

Mass VeneerX: Multi-Performance Optimization of Veneer-Based Mass Timber Panels

by
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THESIS ABSTRACT

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Title: Mass VeneerX: Multi-Performance Optimization of Veneer-Based Mass Timber Panels

Veneer-based Mass Timber panels (MTP) such as mass plywood panels (MPP) offer a structural alternative to steel and concrete as both floor and wall systems. However, constant cross-sectional thicknesses are used due to both design and manufacturing limitations resulting in excess material compared to the structural needs of the panel. The high level of granularity in thickness when manufacturing larger components from veneer and plywood layers enables a yet to be utilized flexibility and tuning of a panels cross section to more precisely meet structural demands. Proposed is a hybrid additive to subtractive approach of designing and optimizing the use of wood fiber within panels at varying thickness. In this process, a thin base panel is augmented with veneer, plywood lamella, or MPP remnant material using polyurethane resin adhesive in a structural press and is then milled down in a subtractive process to reach the optimal geometry for the given design and loading conditions. A parametric shaping model and lightweight finite element analysis model pair with an optimization algorithm to balance fabrication constraints, serviceability, and volumetric reduction objectives to produce optimal geometries. Initial results show a substantial reduction in material is achievable using this fabrication and optimization method with the potential for increased material efficiency and fiber recovery within the manufacturing process through the strategic use of MPP remnant material as additive components.

This thesis includes to be published co- authored material.

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CHAPTER I
INTRODUCTION

1.1 Motivation

As populations grow worldwide, the built environment is expected to grow with it and the total global floor area of buildings is expected to double by 2060 [1]. With this increase in construction, using resources efficiently and effectively in an environmentally conscious way is imperative. Mass timber, a type of wood structural system, offers a sustainable, carbon sequestering alternative to typical building systems such as concrete and steel that are high in embodied carbon, accounting for about 15% of total global CO₂ emissions (Figure 1A) [1]. While mass timber is a better alternative, it too has inefficiencies in both its manufacturing processes and structural use. Within the manufacturing process of mass timber, a substantial amount of material is left as remnant which is typically chipped or burned for energy. In addition, mass timber often does not optimally meet structural demands with material placement, with some studies suggesting up to 66% of material goes underutilized in simply supported beam elements (Figure 1B) [2]. These issues describe a trend of material inefficiency, and as access to forest resources and wood fiber supplies continue to decrease, it is an important next step for mass timber to address these problems.

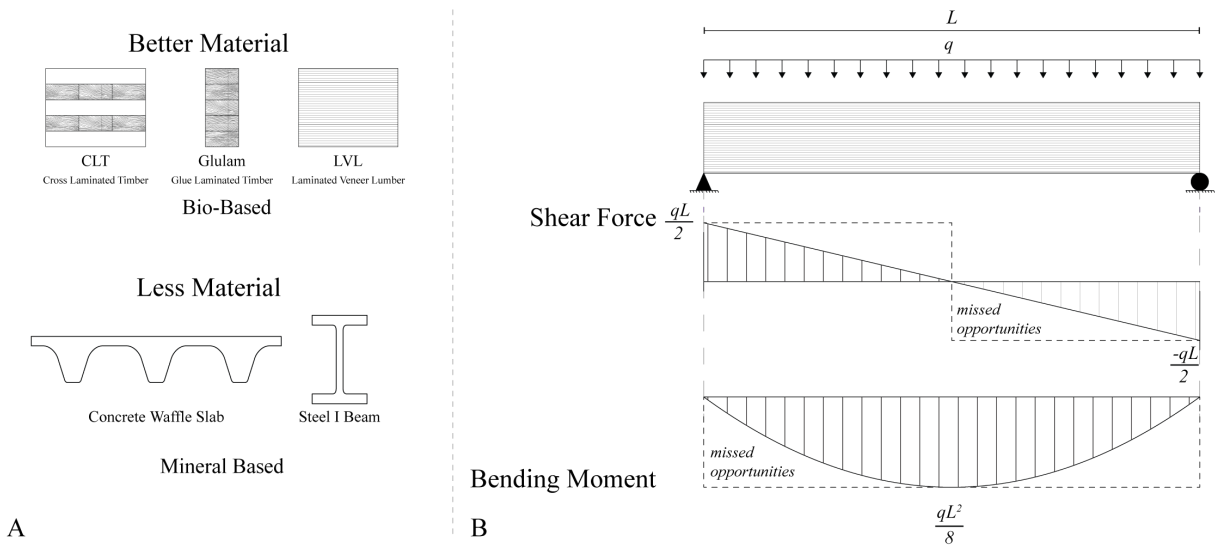


Figure 1. Opportunities for better and less material usage. A: Bio-based, better materials in mass timber, versus strategies of less material in mineral-based materials. B: Missed opportunities in timber elements in bending, adapted from [2]

1.2 Opportunity

A high volume of mass timber is used in panelized plate elements that layer dimensional or veneer lumber to form large cross sections, such as cross-laminated timber (CLT) and mass plywood panels (MPP). In typical mid-rise buildings, a major market for mass timber, floors account for roughly 40% of the total weight [3]. These plate elements often underutilize material relative to structural demand, leading to excess wood fiber use. This presents an opportunity to strategically place material only where it is structurally needed, reducing volume and improving efficiency.

Structural modeling can be used to identify load paths and guide material distribution [2], but shaping timber elements to follow these arrangements can become challenging. While shaping has long been explored in design, it often results in complex geometries that are difficult to fabricate at scale [4]. Subtractive fabrication methods such as computer numerical control (CNC) milling can achieve this level of precision but typically result in significant material loss. Additive methods, seen in veneer-based wood products, allow for finer control of material thickness by layering 1/8-inch veneer sheets. Used together, hybrid additive-subtractive workflows present an opportunity to fabricate structurally optimized, shaped timber plate elements efficiently and with minimized waste.

1.3 Research Question

These opportunities lead to the generalized question of how mass timber can become more material efficient. To most effectively target mass timber, plate elements used in floor and roof systems in both one and two-way bending systems are examined due to their high surface area and uniform sizing in standard usage [5]. Veneer-based mass timber panels (MTP) are targeted specifically for their precise control over wood fiber orientation and placement, giving them a high level of granularity. While this focus area spans multiple disciplines, the approach of this thesis seeks to develop an integrated process that could be adapted and refined within each discipline area. The overall goal is to leverage computational design to develop an integrated framework process that combines geometric design, lightweight structural analysis, and fabrication. With the development of a process the advantages are in adaptable applications and modular refinement to specific methods within the process. From this context the following research questions are developed:

How could a computational design process be leveraged to increase the material efficiency of veneer-based MTPs?

Leading to the following more specific research questions:

- How could shaped veneer-based panel designs be effectively fabricated?
- What are the material savings potential associated with the use of optimal designs in veneer-based MTPs used in bending systems?

1.4 Organization of Thesis

This thesis covers six chapters, (1) Introduction, (2) Background, (3) Scope, (4) Methodology, (5) Results, and (6) Conclusion. Chapter 1 provides a brief overview of the context of the thesis and general motivations of the research. Chapter 2 establishes background on mass timber systems, optimization principles, and related fabrication strategies. Chapter 3 identifies the detailed focus of the thesis and provides a more detailed contextual overview. Chapter 4 provides the methodology, covering the computational tools and workflows used to examine and answer the research questions. Chapter 5 presents the results of methods and studies presented in Chapter 4. The thesis concludes in Chapter 6 with a summary of findings and discussion of potential limitations, impact, and future work.

Chapters 1, 2, 4, and 5 contain adaptations of to be published co-authored material.

CHAPTER II

BACKGROUND

2.1 Mass Timber

Mass timber refers to an engineered wood product (EWP) in which smaller wood elements are adhered together via nails, dowels, or glue to produce large structural components. The most common mass timber products consist of laminating dimensional lumber or veneer in various configurations to form structural panels, posts, or beams. Although many mass timber products exist, this thesis utilizes veneer-based MTPs for their inherent material processing efficiency over lumber-based products, high granularity in material layup, and ability to utilize small diameter logs [6]. The overview in this section serves to outline the current state of the art of mass timber from forestry to market trends, providing essential context for the methods developed in this thesis and their potential impacts.

All mass timber products begin production in forests through growing and harvesting tree stands. Through sustainable forestry practices, logs or roundwood can be harvested in ways that maintain forest health, support biodiversity, and promote regeneration [7]. Certification programs such as the Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI) have helped establish protocols that ensure timber is sourced with minimal ecological disruption [8]. In the current climate crisis, this presents a sustainable method for producing wood building components able to sequester carbon and compete with concrete and steel. However, as demands grow on wood fiber supply and wildfires wipe out large swathes of forestland, wood fiber supplies can become limited quickly [9]. In addition, there is much dispute in federal policy over what percentage of federal forestland should be harvested, with current practices in Oregon limiting federally owned forests to harvest 8% of the total growth rate, whereas privately owned forestland is harvested at about 77% of the total growth rate [10]. In conclusion, while mass timber offers clear environmental advantages, limitations in wood fiber supply emphasize the importance of products and manufacturing processes that maximize material yield and efficiency.

The following will outline the manufacturing processes harvested roundwood goes through to become a veneer-based wood product. Once roundwood has been harvested from forestland it goes through disintegration processing of debarking and then veneer peeling in which 1/8-inch veneer is produced [11]. Veneer is then clipped into smaller sheets or plies and dried. Scanning technologies enable early visual grading of veneer for defects in this process [12]. Clipped offcuts from defective areas are recovered through veneer composing in which small pieces are joined together to form non defective full plies of veneer. After drying the veneer then goes through a lay-up process in which plies are laminated together in various configurations of cross and long grains to specified thicknesses depending on the component's end use. This enables the laminated veneer to have wood fiber in specified directions

according to the specific recipe used in the lay-up. Depending on the lay-up, this can be considered either plywood if the plies are alternating perpendicular to each other or laminated veneer lumber (LVL) if the plies are aligned in the same direction throughout. From here components or lamella are of a standardized 4 feet by 8 feet size and need to be processed again to produce larger structural components.

A notable producer of veneer-based products and mass timber is Freres, Lumber out of Lyons, Oregon. They produce mass plywood panels (MPP). In their manufacturing process, 4 feet by 8 feet sheets of 1 inch plywood utilizing layups of F-10 or F-16 are used in a proprietary process of scarf jointing, gluing, patchworking, and pressing lamella together to create large panel billets up to 24 inches thick, 12 feet in width and 48 feet in length. Freres can manufacture panels in width increments of 4 feet and depth increments of 1 inch. An F-10 lay-up uses 9 plies with every other ply being perpendicular to each other and an F-16 layup uses 9 plies of 3 long ply, 1 cross ply, 1 long ply, 1 cross ply, and 3 long ply [13]. Both F-10 and F-16 layups makeup 1-inch-thick lamellas, typical identification notation for panels is given with the layup ID followed by the inch increment thickness. Freres has certified both their LVL lamella and MPP products in accordance with The Engineered Wood Association (APA) standard for performance-rated cross-laminated timber (PRG 320) through product reports PR-L324 and PR-L325 respectively [14-16]. Life cycle analysis from WoodLife Environmental Consultants was also conducted leading to an American Society for Testing and Materials (ASTM) environmental product declaration (EPD) for MPP [17].

