generally located in close proximity to myriad timber mills throughout Washington and Oregon but are therefore clustered in the northern half of the country. Given the large evident demand for mass timber in Southern California, LCA stage A4 will continue to make a large impact on the Whole Building LCA for those future projects.

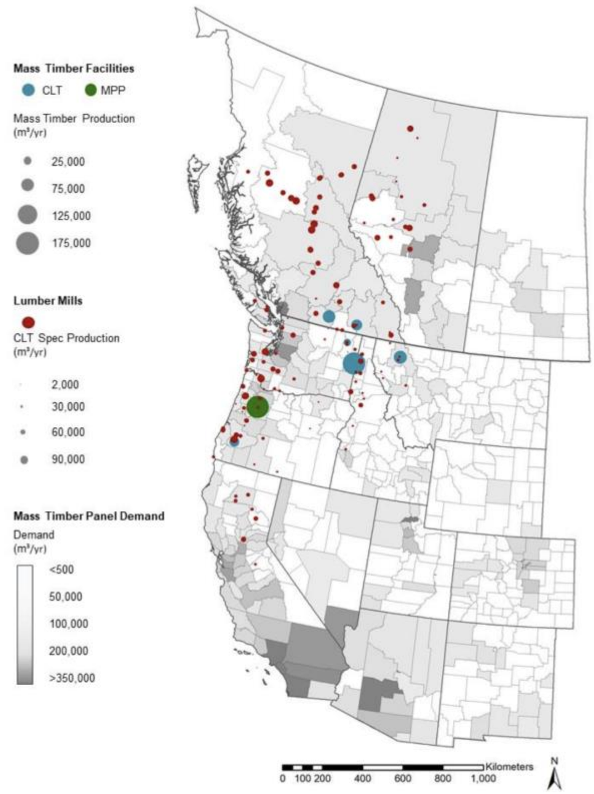


Figure 3: Western North American CLT 2030 demand, CLT and MPP production and lumber mills (Brandt et al., 2021)

This last fact provides a nice segue to the second common environmental concern: If mass timber continues to gain traction in the built environment, can our forests support the demand? A group of forest researchers at the University of Washington in Seattle published a report in 2022 on the added demand mass timber might place on forest harvesting over the next few years. Lumber demand projections for 2035 derived by the Softwood Lumber Board were compared against Forest Inventory and Analysis data provided by the United States Forest Service. The lumber use projections included the increased demand that current adoption rates of mass timber would place on the system. To be conservative, the high-volume use case confidence interval was used (shown here as timber harvest) as was the lower confidence interval for forest growth.

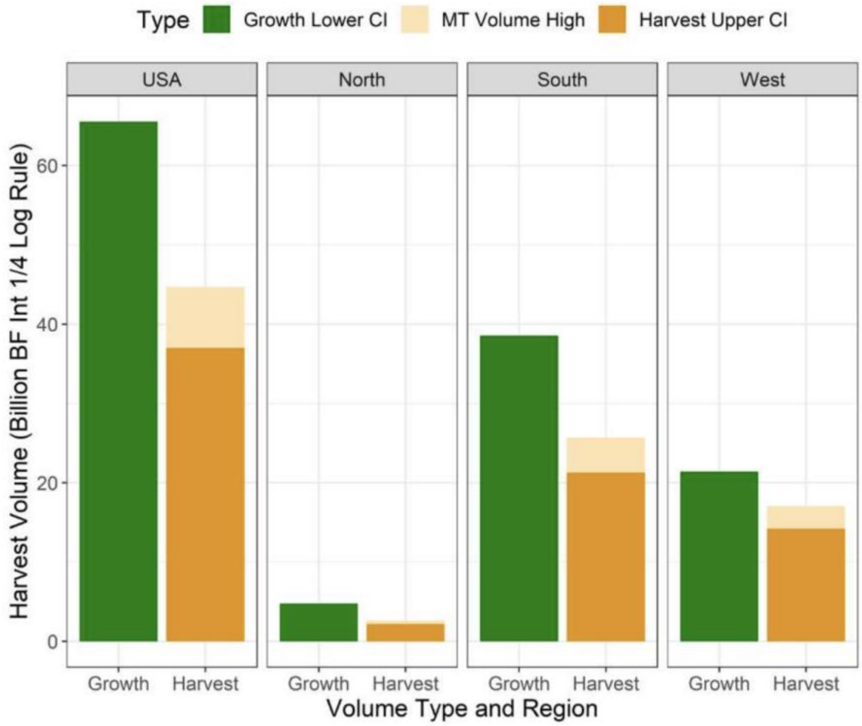


Figure 4: FIA estimated growth and harvest volume with projected mass timber demand—High Volume 2035 Case (Comnick et al., 2021)

For the United States as a whole, growth surpassed demand by 32% (Comnick et al., 2022). In summary, the writers of the report also note:

> “Our results are not particularly surprising to anyone familiar with U.S. Forest inventory data and the history of the U.S. timber supply. It is a well-known fact among forestry professionals, the forest products industry, and related academia that the U.S. timber supply has been expanding for over half a century. However, this is not well known outside those circles. Cognitive dissonance related to a desire to use wood building products for their carbon storage capability but concerns about sustainability is understandable. The results of this research add more evidence that should help allay those concerns. Our analysis clearly shows that the United States can sustainably use more mass timber and reduce greenhouse gas emissions and embodied carbon in our built environment.”

Really this is an optics issue: rarely do people see the wastelands that concrete or steel manufacturing facilities are and even if they do, it is difficult to observe the gravity of their negative environmental impact with our eyes. In contrast, we see large swaths of forest cut down and it strikes us to our core. Hopefully, greater awareness of the material will bring more acceptance and support for modern forestry practices. As mass timber continues to gain popularity, its carbon storage benefits will also grow.

