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Waste Utilization Panels – Design optimization for geometry, structure and material in mass plywood panels additively constructed from offcuts

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ABSTRACT: Mass Timber panels represent a growing sustainable design and structural alternative to steel and concrete as both floor and wall systems. However, mass timber panels made from cross-laminated timber or mass plywood panels, are typically produced in standardized rectilinear volumes with continuous thickness due to both design and manufacturing constraints, resulting in excess material compared to the structural needs of the panel. In this research, we propose an additive approach to designing and optimizing the use of fiber and material volume in a mass plywood panel constructed from thin base panels combined with rectilinear offcut remnant material. A parametric shaping model with simple fabrication constraints is combined with structural optimization to determine the best material placement, adding depth and directionality to the thin plate. Preliminary results in the design phase show a dramatic reduction in material can be achieved by utilizing an existing typology of linear offcuts. Structural testing is planned to verify the stiffness of the geometrically optimized panels.

KEYWORDS: mass plywood panels, shape optimization, material efficiency, upcycling, cross laminated timber

1 – INTRODUCTION

Geometric design and manufacturing constraints lead to material and performance inefficiencies in mass timber panel (MTP) products. In cross-laminated timber (CLT) and mass plywood panels (MPP), geometries are defined by rectilinear volumes with continuous cross-sectional depth throughout. This manufacturing constraint results in excess material beyond what is needed to resist structural demands. Additionally, in the fabrication process the trimming of MTP master panels and cutouts for openings creates a large and consistent resource stream of excess, high value, engineered remnant material (Fig. 1) that is typically discarded or burned for energy [1]. This paper summarizes ongoing research that uses an additive fabrication approach in which a thin, standard production MPP panel is augmented by the addition of rectilinear MPP remnant material to add structural depth in areas and directions of the panel that are needed in specific structural applications. The arrangement of the added material is determined through a computationally light-weight multi-objective optimization (MOO) routine using plugins Karamba3D and Opossum, within Rhino 3D's visual programming environment, Grasshopper [2,3,4,5]. A focus on fast computation time and flexibility is prioritized over an intensive structural analysis to both incorporate remnant material geometry and application-specific parameters and objectives. Through this method a design solution space with many iterations of desirable solutions is achieved, allowing for the matching of various sizes of remnant material. Overall, this multi-objective approach has the potential to reduce the cross-sectional material needed and material needed in production by strategically reinforcing the panel with remnant material from within the MPP manufacturing process effectively making a Waste Utilization Panel (WUP).

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A B

Figure 1. A: panelised MPP remnant material type B: rectilinear MPP remnant material type

2 – BACKGROUND

2.1 Material Efficiency

Material efficiency has become an increasingly popular ideology, with recent studies examining both how fabrication processes can become more efficient and how waste can be integrated into the fabrication process or upcycled [6]. The additive construction of more extensive, purpose-specific blanks is also a well-known method used in woodworking and experimental projects. Several panel systems now consider alternatives to the classic solid CLT, with the incorporation of beams, topping slabs, and other materials as structural reinforcement for thinner MTP slabs [7]. In parallel, panel design and the optimal placement of material in mass timber products have been investigated in digital studies and laboratory scale tests [8,9]. These studies show challenges in applying material optimization models in manufacturing and to panel geometries with lower aspect ratios. These challenges represent a significant opportunity for material savings in mass timber construction. In terms of waste material reuse, many current studies are aligned with niche or small-scale resource streams and unique specialty applications [10], whereas our research investigates an existing and consistent stream of remnant material with high material properties and no current sustainable use.

2.2 MPP

MPP is a MTP product manufactured by Freres Engineered Wood. The production process begins with 3.18mm veneer sheets peeled from logs which are then laminated into 25.40mm plywood panels, which are further laminated into MPP of varying thickness. MPP inherently offers a high level of material efficiency relative to other MTP products due to its makeup through veneer [11]. In addition, veneer-based processes incorporate material recovery processes such as veneer composing. However, this early material recovery process is not replicated later in the prefabrication process where a large amount of material can be lost in panel trimming, cutouts, and offcuts. The geometry of the remnant material is tied to project demands but is largely rectilinear creating a predictable stream of material of relatively consistent sizes and proportions.

2.3 Shape Optimization

Many tools and methods exist for structural optimization; however, a common issue occurs in the rationalization and geometric control of optimized results [12]. Shape optimization in contrast utilizes defined topologies to maintain control over optimized results. 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 [13]. 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 [8,9].