The bulky nature of MPP and all mass timber products creates a problematic scenario for easy job site modifications. All-major cuts are made on billets at the manufacturing plant or at specialized fabrication shops through CNC machinery [18]. Examples of this can be seen in various opening cutouts as well as panel trimming and are often referred to as billet utilization. A recent study in CLT production found that for every 1m³ of CLT produced 1.21m³ of CLT was required, indicating moderately low billet utilization [19]. This level of prefabrication in the manufacturing process creates efficient on-site construction, but it produces a large amount of remnant material waste without proper billet utilization that is not recovered within the manufacturing plant. In many cases this remnant material is of a relatively consistent shape and size, either rectangular or lineal. This creates a predictable stream of high value material, shown in Figure 2, which will be examined later.



Rectangular Remnant

Lineal Remnant

Figure 2. Remnant material of rectangular and lineal sizes from Freres MPP plant

After billets have been prefabricated, they are then transported to the jobsite for rapid construction. Typical structural applications for mass timber and MPP are in floor and roof plates for mid to high-rise buildings. MPP can be used in one-way and two-way bending systems with F-16 and F-10 lay-ups due to the difference in fiber orientation. For one-way bending systems MPP uses typical post and beam grids of 10 feet by 20 feet with F16-5 panels [20]. For two-way point supported bending systems MPP uses a typical column grid of 12 feet by 15 feet with F10-5 panels [21]. Current research at Oregon State University is validating usage of F10-6 panels for a column grid of 12 feet by 16 feet [22]. It should be noted that a large limiting factor in grid sizing is transportation constraints limiting panel widths as anything over 8 feet requires extensive permitting at both federal and state levels [23].

Costs associated with mass timber are different from other building materials as most of the cost is tied directly to wood fiber costs [24]. For comparison, in steel construction the number of pieces used is usually the cost driver and not the raw material itself [25]. In mass timber construction this makes choices of grid sizing and thicknesses of panels a direct driver of volume and costs. Veneer-based MTPs carry slightly increased costs over lumber-based MTPs due to increased processing needs but can match thickness requirements more accurately with their 1-inch lamella makeup, allowing them to compete.

Overall, mass timber is a sustainable, high-performance structural material with veneer-based MTPs such as MPP offering advantages in processing efficiency and fiber utilization. However, wood fiber supply limitations, inefficient billet utilization and transport-driven design constraints restrict the full potential of these systems. A major opportunity to counteract these issues lies in developing design and fabrication methods that reduce the volume of wood fiber needed for structural components.

2.2 Material Efficiency

Material efficiency is a broad topic, taking on different meanings depending on its context and application. In this thesis, material efficiency is approached through the lens of design and fabrication, by minimizing material usage while maintaining or increasing performance. This can also be thought of as optimization which aims to achieve the best outcome of an operation while satisfying constraint restrictions.

Structural optimization most often uses objectives and constraints such as weight, strength, and cost to calculate the best possible formal arrangement of material to a defined structural problem. While structural optimization is not a new topic, with its first origins beginning with Galileo Galilei's study of a cantilevered beam in 1638, new computational tools have drastically changed how it is approached [26]. Prior to computational tools, differential equations were solved analytically, significantly increasing the time and resources necessary to solve optimization problems and limiting the complexity of problems [27].

Advancements in computation along with increased software accessibility have made structural optimization more available for fields not directly acquainted with structural engineering such as architects and designers [28]. Integrating optimization into digital design is an emerging field aimed at achieving high levels of efficiency in the conceptual design phase of buildings. However, in building design many objectives are often at play when considering the performance of the design. Multi-objective optimization (MOO) provides a solution to this issue but also requires a careful approach to balancing complex objectives to find an optimal solution [29].

Rationalization of solutions is another common issue within structural optimization as geometric control is often lost leading to designs that cannot be fabricated. Shape optimization in contrast utilizes defined topologies to maintain control over optimized results [30]. With parametric control over defined topologies through Non-Uniform Rational Basis Splines (NURBS) based geometries and objective functions, an adaptive shape optimization model is achievable [31,32]. Mayencourt and Mueller's use of this methodology highlights the flexibility of the approach through the variation of the height and width of timber beams with an optimization objective function of material volume minimization while maintaining allowable stress conditions [33].

2.3 Emerging Technologies

Advancements in digital modeling and fabrication have led to a variety of program developments and workflows allowing for rapid iteration, optimization, and analysis of complex geometries while providing relative ease of fabrication. In digital modeling, a computer adaptive modeling software, Rhino paired with a visual programming software, Grasshopper creates a highly adaptable parametric design

environment [34,35]. With open-source capabilities, Rhino Grasshopper can integrate plugins for numerous purposes and functions. Karamba3D, a lightweight structural analysis plugin, allows real-time analysis on parametric models for comprehensive iterative workflows [36]. Opossum, a model-based optimization solver, allows for accelerated single and multi-objective optimizations through surrogate modeling, allowing for efficient computation times [37]. This allows for rapid testing of parameter iterations in models while trying to minimize or maximize set objective functions. Through the integration of these tools on one platform high levels of control over variables and objectives are achievable as well as analysis and recording of resulting data.

Advancements in manufacturing technologies have increased the potential for complex geometry fabrication, especially in wood-based products [38]. Primary methods for additive manufacturing in wood-based products revolve around primary actions of picking, gluing, placing, and pressing [39]. These tasks are easily learned or programmed for specific machinery or robots to execute at a high rate [40]. Primary methods for subtractive manufacturing in wood-based products utilize milling through CNC machinery or robots equipped with milling spindles. A major factor in CNC milling is the time some operations can take. However, new products like synchronized multi-head CNC machines can mill through the width of panels significantly reducing total milling time [41]. Robotic solutions for synchronized milling have not been employed yet in timber manufacturing, but similar setups to automotive manufacturing lines could be employed to increase milling efficiency. As technology continues to advance, these trends show it is not naïve to think mass customization or the fabrication of complex geometries at scale could be reached within wood-based manufacturing.

2.4 State of the Art

Current research on structural optimization and design through digital tools and fabrication methods has been largely focused in academia with emphasis on the reduction of material usage for reduced embodied energy consumption. In most cases the material focus is concrete, however the development of computational workflows offers applicability to other materials. CREATE SDU, has developed a framework for material optimization in 3D printed reinforced concrete beams and slabs [42,43]. In this workflow, a mixture of digital software is used to produce and test 3D printed concrete structures. ETH Zurich has also developed a variety of methods for structural optimization of concrete and masonry systems through the Block Research Group [44]. These studies focus on geometric form finding, material reduction through topological optimization, and digital fabrication methods.

In general, there is growing interest in the topic of material optimization for structural applications leading to more innovations in design and fabrication workflows. However, many of these

studies stem from novel approaches and lack consideration of how proposed systems may be implemented at scale to create a competitive building system.

Applications of structural optimization for shaping elements in mass timber is a limited field, however interest is growing along with the development of new fabrication and implementation methods for timber construction. Research at MIT via Digital Structures Research group has been a large contributor to structural shape optimization in mass timber [45]. In Mayencourt's Ph.D. dissertation *Mass Reduction: Opportunities for Structural Optimization Methods to Reduce Material Use in Mass Timber Buildings* methods are examined at optimizing timber beams and plate elements through geometric shaping, as well as how these systems could work together [46]. Here optimization methods for timber elements in one-way bending systems are presented, using numerical and analytical models in tandem to reduce computation time and increase the accuracy of results. Shaped timber beams alter cross sections throughout the beam to reduce material usage. For panel optimization in one-way spans Mayencourt suggests using a hollow core CLT system, taking out middle lamella layers in CLT to efficiently use material only where it is needed in a simplified topological optimization method.

Other research has been undertaken on topological optimization of mass timber, looking at varying configurations of CLT layups for efficient structures [47-49]. These approaches offer relatively novel solutions with high manufacturing costs and times due to the intricate nature of material placement.

CHAPTER III

SCOPE

3.1 Focus

Building from the defined background this thesis focuses on the development of a workflow that integrates structural, geometric, and fabrication-aware optimization for veneer-based MTPs. The thesis specifically targets plate elements in floor and roof systems, where high volumes of material and uniform cross sections present opportunities for improved efficiency. The study proposes a hybrid fabrication approach that combines additive layering with subtractive milling, enabling tailored thickness profiles based on structural demand. Using parametric modeling and multi-objective optimization, the research evaluates the potential of how shaped panel geometries can reduce material volume, align with existing fabrication technologies, and utilize veneer-based material streams. A series of digital case studies of comparative span analyses and implementation within standardized grid systems aim to demonstrate both performance potential and practical applicability of the developed processes and methods.

The scope of this study overall is to develop and evaluate a design-to-fabrication workflow that integrates structural shaping, material efficiency, and digital manufacturing for veneer-based mass timber panels. Many of the concepts examined represent fields of study outside the expertise of the researcher. Therefore, many concepts are approached through informed simplified models and pragmatic testing. The goal is not to solve every challenge within each domain, but to demonstrate how an integrated approach can open new possibilities for mass timber systems by using digital tools and methods strategically.

CHAPTER IV
METHODOLOGY

Portions of work from this chapter are to be published in the proceedings of the *World Conference on Timber Engineering (WCTE)* in June 2025 and in the proceedings of the *Symposium of the International Association for Shell and Spatial Structures (IASS)* in October 2025. Dylan Wood initially identified the opportunity for offcut-based panel fabrication and supported early conceptual development. Paul Mayencourt contributed to the initial development of the shaping model and optimization methods, assisting in adapting methods he had used on timber beams Erica Fischer advised on the refinement of the structural and optimization models and contributed to the framing of engineering objectives. Dylan Wood was the principal investigator for this work. I was the primary contributor in further developing initial methods and integrating models into a complete framework process.