2. Mass Timber Construction

Building with mass timber is a different beast than traditional construction methods like stick framing and poured in place concrete. This is primarily because of a difference in the material stream when building a mass timber building. Regardless of when the various parties start discussing the project with each other, the mass timber panels in a project will move from the planning stage on an architect's desk to a purchase order from the manufacturer of the raw CLT or MPP. The same would be a true of steel components, dimensional lumber, or even a quantity of concrete, but all these materials would then head straight to the jobsite. What makes mass timber different is that it will instead move from the manufacturer to a fabricator to complete

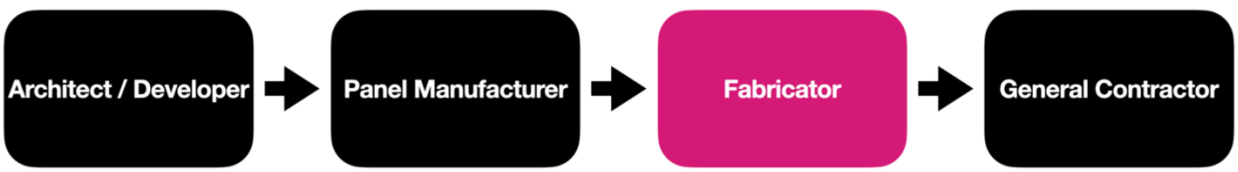


Figure 5: Mass Timber Material Stream

any fabrication operations that are necessary. These facilities use Computer Numerically Controlled (CNC) mills for fabrication operations that include but are not limited to cutting panels to length, cutting window and wall openings, and preparing bracket and fastener locations. Fabricators are even starting to involve other trades in order to better integrate electrical, plumbing, or fire prevention features once panels are installed. There is frequently some preassembly of panels in this factory setting as well. Once all fabrication and factory work is finished, the panels are shipped to the jobsite in the correct sequence to be craned into place. This necessary fabrication and preassembly step is new to the North American construction industry.

The mass timber material stream can be either vertically or horizontally integrated, and the scheme frequently resides somewhere in between. At one end of the integration spectrum is Katerra. They attempted the route of total vertical integration by employing developers, architects, material manufacturers, fabricators, and contractors at the same time. While the specific reason for their bankruptcy and dissolution is unclear, many believe they vertically integrated too quickly and tried to tackle too many parts of the construction industry at once. On the other end of the spectrum is complete horizontal integration. Frequently an architecture firm will only interact with the general contractor hired to build the building. The specific project, developer, firm, or a host of many other factors may dictate exactly when this relationship starts. The contractor must then have relationships with mass timber manufacturers and fabricators. Without involvement from the timber manufacturer early on, this latter scheme can often lead to major inefficiencies in the process in that at least partial redesign might need to occur depending on capabilities of the manufacturer or fabricator.

There are several important tradeoffs to consider with mass timber construction. First, it is generally more expensive to build out of mass timber than reinforced concrete. A 2021 study again compared functionally equivalent mass timber and reinforced concrete buildings looking at both LCA and Total Life Cycle Cost (TLCC). Through stages A1-A5, production (A1-A3) and transport of material to the jobsite (A4) as well as installation (A5), the mass timber building cost 26% more than its concrete counterpart (Liang et al.,2021). However, the writers do go on to say, “these buildings are also expected to be a ‘premium product’ and command higher rents, and thus be more profitable.” While this higher manufacture cost has been a major barrier to entry for widespread mass timber buildings, a second factor to consider is increased speed. Although exact data is hard to come by, an eighteen-story mass timber tower at the University of British Columbia known as Brock Commons reached full height in only eight weeks. Reinforced concrete buildings are built at maximum one floor per week, as the pours must reach a certain cure time before they can support the floor above. This means the mass timber building took roughly half the time vs. a reinforced concrete building. While the resulting decrease in labor cost is still overshadowed by the much higher cost of material, that cost is frequently justified by using sustainable materials. A final factor to consider is the carbon economics of a project. As the climate change conversation continues, building with lower embodied carbon materials or purchasing carbon offsets for a given building project will absolutely be integral to successful development. In the many LCA studies mentioned previously, and even with long transport distances, the mass timber projects outperformed the reinforced concrete buildings in the production and construction stages. Yet these numbers have a glaring omission in common: they don't account for the carbon removed from the atmosphere and stored within the actual timber. A study not yet mentioned applied data to this phenomenon. Again, functionally equivalent buildings—this time in Portland, Oregon—were examined: "From Stages A through C" which includes operational and end of life energy expenditure, "the embodied carbon was 21% lower for the MT building due to these substitutions. If considering carbon stored by the CLT material in the MT building, then the GHG emissions reduction would increase to 69.5%" (Chen, Z. et al., 2020). Therefore, it is imperative to use as much of a billet of material as possible to retain that stored carbon. This thesis will soon discuss uses for mass timber waste, and many of those same ideas can be applied towards the timber that is recovered upon the eventual demolition of a mass timber project.

The mass timber panel has only come about with the pervasiveness of intelligent manufacturing. There is no question that the facilities producing CLT and MPP are truly state of the art. But the widespread use of mass timber is largely only possible due to CNC digital fabrication techniques employed after production of the raw material. Multi-axis machining has existed for over a century but its use in a format larger than the typical mill bed has only recently been achieved with the inclusion of more accurate positioning techniques across longer spans. Mass timber's true utility comes from its machinability—machining timber leaves a clean edge, doesn't put undue wear on tools, and is relatively quick to cut. Prefabrication of large format panels in a factory before delivery to the jobsite is paramount to mass timber's success as a building material, the alternative being attempting to cut thick material on site, accurately, with hand power tools. Instead, panels are processed in a factory where the edges are ensured to be square, exterior dimensions dictated, and all windows, doors, and other openings are cut out.

CNC machining is one of a handful of subtractive manufacturing technologies, meaning that material is removed from the feedstock as a part is made. The converse to this is known as additive manufacturing in which material is built up into the part being made; 3D printing comprises this subset of technologies. Along with machining, subtractive technologies include laser cutting, electric discharge manufacturing, and others. There are generally two types of waste produced by subtractive processes: the material in the path of the bit or cutter and the material in the middle of subtracted features. Examples of the first of the two are sawdust (machining wood), metal swarf (chips from machining metal), and slag (laser cutting). This waste is generally collected at the site of the cutting head either by vacuum or catchment tray and is removed from the manufacturing environment. Particularly in the case of machining wood, sawdust is an environmental health and safety hazard as an airborne particulate. The other major form of waste is quite literally more tangible in that it can frequently maintain a fair amount of mass depending on the feature being created, such as the negative from a window or a doorway cut out of a mass timber panel.