3 – PROJECT DESCRIPTION

This research investigates an additive fabrication approach to designing and optimizing MPP for structural application and material usage. The process additively integrates remnant material onto a thin base panel (Fig. 2). The added material is then subtracted through Computer Numerical Control (CNC) milling to reach a geometry defined through multi-objective optimization.

The first section details the testing of additive fabrication methods for MPP using remnant material. Testing was conducted at the A.A Red Emmerson Advanced Wood Products Laboratory on Oregon State University's

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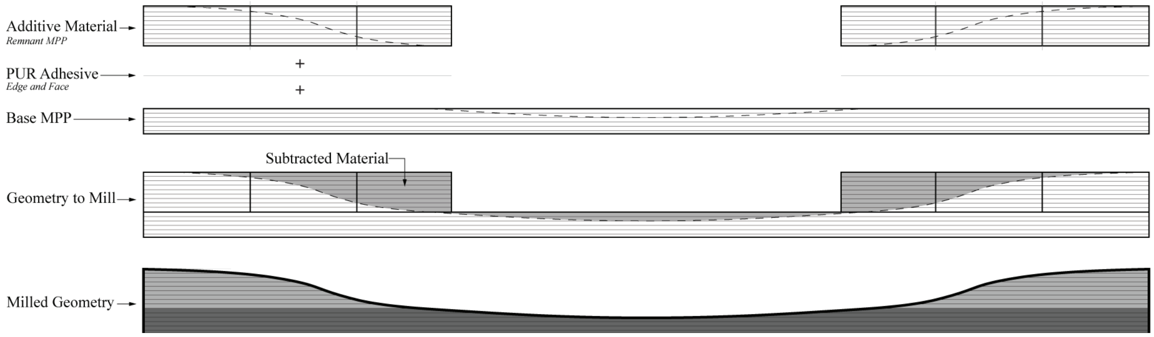

Figure 2. Sectional view example of additive fabrication

Corvallis campus. This facility operates in partnership with the University of Oregon through the Tallwood Design Institute, providing key equipment and space [14]. A range of scales were tested to examine the feasibility of this approach.

The next section describes the MOO routine methodology for geometry shaping, structural performance, and material minimization in MPP panels. In this approach Rhino 3D and Grasshopper are used to define a parametric shaping model analysed with Karamba3D. Opossum then uses objectives taken from the parametric model and Karamba3D to solve for solutions with minimal material volume while ensuring structural serviceability.

The last section examines the usage of the MOO routine for a range of geometry aspect ratios from 1:1 to 1:5, under a load case of a distributed load of 1.5kN/m2 and self-weight. To ensure the congruency of the optimization workflow with the fabrication methodology a 1.22m by 2.44m test panel was produced.

4 – EXPERIMENTAL SETUP

4.1 Additive Fabrication Methods

WUP panels are additively manufactured from a base MPP panel and MPP remnant material. To connect the base and remnant material, a PUR adhesive (Loctite HB X302) is used on both face and edge joints where applicable. The workpiece is then pressed together using a Minda TimberPress X225, following Loctite's manufacturer guidelines [15]. For geometries requiring additive material of different heights, multiple pressing sessions may be required. After pressing, the workpiece is secured via fasteners to a work holding fixture for milling. 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 geometry. Once the machinery is programmed it can then mill the workpiece.

To validate this method several geometries were fabricated (Fig.3). A range of scales were selected as the project developed, increasing in scale as methods became more refined. For all cases, the geometry chosen was designed to mimic an optimized form, but no optimization was conducted to reach these forms. The MPP base panels varied from 25mm to 76mm thick and remnant material varied from 51mm to 178mm thick and was sourced directly from Freres remnant material. A mixture of CNC and robotic milling was done using a Biesse Uniteam and Kuka KR-120. These cases spline together multiple base panels to achieve a larger panel width due to transportation constraints.