4.1 General Methodology

In general, the methods for this thesis seek to develop a shape optimization model for veneer-based mass timber panels capable of integrating both structural and fabrication objectives to develop a solution space of geometries with high material efficiency relative to standard elements. This is achieved through a MOO routine, integrating geometric, structural, and fabrication objectives from shape, fabrication, and structural analysis models to generate a solution space (see fig. 3). To then realize

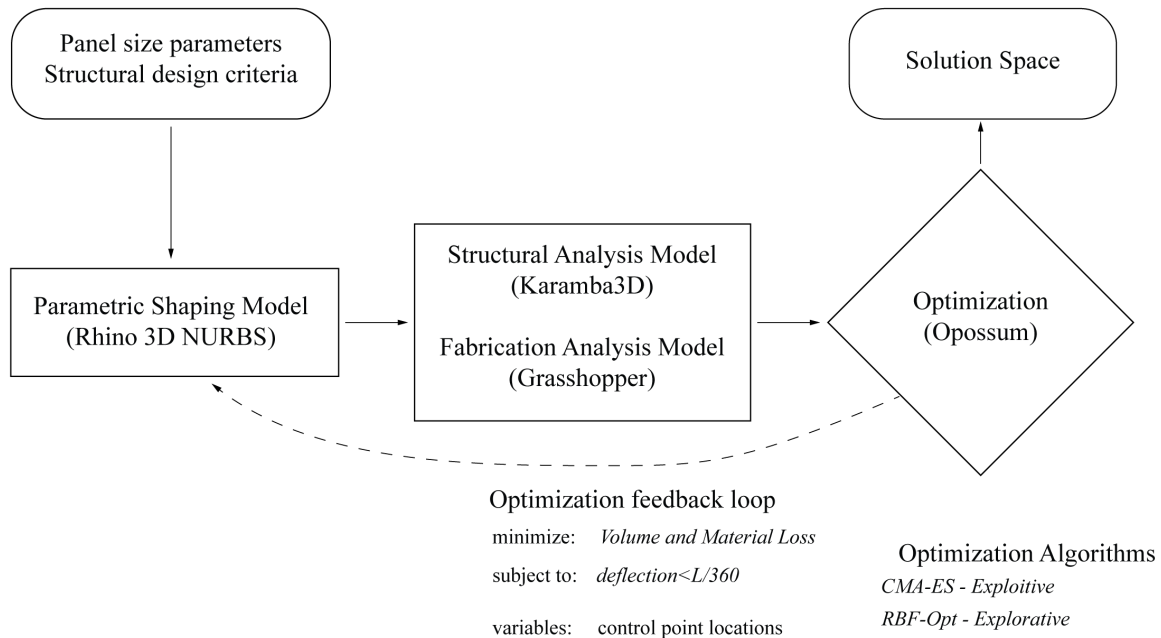


Figure 3. Outline of general methodology

solutions a hybrid additive to subtractive fabrication method is used. Limiting material waste or loss during the subtractive process is achieved through optimally placing and choosing additive material based on geometric features of shaped geometries, calculated through the fabrication analysis model. To understand how the MOO routine accounts for fabrication factors, the fabrication methods will be presented first. Testing of the fabrication methods was conducted at the A.A Red Emmerson Advanced Wood Products Laboratory on Oregon State University’s Corvallis campus. This facility operates in partnership with the University of Oregon through the Tallwood Design Institute, providing key equipment and space for testing fabrication methods [50].

4.2 Fabrication

To fabricate shaped panels a hybrid additive to subtractive method, depicted in Figure 4, is used following common practices used in veneer-based wood products manufacturing. The process begins with a base LVL or MPP panel to which additive veneer-based material is glued, placed, and pressed to, forming a workpiece. These processes could be adapted using various automation strategies to accommodate different additive material types, glue line configurations, material handling techniques, and pressing methods. After pressing, the workpiece is secured via fasteners or vacuum pods to a work holding fixture for subtractive milling. 3 and 5-axis CNC and robotic machining are both viable options for surface milling the workpiece. Both operations require computer-aided manufacturing (CAM) code, which is obtained from a digital model of the shaped panel’s geometry. Once the machinery is programmed it can then mill the workpiece resulting in a finished shaped panel. The difference between the additive material and final shaped panel geometry can be defined as waste or material loss and should be minimized. The overall goal of this method is to strategically place additive material to efficiently match the desired geometry and reduce the material loss incurred during subtractive processing.

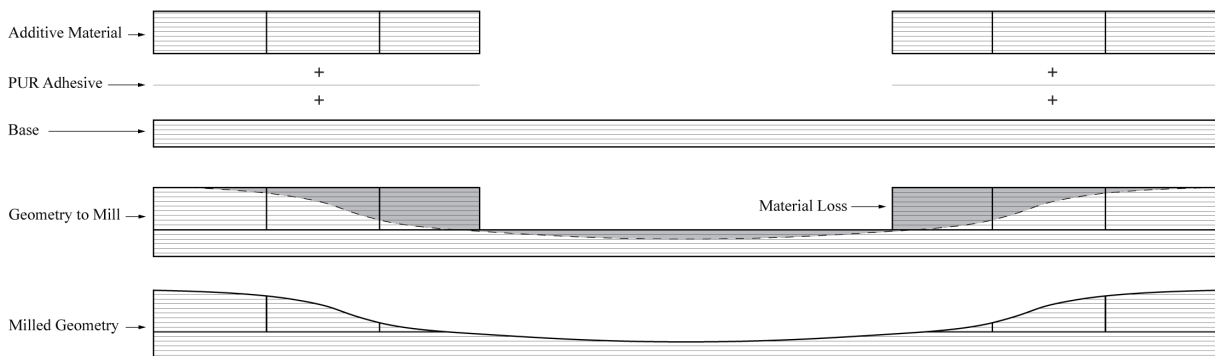


Figure 4. Sectional view example of additive to subtractive fabrication

With the selection of different types of additive veneer-based materials, veneer, lamella, or remnant, material loss and fabrication complexity are directly impacted. This stems from the geometric matching problem of the fabrication method, in which rectangular components of varying thicknesses are arranged to approximate a curvilinear geometry. Although all types could be subdivided into smaller components to precisely match geometry, the feasibility of doing so varies based on each material's level of granularity. In general, the more steps necessary to process material, the more complex the fabrication process will be, but material loss will be reduced. This inverse relationship is depicted in Figure 5.

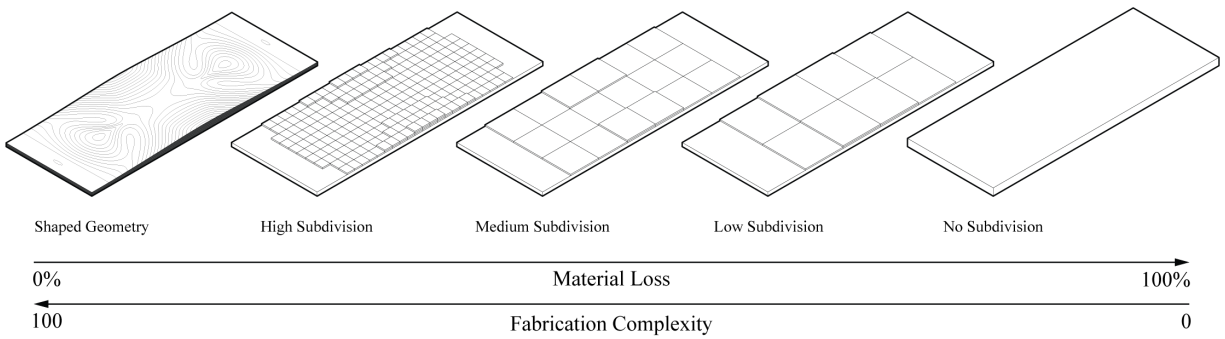


Figure 5. Inverse relationship between material loss and fabrication complexity

Veneer, produced in 4-by-8-foot sheets at 1/8-inch thickness, can achieve a high level of granularity due to its thinness and ease of cutting, enabling precise matching. However, this precision comes at the cost of increased fabrication complexity from the handling and adhesive application of each veneer layer. Inversely, remnant material, thicker and often derived from linear offcuts, has a lower level of granularity, less precise matching, but less fabrication complexity. Lamella, produced in 4-by-8-foot sheets at 1-inch thickness, provides an intermediate level of granularity, balancing precision and fabrication complexity. Figure 6 illustrates typical sizes of these material types.

These inherent granularity characteristics also influence how each material type is best used according to the desired shaped geometry. Coming in typical rectangular sheet-like sizes of small thicknesses, veneer and lamella are well-suited for filling rectangular surface areas with small variations

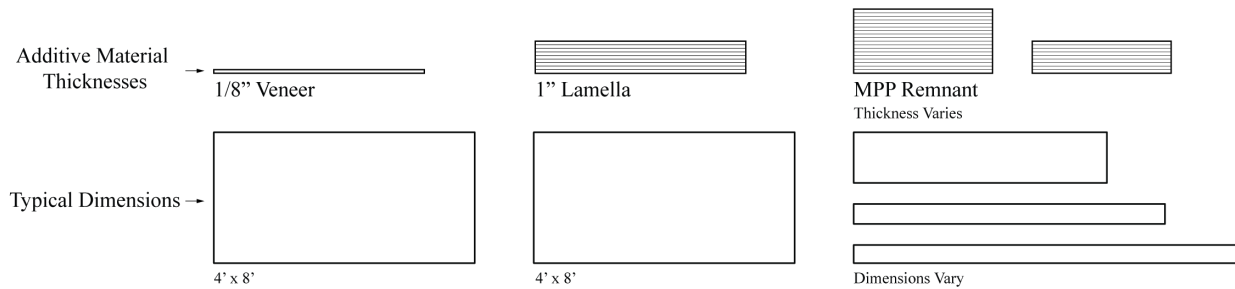


Figure 6. Veneer-based materials typical sizes

in thickness. Remnant material, coming in slender sizes with greater thickness, is more appropriate for filling lineal areas of consistent, larger thickness. By analyzing the distribution and continuity of geometric features within the shaped geometry, it can then be identified as better suited for fabrication with either sheet-based rectangular elements or lineal elements to minimize material loss and ensure a material efficient fabrication process (Figure 7). Later described methods for developing the fabrication analysis model will incorporate these concepts, allowing the digital model to predict the best type of additive material to use for a given shaped geometry.

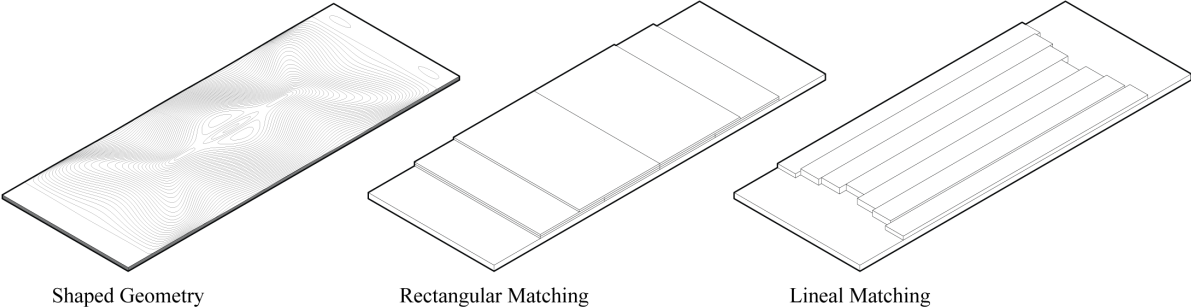


Figure 7. Application of rectangular versus lineal matching to a shaped geometry

Prior to this thesis, physical fabrication methods were tested using remnant material on a range of scales. Most notably a 10-foot by 17-foot shaped panel was fabricated and exhibited as a pavilion at the 2024 International Mass Timber Conference and is now exhibited outside Lawrence Hall on Univeristy of Oregon’s campus (Figure 8). From these early studies outside of the thesis, general fabrication methods



Figure 8. Pavilion exhibition completed for the 2024 International Mass Timber Conference

were explored, prompting further examination through the work of this thesis. Building on this, additional shaped panels were fabricated as part of this thesis utilizing the same methods.