Figure 6: CLT under Construction at Stora Enso (Jones et al., 2016)

Much of what has been discussed in the preceding few paragraphs provides reasoning for why mass timber isn't much more widespread. Industrial equipment, both at the material manufacturer and the fabricator is very expensive and is time consuming to commission. Investors in both the equipment and in the mass timber for the buildings themselves are made hesitant by the up-front cost. For example, the Framework tower that was to be built in Portland, Oregon, in 2018 was cancelled due to a funding shortfall. The planned project would have been the tallest mass timber building in the United States but fell $2 million short of the funding necessary to proceed. Building relationships between architects, manufacturers, fabricators, and contractors familiar with mass timber is a difficult task that understandably takes years to achieve. And simply because mass timber is such a nascent building material in the United States, it is understandable that architects, developers, and contractors would be inexperienced working with it. According to survey results published by the American Society of Civil Engineers in 2021, 70% of architects responding said they had been involved in a mass timber project. However, 45% of them had less than one year of mass timber experience, and another 40% had less than five years of experience. As the writers of the report summarize, “According to [the architects’] observation, lack of awareness is the most prevalent challenge of mass timber. The majority of [survey] participants indicated that this material is fairly new in the US context and the stakeholders are reluctant to use this product because of lack of case study and previous experience.” (Ahmed and Arocho, 2021). Increasing this awareness and building relationships, knowledge, and trust between manufacturers, fabricators, architects, and contractors is paramount to mass timber’s long-term success.

Adoption of anything new in the built environment takes time and experience across trades. Lack of experience and higher costs of material don’t exactly bode well for and architect or developer taking a chance with mass timber. Both issues will mitigate with time, as momentum has been building to use the material more and more in the built environment. With each new mass timber project comes more industry experience and with more experience will come demand for more material. This will inevitably create market availability for new manufacturers and with more material producers the cost will decrease. But in the meantime, mass timber should be more tangible for more designers. Material use inefficiency should be ok.

3. Allowing for Mass Customization in Mass Timber

We know we can manufacture and fabricate mass timber. We know it is generally better for the environment to use mass timber in our buildings rather than reinforced concrete. Our forests won't be depleted with the increased demand mass timber will place on the lumber supply. But building in mass timber generally carries with it a decrease in flexibility. Architects have long pushed the boundaries of what is possible with concrete and steel. Formwork can be modified, and more concrete poured. Steel beams can be welded together or cut shorter, and the scrap recycled. But these materials have something going for them that mass timber doesn't: they are quite literally fluid. Timber panels, on the other hand, are rigid and there is a finality to their shape. To be clear, there are methods of connecting panels at seams and this is a frequent occurrence, but these connections are without any real structural capability. There is very little material forgiveness with mass timber. For it to become a mainstream material—for costs to decrease and supply to increase—it cannot be a design anomaly. Rather, mass timber must fall into step with other common building materials. A wall that may have been poured in concrete or framed with dimensional lumber should be replaceable with mass timber. Additionally, mass timber construction can't be so uniform as to be prescriptive. Architects and developers occasionally want to build the same building over again, but variation and artistic expression are fully engrained in the industry. Mass timber construction must rise to the challenge of complexity it will soon face.

Paramount to allowing for mass customization in mass timber is the ability to punch windows and other necessary holes into solid billets of material. This would allow for mass timber panels to be used much more readily in interior walls and in building envelopes. Punching holes in a billet takes advantage of the whole mass timber paradigm—fully leveraging the digital fabrication and preassembly environment. Avoiding this, or always keeping billets whole, intentionally ignores the paradigm, as this would lead to more installation time on the job site and more on-site construction work, negating much of the utility of mass timber in the first place. If workers must build in a window header and sill between two smaller pieces of mass timber to achieve the same glazing as a window punched in the middle of one larger billet, this is equivalent to designing in construction inefficiency. Similarly, more smaller panels “not only implies an increase in construction costs due to the higher number of fasteners, but also to a higher air leakage risk through panel joints” (Gasparri et al., 2015). The option to punch holes in mass timber panels not only allows for design freedom but is also a sound construction decision.

Throughout the array of literature reviewed for this thesis, the concept of cutting holes for windows and doors in mass timber was mentioned regularly, though there was rarely any follow-up. Authors frequently seemed to acknowledge this inevitability but gloss over reasons for doing so. There were, however, some important mentions of the need and demand for mass timber walls. The first was from a workshop hosted by the UWS Forest Products Laboratory in 2019 meant to discuss the top research needs in the mass timber industry. Out of a list of 24 structural-related research topics, “evaluate the effects of openings on the performance of CLT shear walls” was ranked fifth (Zelinka et al., 2019). Industry professionals want to start using mass timber billets in shear walls but doing so logically still requires allowing for movement through space. Especially for structural scenarios, maintaining panel continuity where possibly is important. From a 2017 article forecasting demand for CLT in the Pacific Northwest, the authors note “the study projects that with improved understanding of the product the proportion of overall CLT demand derived from structural wall applications in office buildings will increase from 5% of the overall CLT demand in the initial years to over 10% by 2030” (Ganguly et al., 2017). And while not a direct endorsement for using mass timber as a substitute, yet another LCA study comparing mass timber buildings to structural steel alternatives, the author notes that “The building envelope components contributed more than 20% of the total emissions in the impact categories of GWP and smog potential. The envelope contributed more than 40% of the total emissions for the categories of HH particulate, eutrophication potential, and acidification potential. This demonstrates that holistic design is best suited for reducing environmental impact of buildings, as all four archetypes buildings would have benefited from a lower emission building envelope" (Allan and Phillips, 2021). That lower emission envelope material could very well be CLT or MPP. Mass timber billets have good insulating properties, are a lightweight substructure for windows and façade materials, and if left exposed can add warmth to the interior of a space.

Punching openings in panels has many advantages. When panels are eventually transferred to the jobsite, punched windows lead to fewer overall panels. A contractor doesn't have to lift two smaller, entirely opaque panels into place and then build a header and sill plate between the two before installing a window. Fewer panels also lead to fewer vertical seems between panels that must be sealed on site, yet another time-consuming operation during which moisture can enter the space. This also decreases cost in that splice plates aren't required. With CNC technology capable of cutting accurate holes in billets on an assembly line, panels can be cut to length and windows punched at the same location before moving directly to a preassembly station for installation of windows, rain screen, and exterior façade. And finally, rather than a steel stud or stick framed header and sill in the aforementioned scenario, punched windows lead to more mass timber in the building, adding to the amount of carbon stored in the construction material and minimizing the overall embodied carbon of the building. Design freedom, the structural benefit of a continuous panel, and simplification of design and construction all contribute to why punching holes should be an acceptable fabrication methodology. As a not yet mentioned LCA study says, "It is also now practical to use computer numerical control (CNC) technology to cut openings of different sizes and shapes on CLT panels for windows and doors with precision value added" (Chen, Z. et al, 2020). What this study doesn't delve into, however, and what is true of many other findings in the literature, is that there is very little discussion of the waste this process creates.