4.2 Digital Workflow

To obtain optimized geometries, a digital workflow integrates Rhino 3D, Grasshopper, Karamba3D, and Opossum. Parametric geometry is defined in Rhino 3D and Grasshopper to form a shaping model, structural analysis is conducted using the finite element analysis (FEA) plugin Karamba3D, and optimization is performed with the solver Opossum. This framework is designed to easily adapt to both fabrication and material constraints, allowing the incorporation of specific types or configurations of remnant material into the shaping model and optimization routine. The shaping model illustrated in Fig. 4 takes initial inputs of panel size, remnant material sizes, and structural design criteria to

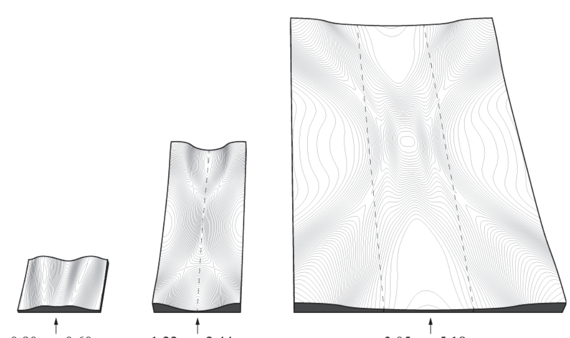

Figure 3. Additive fabrication test cases

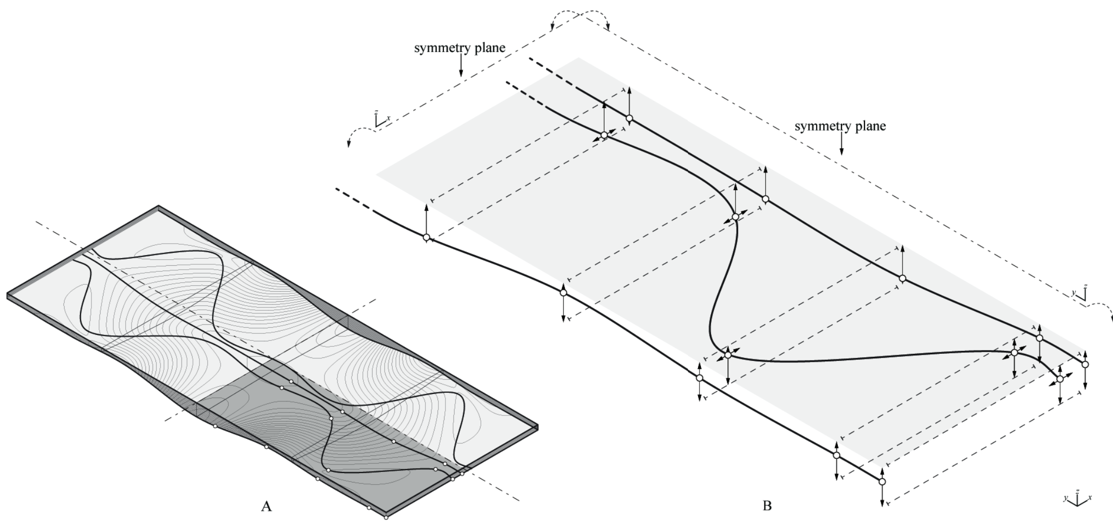

Figure 4. Constructed geometry and shaping model. A: surface lofting through mirrored curves to construct geometry with quadrant darkened. B: shaping model point position variable bounds and curve interpolation within quadrant.

develop a basis for the parametric model. In this model the maximum and minimal thicknesses for the panel geometry are calculated based on input fabrication material sizes. To shape the geometry a series of three-dimensional curves defined by coordinate points are used to shape sections of the panel. First a quadrant of the panel is extracted from the geometry to limit parameters and utilize mirroring operations over the center point of the panel, shown in Fig. 4A. The quadrant is then divided along the *x* axis into three curves. Along the *y* axis the three curves are then populated by a series of five points with *z* height positions defined through parametric variables. The middle curve is also defined by parametric variables along the *x* axis. Specified range bounds constrain the lower and upper values of each defined variable. Arrows in Fig. 4B indicate how coordinate points are defined to move based on variable input. The points are then mirrored over the *yz* and *xz* symmetry planes shown in Fig. 4B. A curve is interpolated through each set of points in the *y* direction. A surface is then lofted through the curves. This works with the top surface of the panel defined through initial panel size inputs to define the volume and shaping of the panel. From these variables the height and directionality of the surface can be altered in an adaptable fashion. Input values from the thickness of fabrication constraints control the *z* height range variables of the points to ensure all possible geometries can be fabricated.