The geometries of the shaped panels to be fabricated were chosen to test how material placement might affect fabrication and for later planned structural testing outside the scope of this. Three geometries were designed in Rhino 3D equating to differing ranges of material distribution with two of each being fabricated. These designs employed additive material of rectangular sizes, with another design selected for an individual panel employing additive material of lineal sizes. Base material consisted of 4-by-14-foot 1.5-inch-thick, 13-ply LVL rated at 1.9E. Additive material consisted of remnant F16 2-inch-thick MPP of a variety of dimensions. To fit the available lab equipment the base panels were trimmed to 10-foot lengths and the additive material was trimmed according to the design of the panel. Figure 9 summarizes the input material and associated geometry to be fabricated from it.

To connect the base and additive material, a PUR adhesive (Loctite HB X302) was used on face joints. Blank material was also cut to the inverse of the additive material and wrapped in shrink wrap to prevent adhesion and ensure evenly distributed pressure. The workpiece was then pressed together using a Minda TimberPress X225, following Loctite’s manufacturer guidelines [51]. After pressing, the workpiece was secured via vacuum pods to a work holding fixture for subtractive milling using a Biesse Uniteam 5-axis CNC equipped with a D30 router bit. The CAM code for the shaped panels was derived from Biesse’s B_Solid CAM software [52], with geometries imported from Rhino 3D.

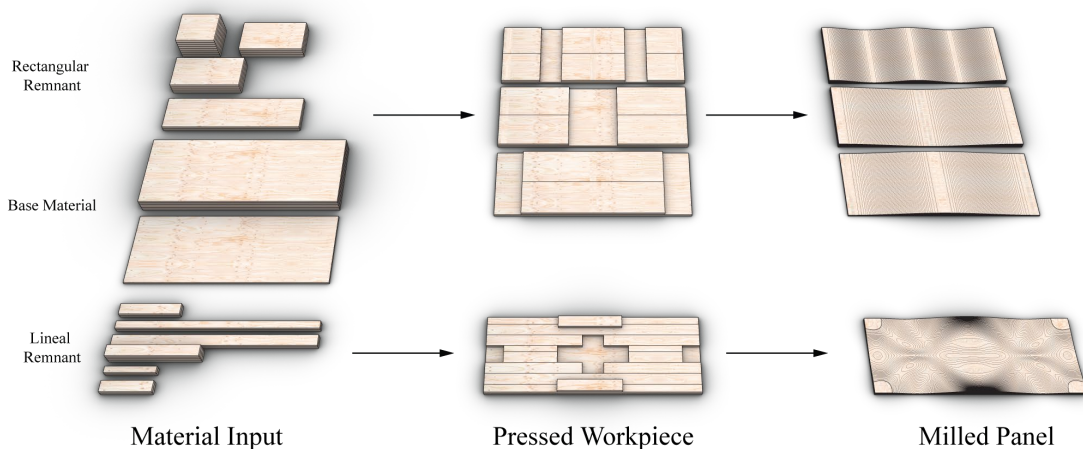


Figure 9. Geometries to fabricate from lineal and rectangular additive material

4.3 Multi-Objective Optimization

To obtain optimal shaped geometries, a digital workflow integrates Rhino 3D, Grasshopper, Karamba3D, and Opossum to form an integrated framework. Parametric geometry is defined in Rhino 3D and Grasshopper to form a shaping model, evaluated by a structural analysis model via Karamba3D and a fabrication analysis model defined in Grasshopper. Optimization is performed with the solver Opossum to minimize objective functions. The shaping model takes initial inputs of base panel size, additive material thickness, and structural design criteria of loading and boundary conditions to develop a basis for the parametric model. This framework, visually outlined in Figure 10, is designed to easily adapt to input criteria, with its modular nature suitable for future refinement of specific models.

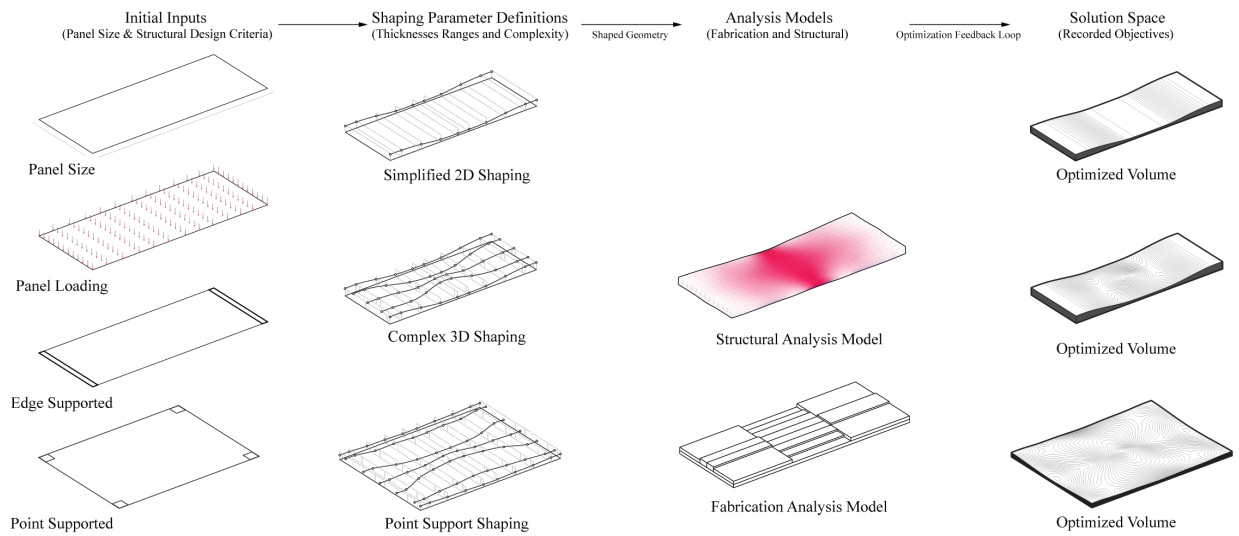


Figure 10. Visual outline of each stage of the integrated framework

Many different methods exist for constructing shaped NURBS based geometries based on a parametric model. An initial conceptual study tested three shaping methods, point-based, principal stress inspired, and control point curves to determine the most effective method for shaping panel geometries while avoiding long computation times. In these studies, optimization for volume minimization subject to defined structural design criteria was conducted, recording the time taken to reach optimal solutions. For each method parameter increments were also tested to understand how increasing the number of overall parameters affected computation time. Throughout these studies the method of control point curves showed to be the most effective, easily controlled, and computationally efficient.

Control point curve shaping works through a series of three-dimensional curves defined by coordinate points used to shape sections of the panel that then create NURBS geometry. First a quadrant of the panel is extracted to limit parameters and utilize mirroring operations over the center point of the panel. The quadrant is then divided along the x axis into a series of curves. Along the y axis the curves are

then populated by a series of points with z height positions defined through parametric variables. Specified range bounds constrain the lower and upper values of each defined variable and can be limited or set to fixed values to reduce specified axis movement within the model. Curves or points can be added or taken out in this method according to the desired complexity of the geometry. The points are then mirrored over the yz and xz symmetry planes. A curve is interpolated through each set of points in the y direction. A surface is then constructed from the curves. This works with the flat surface of the panel defined through initial panel size inputs to define the volume and shape of the panel through NURBS geometry. From these variables the height and directionality of the surface can be altered in an adaptable fashion (Figure 11). Input values from the available fabrication material thicknesses control the z height range variables of the points to ensure all possible geometries can be fabricated.

This shaping method can be further adapted to fit different scenarios where boundary conditions and preferred material arrangement vary. In the context of this thesis, it was utilized with a limited number of variables for two and three-dimensional shaping of one-way spanning panels with edge supports, and for three-dimensional shaping of two-way spanning panels with point supports.

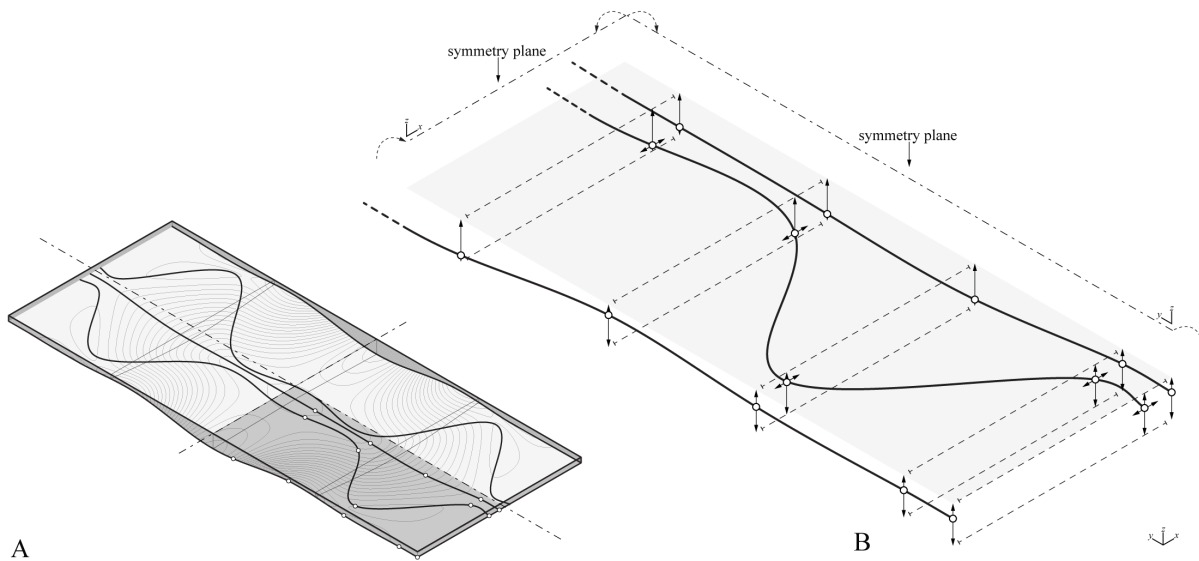


Figure 11. Shaping model for complex edge supported panel

Structural analysis is performed by Karamba3D with a simplified analysis to evaluate deflection as an indicator of meeting serviceability conditions. This is calculated through FEA of NURBS geometry defined through the shaping model. The NURBS geometry is simplified as a two-dimensional shell component model with shell element sizes defined by quad mesh divisions that Karamba3D automates into triangular shell elements [53]. Thickness heights for each shell element are applied using the values calculated from the NURBS geometry (Figure 12). Material properties, boundary conditions, and loading conditions are inputs to the model. Material properties were approximated using design values supplied by Freres [14,15]. The loading conditions can be easily altered through structural design criteria inputs. Boundary conditions can also be easily varied (from point supported to edge supported) to evaluate the deflection of the panels. The maximum allowable deflection is set to the length of the panel over 360 ($L/360$). The overall structural objective of the optimization is to limit the overall deflection to allowable ranges, guiding the solution space results, which be further analyzed by a more robust model. The implementation of this model is not meant to serve as a complete structural evaluation of geometries. It should be considered rather as a preliminary analysis of geometries using simplified assumptions to support early-stage design decisions, shaping a solution space that should be further verified using more robust modeling.