A big disadvantage of punching openings is what gets left behind. If holes are punched in the middle of billets this will lead to a large amount of material not able to function in its originally intended purpose as a wall—or at least, as a substantial wall. The challenge is then to look at small format mass timber in the size realm of a window or double door. The lack of mass timber utilization in façade and wall panels has frankly yet to make large quantities of this small format mass timber a problem, which in turn leads to a dearth of research context. For simplicity's sake, for the moment this material will be referred to as waste. Mass timber panel waste has been minimal to date in practice, or at least has been minimally discussed. In an article discussing the use of genetic algorithms to most efficiently layout structural CLT panels to be cut out of billets, the author mentions that "in the literature, different amount of waste have been reported by the industry reports for the CLT cuts in the CNC milling plants, ranging from 15% to 27% [66,67]. These include the total waste on all panel types, including structural and non-structural elements. Since the designer tries to minimise the number of openings in the structural elements, nonstructural elements will be responsible for a large amount of waste due to openings" (Yazdi et al., 2021). The first of those two sources cited within the article mentions a loss of 27% of the CLT in use in their project as waste, with no follow up (Passarelli, 2018). The second is the next example: In a study looking at the roll of logistics in LCA for mass timber buildings, a table lists that for every 1 m^3, or 472.44 oven-dry kg of CLT produced, a coproduct is 72.06 oven-dry kg of "CNC waste and end cuts" (Chen, C.X. et al., 2019). This equates to 13% waste, and there is no further discussion of where that waste ends up. While these were the mentions of mass timber waste in the literature with the most empirical data behind them, there are a number of other mentions of waste that simply say something to the effect of "panel waste from cut outs is recycled." More examples of what exactly is done with this waste and how it is recycled would be insightful but may very well not exist.

The most common use for panels has been as floor plates laid in place on a structure of either mass timber or reinforced concrete. Other than mounting features for mechanical, electrical, and plumbing systems, the fabrication on these panels is limited apart from cutting them to size and ensuring edges are square. This doesn't produce much waste in that manufacturers can produce panels quite close to the eventual size that a fabricator needs. Such basic utilization doesn't take advantage of modern software and the digital fabrication tools that make using mass timber possible in the first place. In order to allow for mass customization, waste material will become a factor to be dealt with. Along with allowing for mass customization comes the need to maximize the use of mass timber billet. This waste needs to be celebrated and used to its fullest extent.

To ensure common language, a quick note on reuse terminology is necessary. A few terms have been used and occasionally misused in the literature reviewed: downcycle, recycle, and upcycle. Downcycling means converting a material into something of lesser value or utility—like using old clothes as cleaning rags. Recycling means using a material in the same exact utility as the original product. Aluminum cans and their ability to be melted down and made into the same can is a prime example of this. And finally, upcycling means increasing the value or utility of a material. Examples of this are very hard to come by.

Several current pathways exist for mass timber panel waste. Starting with the option that garners the least utility: the waste can be thrown away in a landfill. Many county governments containing large metropolitan areas are outlawing landfill disposal of wood construction waste—including dimensional lumber, plywood, and mass timber—with the intention of promoting material reuse. Nonetheless, the possibility of landfilling of mass timber still needs to be discussed. Per a University of Washington researcher's doctoral dissertation, wood products emit more methane than concrete per unit of material in a landfill (Chen, C., 2019). Furthermore, landfilling of wood is generally thought of as the worst-case end of life scenario as it fails even to recover energy from the material as opposed to the next pathway for mass timber waste: burning in a cogeneration plant (Ramage et al., 2017). This practice, too, is facing legality issues when near metropolitan areas as burning wood contributes more heavily to air pollution. That said, cogeneration plants—facilities that produce both electricity and heat from their fuel source—are common at timber mills, which are frequently also sites of mass timber panel production. Burning mass timber waste as fuel makes sense when a cogeneration plant is on site, but the carbon cost of transportation can make it nonsensical (Chen, C., 2019). Additionally, permits for cogeneration plants are hard to come by. While burning is theoretically a downcycling of the material, there are downcycling options that have a marginally higher degree of utility. CLT waste can be chipped up and turned into oriented strand board (OSB), ground even finer and made into particleboard, or simply left as chipped and used as animal bedding. With its higher glue content, MPP may make these options more difficult, but they are currently under investigation.

A high utility use case of small format CLT was presented in a paper discussing how design parameters can both limit architects and provide possibilities, especially in the context of modern design tools. The project that was the framework for the subject matter was a small, 15m^2 dome cabin that uses CLT paneling for the entire structure apart from the foundation (Houck et al., 2019). Small sections of CLT are beveled on their edges such that they self-support in a dome formation, though screws are added to ensure a snug fit. The authors note that their feedstock was 1.2 meter across or roughly 4 feet which is quite small. While certainly an interesting use case, this was a one-off project.

As of this writing, only one public company could be found that is actively addressing the concept of mass timber waste. Founded in 2021 as an offshoot of Nordic CLT in Latvia, Recycled CLT is buying waste material from secondary manufacturers in the Nordic Countries and is attempting to reuse that material in an intelligent way. No information could be found on their specific process, but photos of their work seemed to show them gluing odd-ended pieces of CLT together into a larger billet, perhaps with or without additional layers. If only edge-glued without an additional continuous layer, the CLT may buckle at the glue joints under high compression. That said, if used in a non-structural way this could be an approachable use case for small format mass timber.

Figure 7: (Recycled CLT)

These different avenues of using mass timber waste have varying degrees of eventual utility. Further productization of the material in some form and sale direct to consumer will happen at some point, undoubtedly. Using it as shipping dunnage or as railroad ties is straightforward, but the material will still be exposed to the elements and eventually decay, negating any carbon capture benefits. Turning the scrap into oriented strand board or other similar materials would be useful but requires energy and ignores any of the inherent strength properties in larger pieces of timber. Burning it in a cogeneration plant works for those manufacturers or fabricators—like Freres lumber—that already have a facility on site. And while any of these options are better than throwing the material into a landfill, that is also a current method of disposal. It's no wonder that waste isn't discussed in the literature, though there were many images of punched openings in CLT and MPP panels in the articles reviewed. Waste usage should follow the path of a circular bioeconomy, in which timber is used in its largest, most structurally advantageous form first and steadily downgraded until it is eventually a pile of ash.