Structural analysis is performed by Karamba3D with a simplified analysis to evaluate serviceability conditions (deflection and element utilization). This is calculated through FEA of the 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 [16]. Thickness heights for each shell element are applied using the values calculated from the three-dimensional geometry. Material properties, boundary conditions, and loading conditions are inputs to the model. Material properties were approximated using design values supplied by Freres [17]. The loading conditions consisted of a distributed load of 1.5kN/m^2 and the self-weight. Specified loading conditions can be easily altered through structural design criteria inputs. Boundary conditions varied (from point supported to edge supported) to evaluate the deflection of the panels. The maximum allowable deflection for the panels was L/360 and the maximum element utilization was 100%. The structural objective of the optimization was to limit the overall deflection and element utilization of the panels.

Optimization is performed by Opossum using variables from the parametric shaping model and objectives extracted from the NURBS geometry and structural analysis. With control over the shaping model variables, Opossum has full control over the geometry while maintaining fabrication constraints defined through the range bound values set in the shaping model. Objectives include material volume obtained from the NURBS geometry and deflection and element utilization from the Karamba3D analysis. When both variables and objectives are input into Opossum it uses radial basis function optimization (RBFOpt) to create surrogate models to guide the search for good solutions based on the minimization of the given objectives (Fig.5). As opposed to evolutionary optimization using meta-heuristics this model-based approach can more extensively map out good solutions. To aid in expediting this process the structural objectives are filtered for serviceability with penalty functions before being input into the optimization model. For deflections greater than L/360 and element utilization greater than 100% a value

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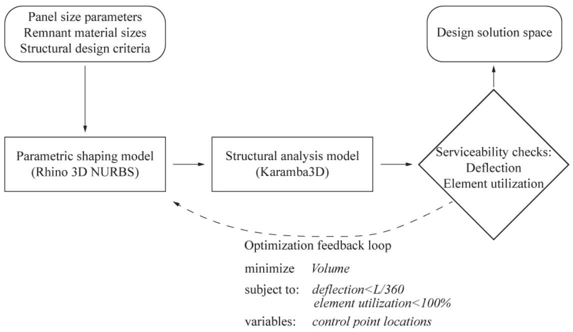

Figure 5. General optimization methodology

of 100 is added to the objective function allowing for easy identification of invalid solutions. As Opossum runs through iterations testing different input parameters from the variables to find minimal objective function values, a design solution space is formed. Objective function data and parameter variable data are recorded throughout this process allowing for sorting through the design solution space and reinstating solutions.

4.3 Aspect Ratio Case Study

To test the digital workflow and determine volume reduction savings for optimized panels, a series of panel sizes were put through the optimization routine for 2000 iterations. Panel sizes represent aspect ratios listed in Table 1. These relate to typical spans achieved by typically manufactured single cross-section thickness MPP slabs under a load case of a distributed load of 1.5kN/m2 and self-weight [18]. Boundary conditions of both point supported, and edge supported were used for each case. The typical slab depth is used along with the panel dimensions to determine the volume optimized panels will be compared to for volume reduction percentage calculations.

Table 1. Case study aspect ratios, sizes, and typical MPP slab depth for defined span (y size)

Aspect ratio	*x* size (m)	*y* size (m)	Typical Slab depth (mm)
1:2	1.22	2.44	77.79
1:3	1.22	3.66	103.19
1:4	1.22	4.88	130.18
1:5	1.22	6.10	155.58

To ensure the congruency of the digital workflow and additive fabrication methods a 1.22m by 2.88m optimized test panel was produced following the methods outlined in the previous section. Material thicknesses of 38mm and 51mm were used for the base panel and remnant material.

5 – RESULTS

The first iterations of the WUP have shown the viability of a digital fabrication workflow using actual MPP remnant material from Freres manufacturing plant in Lyons, Oregon. The cases shown in Fig.3 fabricated in the winter of 2023- 24, demonstrate the viability of the manufacturing workflow and its scalability as no major complications arose throughout their production. The larger 3.05 m by 5.18 m panel, part of a pavilion design for the International Mass Timber Conference 2024 and currently exhibited outside on the University of Oregon’s campus, showcases the aesthetic qualities of the WUP system and its potential as a structurally efficient panel with reduced material usage (Fig. 6). The panel achieves a volume reduction of approximately 30% compared to a typical 127 mm thick panel. Although structural testing was not conducted, the panel’s successful assembly and installation suggest promising performance characteristics that warrant further analysis.