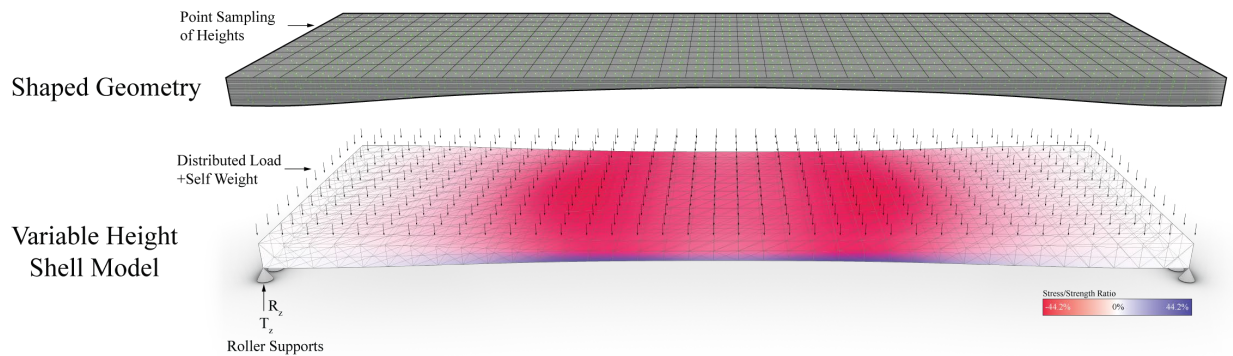


Figure 12. Conversion of shaped NURBS geometry to Karamba3D shell model

The NURBS geometry from the shaping model can also be used to approximate a fabrication model capable of estimating material loss and extracting geometric features indicative of the distribution and continuity of additive material. As described in the fabrication methods, this can be used to identify the best suited additive material type to use for a material efficient solution.

To approximate material loss the panel is subdivided into a rectangular grid with defined cell dimensions. To avoid long computation times and unrealistic evaluations a moderate grid size is used. Each cell's center point and relative point on the shaped surface is then found to determine the necessary height needed for each cell to produce the shaped panel. To account for additive material thickness, the height value is rounded to the nearest 1/8-inch or 1-inch increment depending on the size of desired additive material. The height is used with the grid cell's width and length dimensions to calculate the volume at each cell. A summation function then calculates the overall additive volume needed for the geometry. Subtracting the volume of the shaped geometry from the additive volume then gives an approximation of the material loss. Figure 13 illustrates this process.

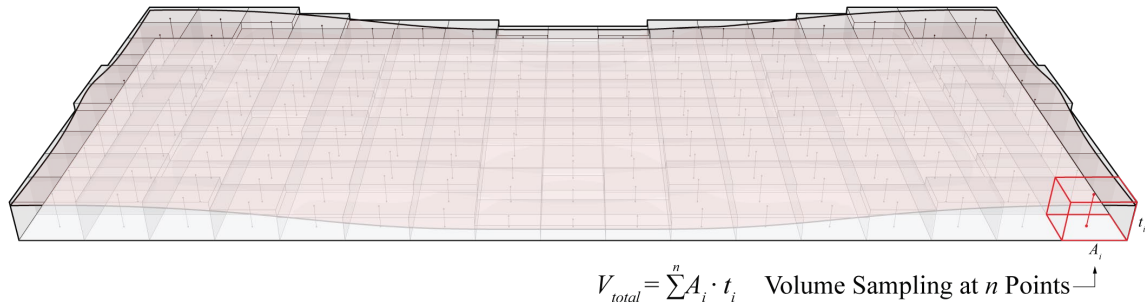


Figure 13. Material loss calculation from grid-based point sampling

To assess material distribution and continuity within the shaped geometry, two metrics are applied. Standard deviation is used to quantify variation in material thickness throughout the panel. Height values from each grid cell are used to calculate this. Low standard deviation equates to a shaped geometry with relatively even or sporadic distribution of material whereas high standard deviation equates to more concentrated zones of material. A spatial connectivity analysis is used to evaluate grouping and continuity to inform how the additive material is arranged. It works by filtering grid cell points by their height. This approximates the fabrication material above the base. Once these points are selected, an algorithm similar to the k-nearest neighbor algorithm selects groups of points based on a threshold distance derived from the grid cell size. From this analysis an output of the number of groups is given along with the approximate length to width ratio of each group. This indicates whether the material is in one contiguous region or in separate smaller regions as well as the proportions of each region. Overall, values from both the standard deviation and the spatial connectivity analysis can be used to predict what additive material type, rectangular or lineal, is best suited for the given shaped geometry (Figure 14).

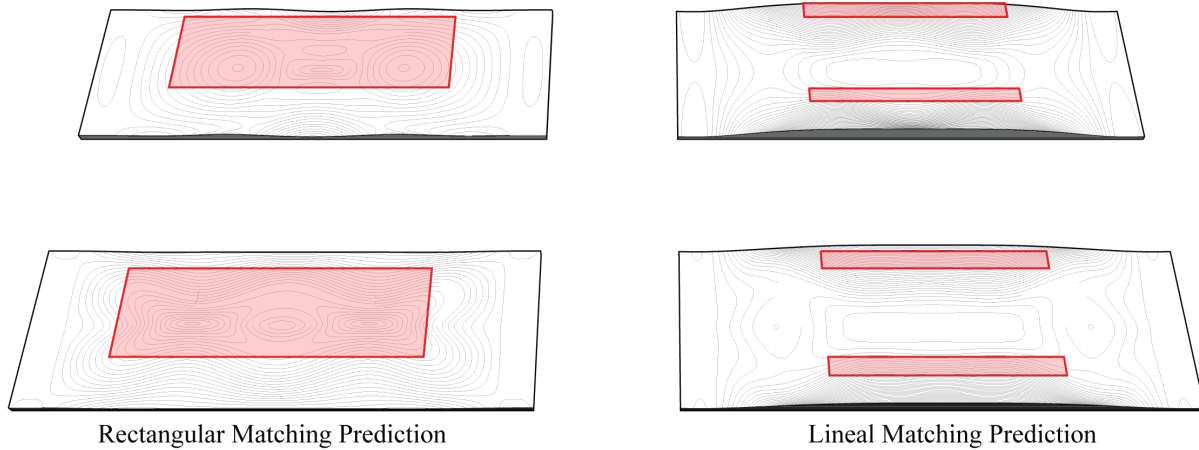


Figure 14. Fabrication analysis model predictions for different shaped geometries

Optimization is then performed by Opossum using variables and objectives from the shaping model, structural analysis model, and fabrication analysis model. With control over the shaping model's control point curve variables, Opossum has full control over the geometry. Objectives include material volume, material loss, and deflection. Deflection is implemented as a penalization function, as a minimization of deflection would result in the thickest panel possible. For deflections greater than $L/360$ a penalty value of 100 is added to the objective function allowing for easy identification of invalid solutions.

When both variables and objectives are provided, Opossum uses Radial Basis Function Optimization (RBFOpt) to construct surrogate models that guide the search for high-performing solutions by minimizing the objective function. This can be applied to single-objective functions such as minimizing material volume only, or to multi-objective problems, where the algorithm searches the Pareto front for optimal trade-offs, such as between material volume and fabrication loss. Unlike evolutionary methods based on metaheuristics, model-based optimization can more efficiently explore the design space by using machine learning to build and continuously refine surrogate models, improving prediction accuracy with each evaluation. However, Opossum also supports metaheuristic approaches, such as CMA-ES, which can be more effective in problems with more noise or high-dimensional search spaces. The choice between these methods depends on the complexity of the objective functions' solution space, the dimensionality of the problem, and the computational cost of evaluation.

As Opossum runs through iterations testing different input parameters from the variables to find minimal objective function values, a solution space is formed (Figure 15). Finding a range of solutions is advantageous as it gives designers more freedom to choose solutions that best fit the given problem and allows for different fabrication strategies. Objective function and parameter variable data are recorded

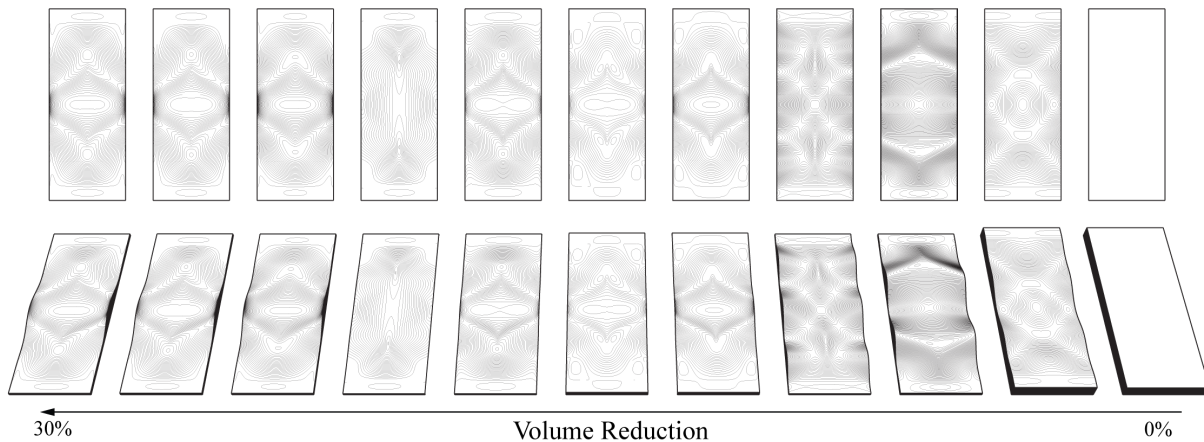


Figure 15. Example of range of results in the solution space

throughout this process along with values from the fabrication analysis model allowing for sorting and classification of the solution space. This also allows solutions to be reinstated by putting variables back into the shaping model to visualize geometries in the solution space.