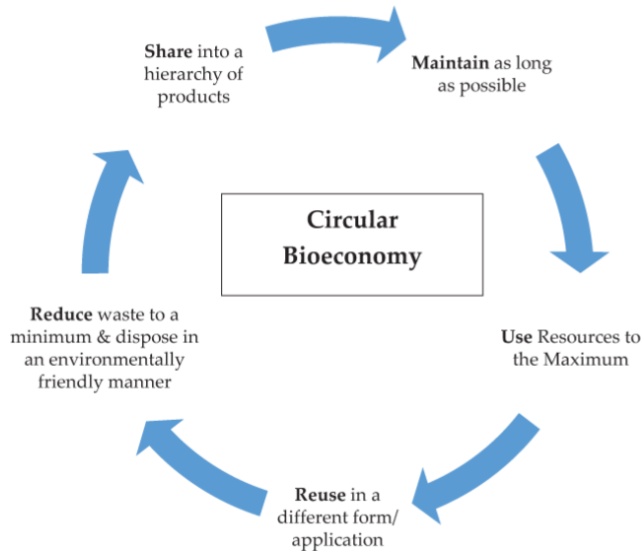


Figure 8: Circular Bioeconomy (Baldwin, 2020)

To support flexibility with mass timber while simultaneously taking advantage of carbon capture benefits, creative solutions for waste utilization are imminently necessary. This isn't a call for designing waste out of a project, but rather celebrating the material that is created through the preexisting design work and thinking critically about how it could be used. An avenue that quickly gained interest was attempting to reintegrate extra material created back into the project from which it came. The basic concept was to find smaller project features and parametrically nest them into waste material created by the project. This line of thinking had several benefits for a given project. First, the total waste percentage from the project decreases, thereby sinking more carbon into the project. Secondly, the total quantity of material needing to be purchased decreases, and therefore overall material cost decreases as well. And third, the material did not need to be stored before being used but instead could be incorporated directly into the construction timeline. While keeping mass timber dry before use is necessary to prevent decay or swelling of the material, storage of large quantities of material requires expensive real estate inside an auxiliary warehouse or within the manufacturing facility itself.

4. Ideas in Practice

A new company ("The Company") has an offsite mass timber prefabrication venture starting up in the Pacific Northwest. They plan to work with architects during the design stage of a building such that their prefabricated timber can be the main structural componentry of the building. While mainly focused on low-rise buildings at the moment, as codes becomes more accepting of taller timber structures they see no reason why their model can't scale accordingly. The Company will implement both a post and beam mass timber skeleton as well as utilize a large quantity of panel material in two locations. The first of these is in floor cassettes, which will be built on a mass timber substructure, and have integrated mechanical, electrical, and plumbing (MEP) features. These will be preassembled in a factory before they are transported to the job site. The second location in which a large quantity of mass timber will be used is in engineered façade panels. Again, the timber will be fabricated in a factory and the insulation, rain screen, windows, and façade exterior will be preassembled in the manufacturing environment.

The Company is partially vertically integrated. They have a team of architects working with outside firms in a design assist capacity to fit their timber substructure to the building's conceptual framework. They also employ a manufacturing team managing a facility built to handle all fabrication and preassembly of timber billets and all other mass timber components. While they don't intend to ever start manufacturing the raw material, they have built relationships with both CLT and MPP suppliers and can source material manufactured very close to their dimensional specifications. The Company also doesn't plan on being the general contractor for their buildings. They will provide some construction support if necessary but won't be primarily in charge.

What makes them most interesting to the topic at hand is that they plan to punch windows in solid billets of material, thereby creating a large quantity of small format mass timber. After working with a façade engineer for a few years, they have concluded that pursuing this methodology will help them achieve many goals simultaneously.

Punching windows provides design freedom in that windows can be placed wherever required and still allows for near total preassembly of the building envelope in the manufacturing environment. This also removes the need for exterior scaffolding on the job site. Having fewer, larger exterior panels with punched windows decreases the total number of panels that need to be craned into place and minimizes the time the building interior is exposed to the weather. And utilizing larger mass timber billets in the building envelope helps the company to achieve passive house standards both in the insulative properties of the timber itself and in the lower number of vertical joints between exterior panels that need to be properly sealed. All that said, The Company doesn't currently have a plan for what to do with the cut outs created from punching these exterior openings. In their manufacturing environment they are gathering their sawdust and plan to turn it into fuel for wood stoves. The key is to find a use for this larger material that has a much higher utility than being ground into sawdust and following the same pathway.

As a case study, The Company provided design data for a project ("The Project") that has yet to be built but for which fabrication and preassembly has started. That is to say that any findings from this case study won't be immediately realized but can certainly provide valuable learnings for future projects. The Project is a three story, 21,000 ft^2 mixed use building with retail on the ground floor and two floors of residential above. The first floor is reinforced concrete with the upper two being entirely mass timber. The Company is using this building to test some construction techniques and is purposely using a system that is well suited for mid to high rise buildings as well. The Project has a mass timber sub-structure and utilizes mass timber billets, specifically MPP, in both floor cassettes and in façade panels. There are forty-four planned window openings in the façade panels, the negatives of which are the waste material to be reintegrated. An investigation began into how other project features could be nested into this waste material.