Initial results from the aspect ratio case studies of the digital workflow demonstrate the capabilities of the WUP and its adaptability to incorporate fabrication constraints along with performance objectives to generate a design solution space with a sizable reduction (20-60%) of volume compared to panels with a single height cross-section (Fig.7). It should be noted that volume reduction is highly dependent on project parameters and structural design criteria for the panel. In cases using edge supported boundary conditions a volume reduction of 10-30% from a typical panel volume was achieved while cases using point supported boundary conditions achieved a volume reduction of 20-60% from a typical panel volume.

Using the digital workflow to produce and fabricate an optimized 1.22m by 2.88m panel further validated the feasibility of a pipeline of optimized geometries to fabricated panels. Throughout the fabrication process for the optimized panel the adaptability of the digital workflow proved a key asset. This was especially useful

Figure 6. WUP pavilion on 127mm MPP base slab

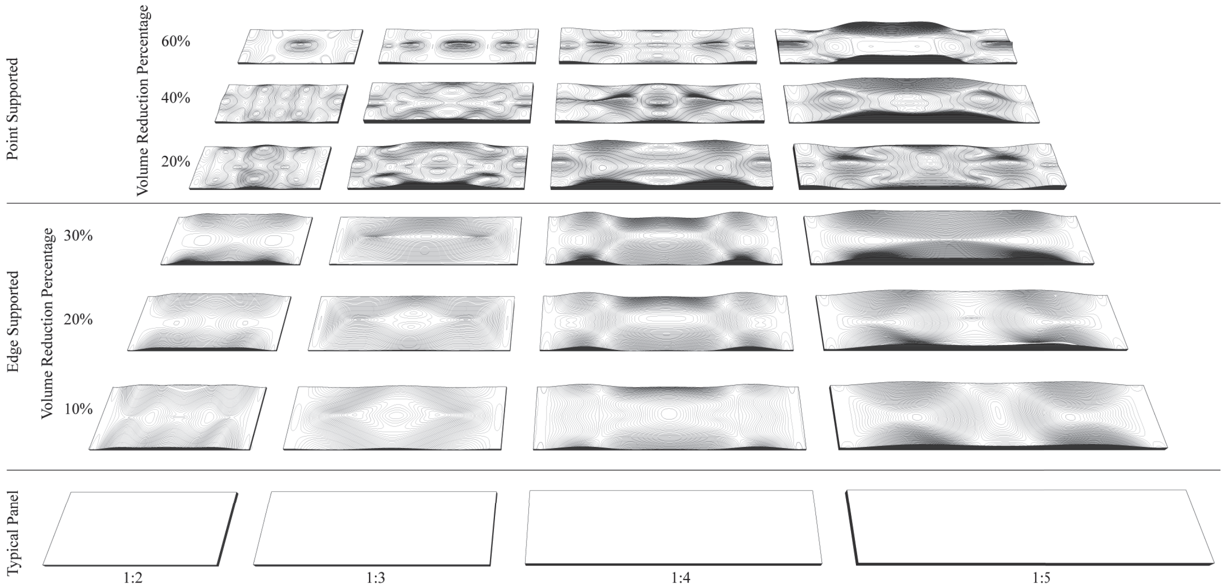

Figure 7. Example of design solution space with samples of edge and point supported optimization cases at incremental volume reduction percentages. The panel geometry is flipped to show the thickness throughout the panel.

for quick calculations using input remnant sizes within the workflow as the condition and quantity of remnant changed frequently during production due to ordering, scheduling, and procurement.

6 – CONCLUSION

This initial research shows that additive fabrication methods utilizing MTP remnant material can be used in conjunction with shape optimization for the potential of more efficient systems from a material and structural aspect. However, future refinement of the digital workflow is needed to more accurately conduct structural analysis on input geometries via Karamba3d or other FEA software to produce a more informed solution space, accounting for the mechanical behaviour of shaped timber and fiber breakage. A mechanics model still needs to be developed for the proper stress distributions. Structural testing of a sampling of the solution space should also be conducted to provide benchmark comparison values between the digital and physical structural analysis and gain a further understanding of how the additive fabrication method effects the structural performance of the geometry. The implementation of these methods at an industry scale should also be considered to provide a valuable tool for fiber recovery within MTP production. The potential for circular economic practices is inherent with the WUP system as remnant material is upcycled from within the manufacturing process. This has the potential to further cut down on manufacturing waste and promote a more efficient use of fiber in mass timber production. The exploration of cost models within this system also has potential to drive the industry implementation of WUP's as in most cases remnant material has already been sold within its machined panel billet, this process would allow the material to be upcycled and effectively sold twice.

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