4.4 Comparative Span Case Studies

To evaluate the effectiveness of the optimization methods in reducing material while maintaining structural performance, the comprehensive model was run for a variety of comparisons relating to the maximum spans achievable by regular MPP. The goal of these case studies was to find the material savings potential a shaped panel could reach compared to regular MPP. To quantify this savings potential, the volume to span area was recorded for each solution from the model and typical panel expressed in volume per area. To reduce computation time and find only the best possible savings potential only the single objective optimization function was used for these studies, but values were still recorded for all objectives. This enabled the sorting of results based on the best material loss minimization achievable within solutions with minimum values of material volume. The following will describe the model setup for one-way spans using both a simplified and complex shaping model and for two-way spans using a shaping model adapted to point support constraints (Figure 16). For all studies a load case of 40 pounds per square foot plus the self-weight of the panel was used.

For one-way spans the model was compared to maximum spans of F16 MPP at 40 pounds per square foot ranging from 3-inch thick to 8-inch thick (Table 1). A panel width of 8 feet was used, representing a common size used for mid-rise buildings. The simplified shaping model consisted of eight total curves defined by three variables, limiting the shaping to only the z direction on the panel. The complex shaping model consisted of five total curves defined by fifteen variables allowing shaping in all

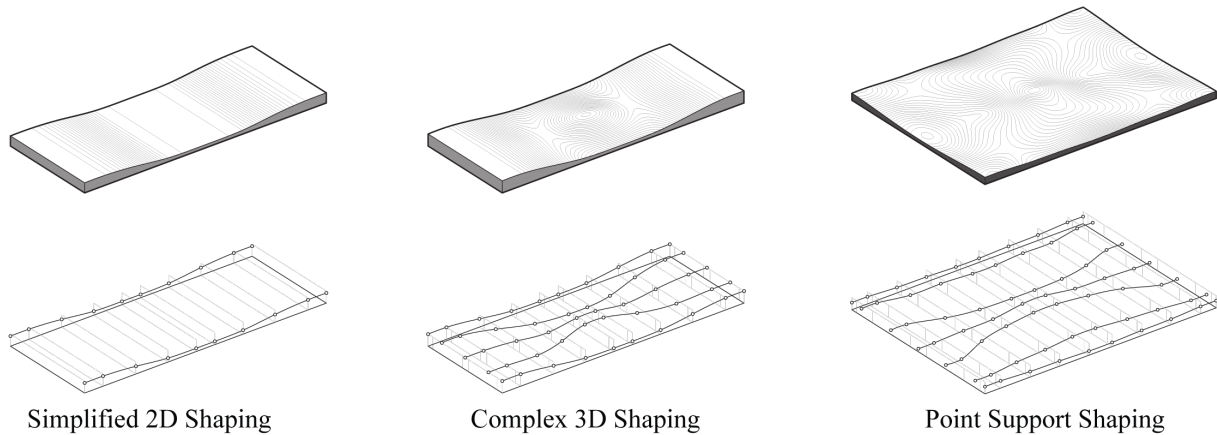


Figure 16. Shaping models used in comparative span case studies

directions. For the simplified model, the RBF-opt algorithm was used with 2000 iterations for each case. For the complex shaping model, the CMA-ES algorithm was used with 2000 iterations for each case due to the noise from the number of variables.

Table 1. Freres F16-3 – F16-8 maximum spans at 40psf

Layup ID	Thickness (in)	Max Span in Major Direction (ft)
F16-3	3	12.00
F16-4	4	15.80
F16-5	5	19.44
F16-6	6	22.97
F16-7	7	26.43
F16-8	8	29.76

For two-way spans the model was compared to maximum spans of F10 MPP at 40 pounds per square foot ranging from 3-inch thick to 6-inch thick (Table 2). The panel width for this case study ranged from 7-12 feet. The shaping model consisted of seven total curves defined by twenty-two variables. The increase in variables is due to a more complicated boundary condition of point support being implemented in the shaping model. The CMA-ES algorithm was again used with 2000 iterations.

Table 2. Freres F10-3 – F16-6 maximum spans at 40psf

Layup ID	Thickness (in)	Max Span in Major Direction (ft)	Max Span in Minor Direction (ft)
F10-3	3	9.41	7.36
F10-4	4	12.28	10.74
F10-5	5	15.18	12.00
F10-6	6	17.90	12.00

4.5 Implementation Case Studies

To explore how shaped panels could interact with typical grid systems, the comprehensive model was adapted to fit standard rectilinear bay configurations in both one-way and two-way spans. For one-way spans, a grid of 10-by-20 feet was examined and for two-way spans a grid of 12-by-16 feet was examined (Figure 17). The material savings were evaluated based on comparison to F16 5-inch MPP and F10 6-inch MPP respectively. In addition, the potential for increasing the performance or span of the panel through shaping was also examined. The goal of this study was to again evaluate the material savings potential while also examining the architectural implementation and potential of the shaped panels to form different spaces relative to regular MPP.

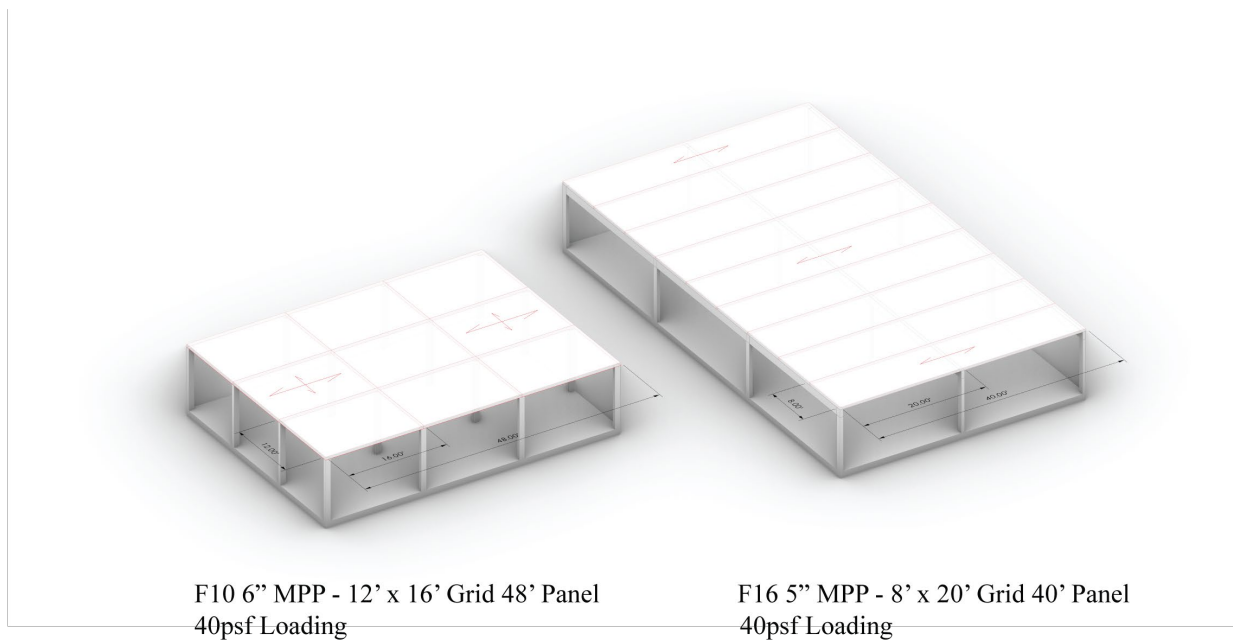


Figure 17. Typical grid layouts for MPP in one- and two-way spans

CHAPTER V

RESULTS

Similarly to Chapter 4, work from this chapter is to be published in the proceedings of the *Symposium of the International Association for Shell and Spatial Structures (IASS)* in October 2025. Dylan Wood identified initial opportunities for fabrication methods. Paul Mayencourt contributed to the initial development of the shaping model and optimization methods. Erica Fischer advised on the refinement of the structural and optimization models. Dylan Wood was the principal investigator for this work. I was the primary contributor in physical fabrication and in running case studies through the framework identified in Chapter 3.

5.1 Fabricated Samples

The production seven panels produced for this thesis (Figure 18) serve as proof of concept for an automated workflow and implementation in high volume manufacturing. Manual production made it obvious that utilizing commonly used machines like glue lines, robotic handling, and conveyors could significantly speed up the production process. A key finding was also in the simplicity of using additive material of rectangular sizing to cover more area as opposed to smaller lineal sizing. This confirms the relationship between fabrication complexity and material processing times. However, most of the overall time spent on production was in the pressing and milling of the panels, suggesting the complexity of the additive material layup is not the limiting factor in production time. The pressing time was dependent on

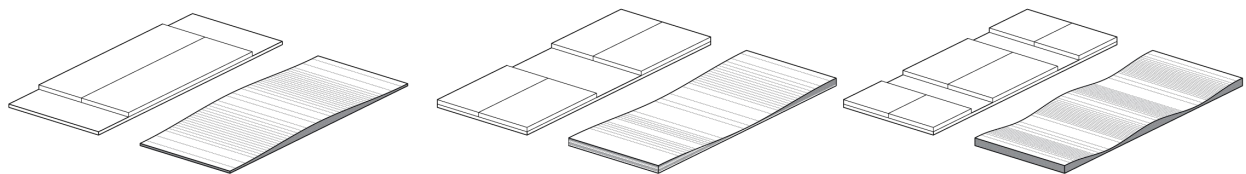


Figure 18. Fabricated panels from rectangular additive material

the glue type used. For this study using a PUR based adhesive decreased the press time to just under two hours, but other adhesive types could lengthen this time considerably. In the milling, the effectiveness of the additive material's matching to the shaped geometry directly affected the time taken for milling as some areas needed multiple passes. This was exacerbated as the software had limited control and required full panel area passes, resulting in milling air for much of the time, taking about three hours per panel. All panels will always require at least one tooling pass over the entire surface of the geometry, but in theory, the time could be significantly reduced with more aggressive tooling heads, multi-head approaches, and a more refined tooling path.

The surface quality from the milling also produced interesting results with the tool head's slight curvature producing unique qualities. For two panels milled with only three axis machining this produced a feather like pattern, whereas panels milled with five axis machining produced a line-like pattern, exposing the layers of veneer within the panel (Figure 19). With parameters in the milling process like the spacing of passes, and tool head diameter, the surface quality could be altered to meet specific design requirements but could result in longer milling times.