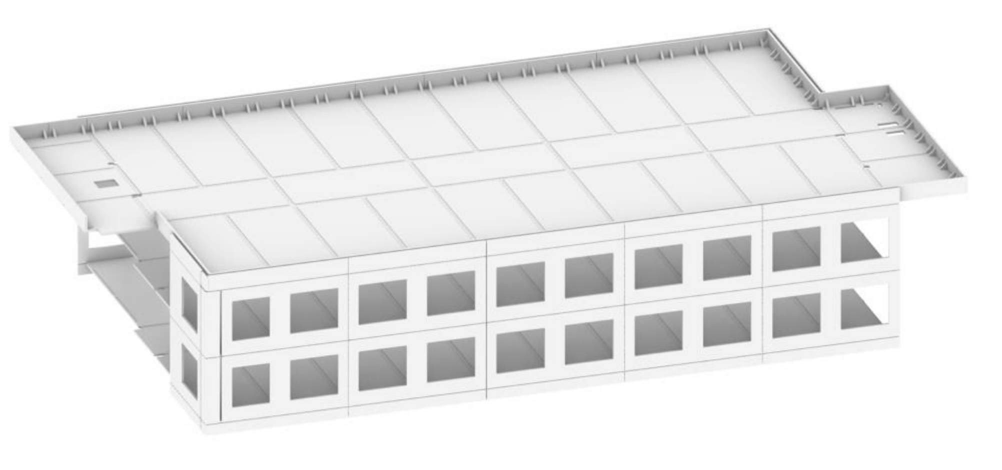


Figure 9: Project Data in Rhino

The most straightforward path to pursue this avenue of reintegrating waste was with parametric design tools. The data stream can be seen below but is essentially as follows. Buildings are first designed in Revit. The Company then works with a consulting group to model all mass timber components in manufacturing level detail in a Mechanical Engineering CAD program (MCAD). The Company's fabrication team uses the MCAD data for manufacturing related tasks and to program their CNC machines. This data is then pulled into Rhino and modified and analyzed with Grasshopper, an algorithmic geometry editor. While Revit is a great tool for Building Information Modeling (BIM) in terms of the level of detail the program can handle, it isn't the most fluid ideation environment, nor does it provide the most specific manufacturing data. The Grasshopper geometry editor for Rhino, however, allows for fully parametric modeling techniques and can rely on Rhino's ability to read many different file types. While there are ways to work with Revit data in Rhino such as Rhino.Inside and Conveyor, the MCAD data provided by The Company's consultant was the most readily applicable. This data was distilled down to just the mass timber components without any of the rest of the building's data that is normally included in Revit. The Grasshopper workspace will make it easy to analyze how much waste is being created, and then allow for parametric, intelligent nesting of other project features into those unused pieces.

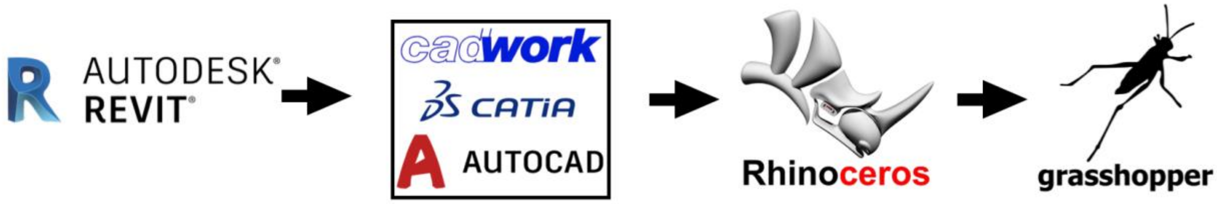


Figure 10: Data Stream

Reintegrating mass timber project waste requires finding project features that can be built from that material. The Project made that task straightforward in that there is an interior parapet wall known as the “cassette stand” made from MPP. There are 70 of these pieces, which stand vertically, perpendicular to the roof cassette and acts as reinforcements for the parapet. Supporting the cassette stand are triangular braces, also made from MPP, of which there are 140 in the project. These two features are prime subjects for being nested into window openings to further the use of the overall façade billet. Once a billet of material is placed on the CNC, more cutting operations are very quick and easy to include. That is to say that the fabrication of these nested components should be completed when the main opening cuts are done to efficiently move material through the manufacturing environment. Knowing which components come from which original billet is of great organizational import, and with Grasshopper, this is easy to accomplish. Keeping track of which project features are cut out of which billet is built into the data stream of the Grasshopper model.

The basic methodology of the script written in Grasshopper will now be explained. There is one manual step required before the parametric environment can be utilized, and that is classifying geometry in Rhino based upon a layer name. Components are placed onto layers labeled “parapet,” “façade,” “floor cassette,” etc. Building data is then pulled into Grasshopper from Rhino based upon that layer. Sublayers can either be parsed out or included under the heading of the main layer, thereby allowing for only a certain specific type of façade panel to be included in nesting operations, for example. As façade panel data is brought in, these are broken down into exterior perimeter curves and interior curves, the latter of which are features to be cut out of the panels. These interior curves are sorted based upon the area and dimension of the cut out they describe. Only curves describing a certain user-defined dimension of material—in this case at least one foot on each side—are dealt with throughout the remainder of the script. This geometry is redrawn by grasshopper such that it can be resized, and the project data can be viewed in the form in which it was originally imported. Doing so allows for the user of the script to observe in real time the effect that minor changes in geometry can have on both building design and the efficiency of the nesting operations. The cut-out geometry is also arrayed flat on the XY plane as this is a logical location to perform nesting operations. The cassette stand geometry is both redrawn in its original location and oriented to the XY plane to maintain consistency. A plugin for grasshopper called OpenNest is then used to nest the cassette stand and corner brace features into the interior curves from the façade panels. Any geometry not able to fit into the waste material is specifically set aside such that the user notices and can resize geometry accordingly. After the nesting step, the remaining material is again sorted based on side length such that the amount of usable material leftover can be quantified, and its form observed. Within the Rhino interface, the percentage of façade panel considered to be waste based upon window cut out size is displayed as is the reintegrated waste percentage—thus providing the user with real time numerical feedback to accompany the visual feedback of the nesting operations.

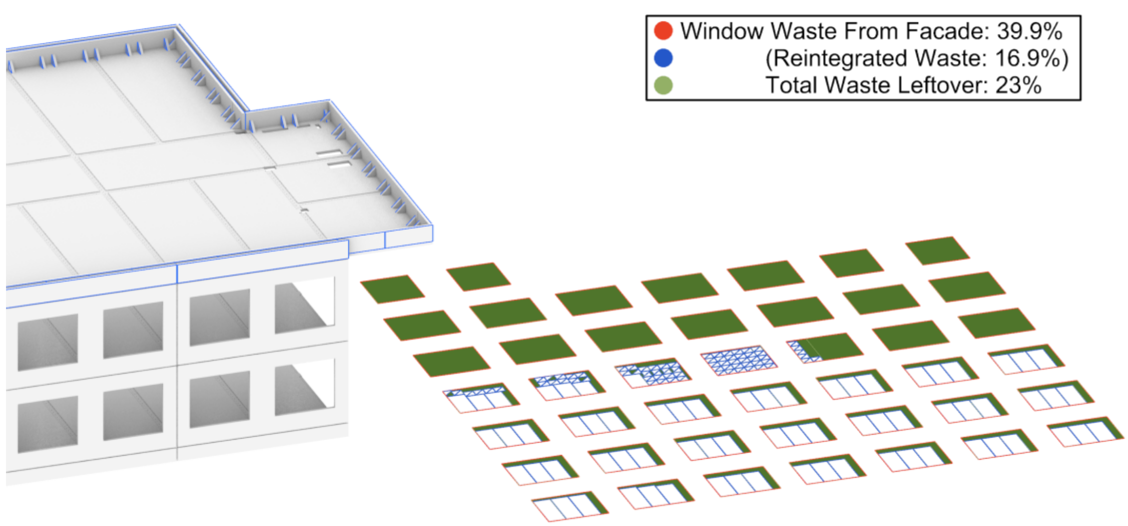


Figure 11: Option 1 (see below). The larger rectangles are the window openings, smaller rectangles are cassette stands, and triangles are the corner braces.

There is a tradeoff spectrum to be considered between architectural intent and waste utilization. If design intent is of paramount importance and the design of a building is left entirely untouched, that will likely lead to worse utilization of waste. Project features remain stagnant, and the problem is purely attempting to fit pieces into the available area. At the other end of the spectrum, however, is a project that puts waste utilization at the fore and allows for the design to be tweaked or even drastically changed to ensure that waste is used. Put another way: the puzzle changes shape to fit its pieces. This spectrum was explored with the case study Project, though when features were allowed to change dimension, this change was limited to plus or minus 10% to maintain architectural intent. This is a nesting exercise after all, not a redesign. Listed below are four options for implementation of this parametric nesting script, with progressively more design control:

Option 1: No change in architectural intent; the design features are locked. The cassette stands and corner braces are fit into the window openings as best as possible.

Option 2: Minor change in architectural intent. The cassette stand can increase or decrease in height, thereby providing the ability to fill out the window openings more accurately and save material from ending up as unusable.

Option 3: More change in architectural intent. Along with the cassette stand changing in height, the window openings themselves can change in both width and height, further minimizing the creation of slivers of material that can’t be used elsewhere.

Option 4: Maximal change in architectural intent. Along with features changing dimension, other project features not originally intended to be made from solid mass timber are called into question. Could stair treads be made from mass timber? What about kitchen islands? Retail infrastructure?

Below is a table listing each implementation option with the initial façade panel waste, the eventual façade waste after reintegrating some portion of it, a square footage of usable material leftover, and a visual representation of that leftover material. For each option, design changes were optimized to minimize eventual façade panel waste while ensuring that all cassette stands and corner braces were able to be fabricated. Option four included the fabrication of stair treads for four flights of seventeen stairs each, for a total of 68 treads that measure one foot by four feet. Optimization was performed with the Galapagos component of Grasshopper, which is an evolutionary solver that takes in any number of variables and can minimize or maximize a given output. As a base case, the “control” is listed and provides data for the case with zero waste reintegration. If the cassette stand and corner braces were to be fabricated from raw material from the manufacturer, four billets measuring 10’ by 20’ (the dimension of the raw billets to be purchased for the fabrication of each façade panel) would be needed. Even option 1, which has no change on architectural intent, eliminates the need to purchase this extra 800 ft^2 of material. Given that there simply isn’t a reason *not* to do this, just the very act of implementing any sort of intelligent nesting has a positive impact on the project’s bottom line.

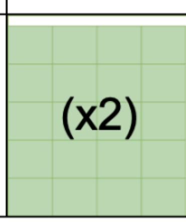
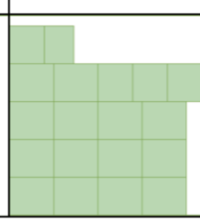
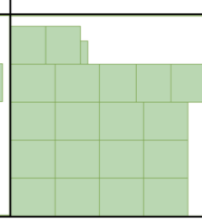
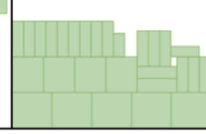
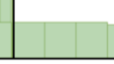
Implementation Option	Control	Option 1	Option 2	Option 3	Option 4
Design Change	—	—	Cassette Stand Height	Cassette Stand Height Window Width/Height	Cassette Stand Height Window Width/Height Additional Features
Initial Façade Panel Waste	39.9%	39.9%	39.9%	33.4%	33.4%
Eventual Façade Panel Waste	39.9%	23%	21.5%	15%	9%
Usable Material Leftover	1812 ft^2	748 ft^2	759 ft^2	475 ft^2	92 ft^2
Usable Material Leftover (form)					

Table 1: Waste Percentages per Different Implementation Options

As mentioned in the description of script methodology in Grasshopper, before implementation of any nesting operation the script dispatches with any pieces of waste material that are too small to consider using. These are pieces less than one foot long on a given side. These pieces are also excluded from the usable material leftover calculation. However, for the total waste percentage, all material was included in the calculation. That is to say that the usable square footage number doesn't equate to the waste percentage number. At some point it doesn't make economic sense to keep finding uses for smaller and smaller pieces. This specific Project didn't have any façade openings that were excluded to begin with, but as project features were cut from waste material, many pieces of timber were left in this category of "unusable." What exactly should be done with this timber is up for debate. The Company already has a plan in place for dealing with sawdust from their fabrication environment, so wrapping up this extra waste material into that scheme may be the easiest. But in keeping with the circular bioeconomy approach, the best option is the one that keeps the most amount of wood fiber intact. Similarly, the table above optimizes nesting solutions purely based on minimizing waste, without any thought given to the quantity of usable leftover material nor its form. But if specific use cases were found for certain sizes of mass timber panels that could be productized or used in some other intelligent way, the creation of this size of material could be prioritized. Goals for the script can very easily be shifted towards this end or any other.

What this Grasshopper script does first and foremost is to start a conversation between architect and fabricator. Option four includes stair treads and the optimized solution has the cassette standing increasing in height by 10% and the window decreasing in width by 10% and height by 6%. This may very well not be amenable to the architect, and concessions for more waste production may have to be made. Working towards minimizing waste is important but not at the cost of over prescription in design nor minimizing utility of a space in the building. This whole exercise is predicated on designers wanting to do *something* with waste. It asks the architect to use mass timber panels but also use them well to build incredible structures with varied design such that demand for the material is driven just by observation of the structure, thereby furthering the industry on the whole.