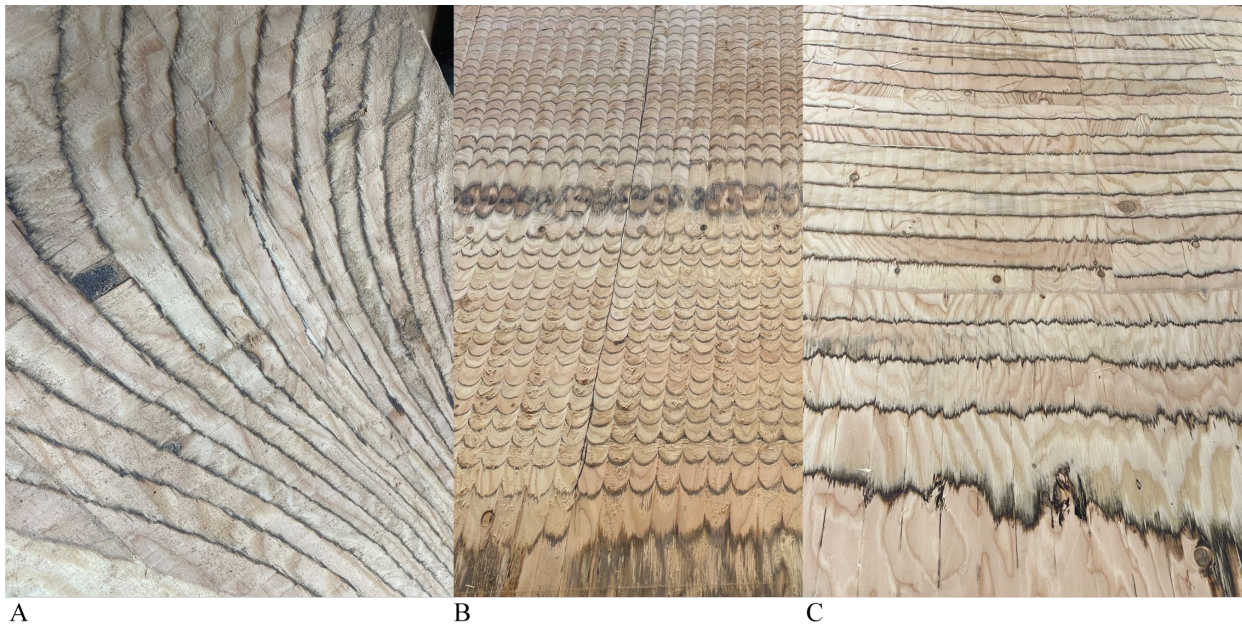


Figure 19. Surface quality finishes. A: 5-axis milling of complex geometry. B: 3-axis milling of simplified geometry. C: 5-axis milling of simplified geometry

5.2 Comparative Span Case Studies

Across all case studies, most solutions exhibited an increase of material around the areas with highest stresses. In most solutions this resulted in clusters or concentrated areas of material about the center point or long edges of the panels. This follows intuitive structural logic but, in some solutions, it becomes clear that the mechanical properties of the model are not quite robust enough to consider areas where shear becomes the governing factor. This is most likely due to the use of a simplistic shell model with limited performance for composite materials. For example, some panels exhibit very thin portions where rolling shear failure would likely occur. To counter this, a more robust model could be swapped out within the digital workflow, or the best performing solutions could be further analyzed to check the results. Regardless, the scope of this thesis is aimed at exploring design solutions with the idea that perhaps not all solutions are perfect but rather indicative of where the design of mass timber systems could get to with further development and the leveraging of digital tools.

The results from the simplified one-way span shaping model indicate a material savings potential of around 10-15%. Solutions shown in Figure 20 further show the model's preference for placing material about the center point of the panel. Solutions from the simplified model are particularly interesting for their ease of fabrication. For some of these solutions a shaped panel could be fabricated by adding a relatively small amount of material to the center of the panel. As an example, for a F16 4-inch thick MPP panel at a span of about 16 feet, a F16 3-inch thick MPP panel could have a small amount of material added to the center to match the performance, effectively upgrading the 3-inch panel to a 4-inch panel. When considering doing this with remnant material this could also carry economic advantages for manufacturers in that they could recover wood fiber and sell a higher-grade product.

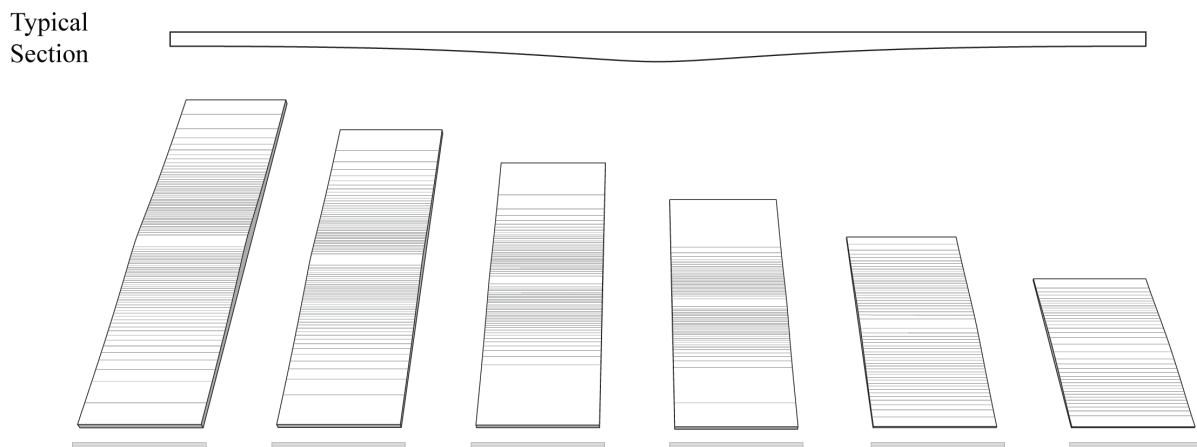


Figure 20. Results from simplified one-way shaping model, percentage values indicate volume reduction compared to typical F16 MPP

From the complex one-way span shaping model, a material savings potential of about 20-30% was reached. Like the results from the simplified model, most solutions concentrate material towards the center of the panels. Solutions exhibiting this arrangement had volume reductions in the 10-20% range. With more freedom the model also finds solutions with material concentrated to the long edges. These solutions are similar to edge stiffened slabs seen in concrete design where beams are essentially built into

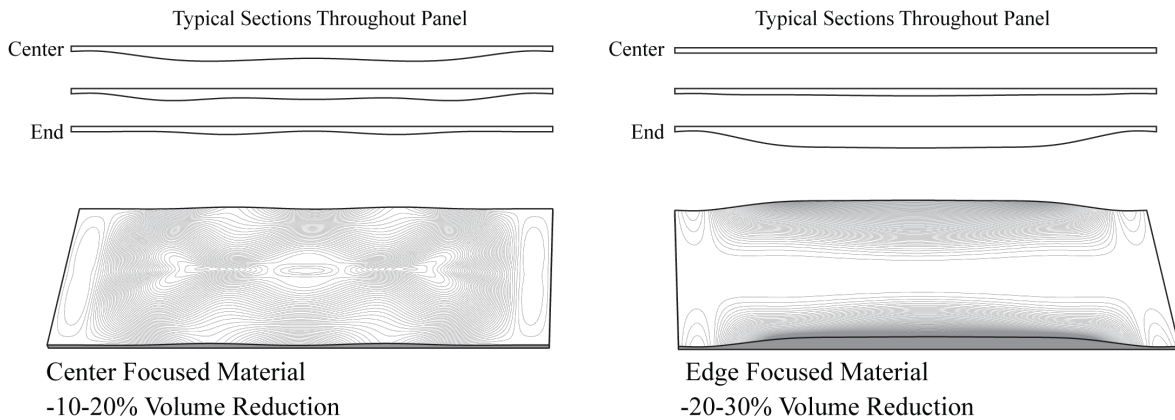


Figure 21. Typical solution types from the complex one-way shaping model. Typical sections show differences in material distribution throughout panels,

the panels. Another comparison is to a CLT ribbed composite slab where adhered glulam beams act as stiffeners to a thin CLT plate [54]. Volume reductions of up to 30% were found for solutions with this arrangement of material. Figure 21 exemplifies typical geometries for the differing solution types.

Similarly to upgrading panels in the simplified model using rectangular additive material, in this case lineal additive material could be used to increase performance.

Results from two-way span shaping allowed for greater freedom of altering the volume, resulting in an increase in potential savings at 30-45%. Material placement for most solutions was focused about the center point and support points, with some solutions having more sporadic and localized concentrations of material throughout the panel (Figure 22). With more complex structural behavior there is also more room for error in the model indicating areas for further examination and improvement. While the material savings are promising, they may partially reflect modeling assumptions or simplifications that warrant further validation. Overall, the results show slightly less predictable material placement, with more expressive shaping than the one-way spanning models.

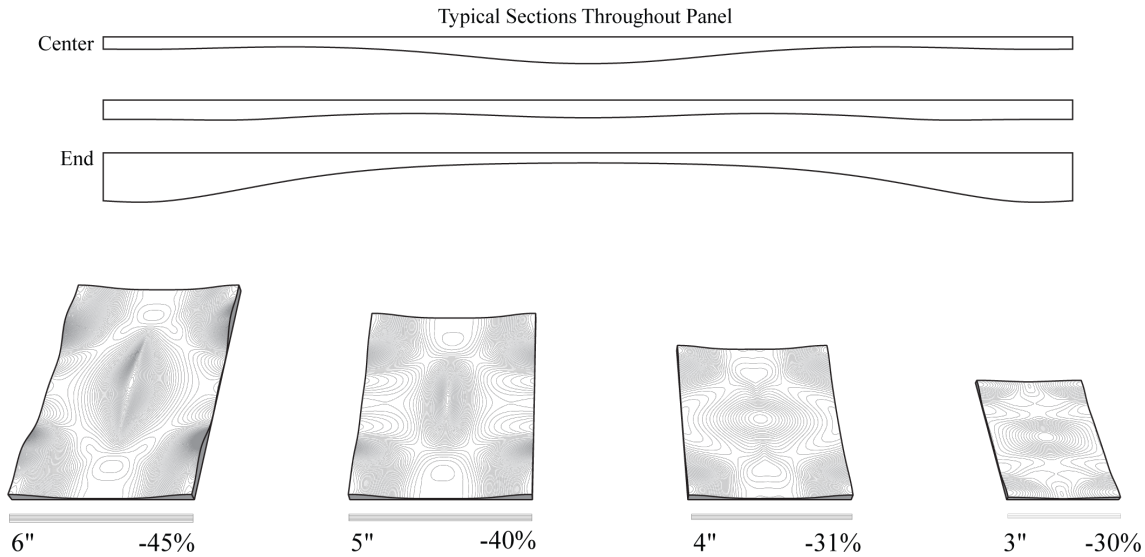


Figure 22. Results from point support shaping model, percentage values indicate volume reduction compared to typical F10 MPP

5.3 Implementation Case Studies

For typical F16 5-inch MPP a span of about 20 feet can be achieved with transportation constraints limiting the width of the panel to 10 feet for practical usage. This leads to a typical grid of 10-by-20 feet with panels of 40 foot in length being utilized. Other factors like the intended spatial function of the building are also contributors to desired grid sizes. In fitting shaped panels in one-way spans to this grid, the overall volume was reduced by about 30-32%. The increase in material savings in this case can be attributed to the change in boundary conditions to a continuous spanning panel. Freres produces panels in billet sizes of 48 feet in length; by increasing the performance of the panel through the optimization framework, results indicate a 5-inch-thick panel could reach a span of 48 feet, utilizing the entire billet size (Figure 23). This increase in performance through an increased span shows the potential of the methods when used to increase performance as opposed to only volume reduction.