As buildings are very likely designed differently, it is expected that this script will have to be tweaked from project to project. While there is certainly some knowledge of Grasshopper required, it should be quite possible to use this script with any other mass timber project utilizing billets to their fullest extent. Future work should investigate the direct data stream from Revit into Grasshopper using Rhino.Inside. This would allow for implementation of this script from a very early design stage and therefore would provide architects with powerful feedback. With The Project, the cassette stand and corner braces were easy items to nest into waste material. Other projects may either have different features as nesting candidates or will necessitate the productization of waste material and as such be trying to nest different shapes into negatives created by design.

5. Conclusion and Next Steps

This research showed that with no change to the architectural intent of the building, the simple implementation of a nesting algorithm on a given mass timber project could cut façade panel waste nearly in half from 39.9% originally down to 23% post-implementation. It was then shown that a small adjustment of building features can have a large impact on the amount of waste created: by increasing the height of the cassette stand by just 10%, equivalent to only 2.5”, the waste can decrease by another 1.5% down to 21.5%. Even greater ability to change architectural intent, as exemplified by resizing window openings, can have a more drastic effect on waste creation in that dimensions of project features can be further entwined to maximize efficiency. And if further utility can be found in a certain dimension of leftover material post-nesting operations, that waste percentage can decrease even further.

The case study presented explored the concept of reintegrating project waste back into the same project from which it came. In doing so, the total volume of mass timber necessary to build the project can be minimized. This is done by finding smaller features that can be cut from small format mass timber billets. These unused pieces are created from openings punched in panels used in the building's exterior envelope and elsewhere. The different implementation options explored occasionally ask designers to give up a small bit of architectural intent to better utilize the waste that is created. However, none of the options try to remove the window openings from the project entirely. It is understood that these negative building features are both necessary and celebrated to fit the mass timber paradigm of fabrication and pre-assembly in a factory before delivery to the jobsite for a fast, waste free construction period of the building. If parametric design tools are employed at early stages of a mass timber project, relationships can be formed between these negatives and other positive features to create synergies of material use efficiency that allow for design flexibility. Pairing digital fabrication with parametric design techniques is key to unlocking the full potential of the mass timber panel.

The intent of this thesis is to show how mass timber can be fully utilized in a building while allowing for design freedom. If Architects start talking to fabricators very early on in the building design process, they can glean meaningful feedback about how their designs create waste. This work presents an avenue for closing the feedback loop in manufacturing for buildings. While common practice in other industries such as automotive and aerospace, given that this manufacturing step is so new to the construction industry this feedback loop simply hasn't yet found its footing. The ability to present manufacturing data paired with parametric design tools early on in design phases is a radical development. Both parties can undoubtedly benefit from that feedback to maximize material efficiency while still allowing for great design flexibility. While the focus of this research was on waste reduction, this approach could be leveraged to minimize cost as well, which speaks more loudly to developers and is the true enabler of industrialization in the architecture and construction industries.

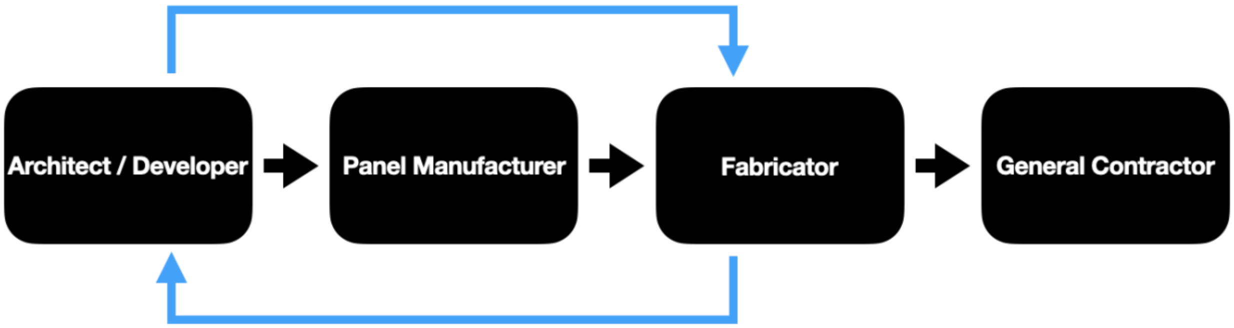


Figure 12: Closing the Feedback Loop

This investigation has led to several general thoughts on the mass timber industry. The first topic of interest concerns the use of CLT vs. MPP. The two panel products have similar strength characteristics, though if anything CLT is slightly more anisotropic (Soti et al., 2021). During manufacturing of the raw material however, the manufacturing method for MPP of peeling and laminating veneers is a much more efficient use of the log. Freres lumber claims the production of MPP is 20% more efficient than CLT, and the figure below argues the disparity is even greater. Why would we use a material in which a huge material inefficiency is a built-in consequence? CLT does have some aesthetic qualities over MPP, but appearance grade veneers can be applied over the top to make the two types of billets on par with each other.

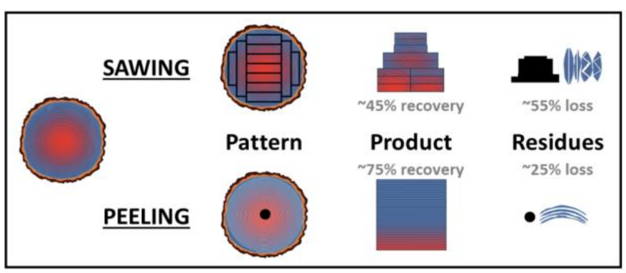


Figure 13. (McGavin et al., 2020)

The second and perhaps more important area of interest stemming from this thesis is innovating on the manufacturing processes for these mass timber panel products. This manufacturing should take full advantage of modern capabilities. At the moment, panel manufacturing is half-way there—at best. What if there was a way to incorporate wall openings into the press, such that when a billet was manufactured all the fabrication that was necessary was to trim up those openings and ensure they were square? This would require some advanced layup algorithms and the ability to place collapsible frames into billets that hold their shape while under extreme pressure during lamination. Further capital investment is required by the manufacturers and the development of tools like these would negate the need for the Grasshopper script created in this investigation. But taking the conversation around waste creation directly to the manufacturer would save material, time, and energy, while allowing for supreme flexibility with mass timber panel products. This would truly propel the industry forward into the future.

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