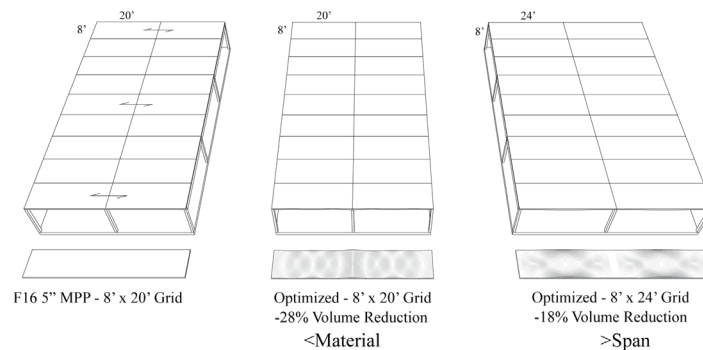


Figure 23. Optimized panel usage in F16 5'' MPP typical grid layout for impact of less material or greater span

Two-way spanning point supported grids in mass timber construction offer more flexibility in spatial arrangement with the elimination of beams, and greater fiber utilization within panels. Current limitations are mainly due to a lack of reinforcement strategies for punching shear at columns and overall limited experience with the system by industry and design codes [55]. The implemented shaping model allows for an opportunity to address the high-stress zones near columns while reducing unnecessary volume elsewhere. Through these localized increases in thickness, the overall height of the space is varied, creating a unique spatial experience from an architectural perspective. Similar to the span comparison, a volume reduction of about 30-45% was reached. Solutions presented in Figure 24 exhibit more moderate volume reductions and show the potential for panels to fit to a typical grid or increase spans. While the point support cases are more aggressive in their assumptions, they serve to illustrate the potential of point-supported mass timber and how it might develop new directions in design. Figure 25 presents an early concept design of how a point support system could work in a mid-rise building.

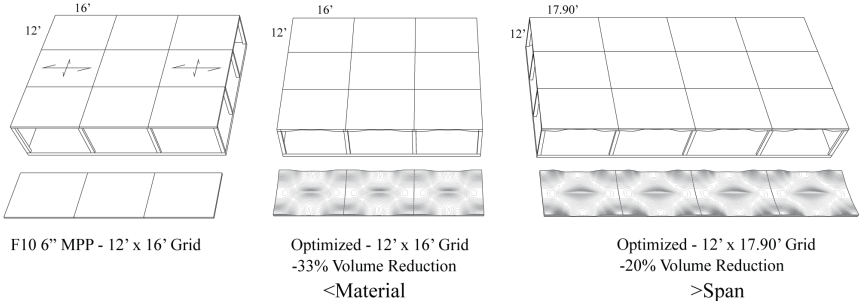


Figure 24. Optimized panel usage in F10 6" MPP typical grid layout for impact of less material or greater span

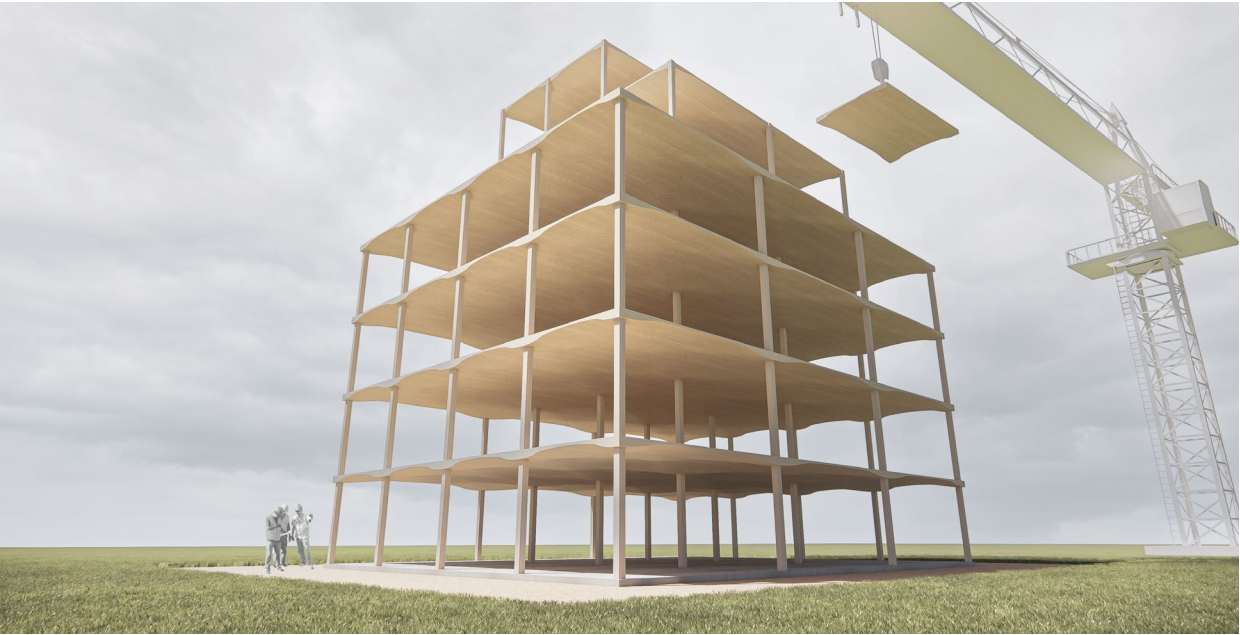


Figure 25. Conceptual design of optimized panels used in point support construction

CHAPTER VI

CONCLUSION

6.1 Summary

This thesis presents a multi-performance optimization framework for veneer-based mass timber panels using hybrid additive-subtractive fabrication. Through the integration of parametric shaping, lightweight finite element analysis, and fabrication-aware optimization, the study explores new possibilities for improving material efficiency in timber plate elements. Veneer-based products were chosen for this approach due to their high level of granularity, offering a number of strategies to fabricate complex geometries using common industry practices.

Through digital case studies an indication of the potential for the framework was examined. Case studies conducted across common MPP spans indicated potential for material savings, depending on complexity and boundary conditions. One-way spanning panels achieved potential material volume reductions of 10–30% depending on shaping complexity, while two-way panels demonstrated potential savings of up to 45% under point-supported conditions. Implementation studies on typical grids showed not only how optimal designs could be used for volume reduction but also highlighted the possibility of increasing performance to achieve longer spans. Fabrication tests confirmed the early-stage viability of constructing shaped panels using veneer-based products, examining associated advantages and disadvantages with different types of additive material.

Together, these findings address the research questions posed in this thesis. First, the study shows that computational design could be effectively leveraged to increase the material efficiency of veneer-based mass timber panels through the development of a multi-performance optimization framework incorporating a number of relevant variables and objectives. Second, it demonstrates that these shaped designs can use industry adjacent processes for effective fabrication. Lastly, the case studies quantify the potential for material savings across different span types and building conditions. While specific methods require more robust development, the framework presented provides a foundation for more sustainable, efficient, and customizable mass timber systems.

6.2 Limitations and Future Work

The contributions of this thesis have primarily centered around the development of a multi-performance optimization framework and proof-of-concept fabrication method. Several limitations exist in these developed methods. They do not dismiss the results but instead highlight areas where further refinement and robust validation are needed. Important next steps include refining the structural and

material modeling methods, expanding the considered design constraints, and conducting full-scale structural testing.

The structural analysis model used requires robust validation. While the Karamba3D shell model is sufficient for identifying general trends in material distribution and deflection behavior, complex behaviors may not be adequately captured, especially with complex materials like wood composites. Refining this model or replacing it with a more detailed one are potential routes for future work. Material properties should also be validated, with potential for much development as veneer-based products can alter significantly with their layup.

While many design constraints are considered in the optimization framework, key components missing are connection and fire design. While geometry flattening roughly accounts for panel connections at supports, more development could occur in panel-to-panel connections. Similarly, fire design is roughly considered through allowable minimum thicknesses in the optimization framework but should be further refined.

Overall, these limitations frame the work as an early-stage design and fabrication method intended to provoke further research and development in the field. Future work will need to address these issues to bring shaped veneer-based mass timber panels into broader use within practice.

Further opportunities also exist for future work, especially surrounding acoustics, vibration, lighting, and air quality. These areas for future work relate mostly to the shaped surface formed by the panels, creating a vastly different condition from typical flat ceilings. The shaped ceiling surface introduces spatial and material variation that can influence how sound is absorbed, how vibrations propagate through the structure, and how light is reflected or diffused. Air quality may also be affected due to the exposed wood fiber at each veneer. These opportunities point to the potential of shaped panels as multi-functional architectural elements capable of actively contributing to the environmental and experiential performances of interior spaces.

6.3 Impact

The work presented in this thesis offers a contribution to advancing material efficiency in mass timber and opening new opportunities for architectural design. By integrating computational design, structural optimization, and fabrication-aware modeling into a single workflow, the project shows how architectural, and engineering goals could be aligned to use fiber effectively and unlock new design potentials. From a design and architectural standpoint, the shaped panels developed through this methodology introduce expressive geometries, unique surface finish qualities, and possibilities for increased grid spans.

From an industry perspective, the hybrid additive-subtractive fabrication method is grounded in existing practices, making it feasible for near-term implementation. The process introduced through the framework of the thesis enables the use of a variety of veneer-based wood products through a recomposition method. This provides an intelligent way to recombine veneer-based products, further advancing the general concepts behind common engineered wood products like plywood. Integrating digital and computational tools with this process allows for the potential of even more efficient wood products. In addition, it offers an avenue for upcycling wood products. With the use of remnant material, manufacturers could effectively recover fiber while producing high performing products, offering economic incentives. The overall framework could also be adapted to different industry products for remnant recovery as the issue is prevalent across MTP prefabrication and manufacturing. The adaptability of the framework is a key highlight of the thesis and aims to provide a more refined perspective on mass timber manufacturing.

As timber continues to gain momentum as a low carbon building material, increasing its material efficiency is essential for scaling its use while protecting limited wood fiber resources. The multi-performance optimization framework presented provides a holistic approach to developing solutions for material efficient timber systems that are both ecologically responsible and architecturally expressive.

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