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Advancing Timber for the Future Built Environment

OPTIMIZING MASS TIMBER STRUCTURAL GRID FOR FUNCTIONAL ADAPTABILITY

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ABSTRACT: Mass timber buildings are valued for their carbon storage capabilities, making their extended lifespan critical for sustained carbon sequestration. Building adaptability, which encompasses the capacity for future modifications throughout a building's operational lifespan, can support this goal. One criterion involves optimizing three-dimensional structural grids, part of a broader set of strategies designed to enhance a building's adaptability. This research presents a novel optimization workflow that integrates databases of standard products from timber manufacturers, structural and technical requirements from building codes, and the program's objectives to inform the early-stage design of mass timber buildings, emphasizing adaptability. The system iteratively refines designs for structural grid efficiency using a product-specific material database and parametric design tools. The study underscores the importance of using standard market products and fostering multi-disciplinary collaboration to address material and design constraints. This approach differs from current optimization practices, which are typically tailored to create one-of-a-kind, complex, form-driven geometries that require customized manufacturing and fabrication. Instead, it intends to support the design of more conventional systems for applications in the mass timber industry at scale. The preliminary results, presented in this paper, demonstrate the feasibility of this workflow for extended grid spans and floor-to-beam clearance while adhering to structural performance criteria on a sample building outline, utilizing post-and-beam structures with American glulam products.

KEYWORDS: mass timber, adaptability, optimization, parametric design, convergent design

1 – INTRODUCTION

Mass timber (MT) buildings are recognized for their capacity to store carbon above ground, playing a vital role in carbon sequestration [1], [2]. Extending the lifespan of these structures can significantly prolong carbon storage. Considering that approximately 60% of buildings are demolished before reaching their physical end-of-life [3], increasing buildings' lifespan can reduce waste and end-of-life carbon emissions from premature demolitions and conserve the energy and resources required for new constructions. Ensuring flexibility and adaptability, which involves enabling future reconfiguration of buildings throughout their lifespan, is pivotal in achieving this goal.

Our earlier research, which reviewed literature and practice in the adaptable design of MT buildings, identified a set of criteria for physical flexibility [4]. Among these, four criteria emerged as key factors in achieving adaptability in MT design and were most frequently applied in practice: (1) grid configuration for wide clear spans in the structure, (2) geometry and dimension of space enabling open plan layouts, (3) location and zoning of vertical service shafts, and (4) functionally neutral or multifunctional spaces that can accommodate various space uses. Among these, grid configuration stood out not only as the most recurring criterion across MT case studies but as a foundational enabler for the other three. This paper, therefore, focuses on the role of three-dimensional structural grid design, specifically span length and floor-to-ceiling clearance, in enhancing long-term adaptability of MT buildings. Wide grid spans enable more flexible architectural layouts, and greater clearance under beams facilitates future alterations of the Mechanical, Electrical, and Plumbing (MEP) services [4].

In fact, from an architectural and space design standpoint, a larger grid enhances flexibility by providing more freedom in the placement of the interior walls and dividers; consequently, reducing future modifications' conflict with structural elements. MEP systems are often tightly coordinated with the structural elements. MEP

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systems are typically embedded within floor and wall panels, routed through beam cavities and predefined chases, or placed behind MT panels. Therefore, maximizing the area beneath beams accommodates accessible horizontal routes for future modification, addition, or removal of services [4].

This grid span criterion becomes particularly important in Mass Timber Construction (MTC), as concrete and steel systems can already rely on standard configurations for commercial construction, such as a 9×9 meters bay concrete flat slab with 4 meters floor-to-floor height or a 9×12 meters bay with steel beams and open web steel joists. In contrast, MT buildings are often constructed using a unique structural system for each project [5].

One example of the impact of unique grid spacing on adaptability is the design for the District Office in Portland, Oregon, where a colonnade of glulam columns is spaced approximately 3 meters (10 ft.) on center for efficient one-way Cross-Laminated Timber (CLT) floor spans. This configuration creates 12-meter spans on one side and 9-meter spans on the other for daylight penetration, meanwhile creating a spacious, open office layout for maximum flexibility [6], as pretend in Figure 1. While low-impact MEP systems, such as electrical conduits, were routed through the gaps between CLT panels, grid decisions facilitated the coordination of primary Heating, Cooling, and Air Conditioning (HVAC) distribution systems within the exposed timber structure. Because the designed bay eliminates the need for cross beams, mechanical systems can branch into each bay without dropping below a beam or requiring pre-drilled penetrations in beams.

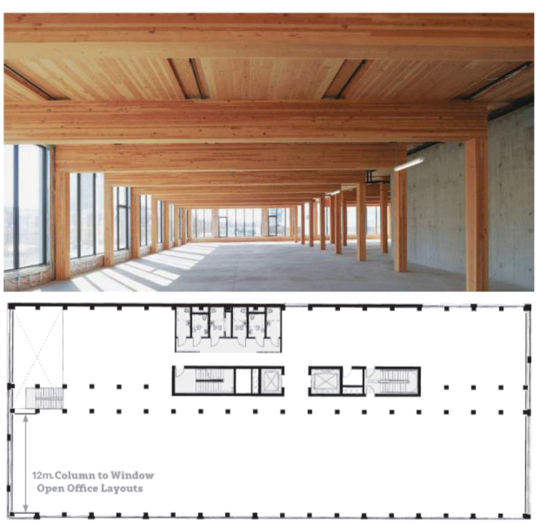

Figure 1: *An interior view (top) and floor plan (bottom) of the Timber District Office building, designed with large grid spacing for higher interior design flexibility [6].*

Finding an optimal three-dimensional structural grid that aligns with architectural, structural, and MEP requirements necessitates collaboration among different stakeholders and seamless interoperability between the tools used in the process. The American MT market, which is still evolving, is dominated by a few manufacturers and fabricators, while designers and engineers remain dispersed and less specialized. Innovation is largely enabled, and in many cases initiated, by manufacturers [7], [8]. However, when traditional delivery models are employed, this often results in a more fragmented process compared to that of more established construction systems. This underscores the need for a more integrated and collaborative workflow in decision-making.

The process of generating optimal solutions that considers constraints from multiple stakeholder perspectives is commonly addressed by multi-criteria optimization [9]. However, standard structural design software primarily validates a given design input, and traditional design workflows do not support iterative explorations of design alternatives for architectural or structural objectives. While emerging digital tools developed specifically for the MTC industry enable users to evaluate trade-offs between factors such as weight, cost, and carbon emissions or assist with preliminary structural design using market-available components, they typically lack automated generations of design alternatives and true optimization capabilities. Existing research in MT structural optimization has predominantly focused on optimizing either members (e.g., minimizing material usage or member weight) [10] or whole structure in small-scale projects [11] that are not representative of common building types such as retail or residential. These approaches often result in non-orthogonal cross-sections that require custom manufacturing.

The MT industry currently does not operate as a commodity market. Instead, it is composed of specialized products that differ in availability, performance characteristics, and sizes across various manufacturers. Additionally, while advanced manufacturing techniques such as CNC machining, 3D printing, and robotics can address the fabrication complexity of material optimization, they are generally highly customized and not easily replicable at scale. In response to these challenges, this study focuses on a method that utilizes MT elements available from manufacturers in North America to design replicable structural systems for common building types. Therefore, the novelty of this research lies in developing an industry-informed optimization approach for spatial geometry that enhances

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cost efficiency and minimizes material waste. Unlike existing tools, which typically assist with evaluating predefined solutions or conducting preliminary engineering design, this approach actively generates optimized design alternatives based on multiple stakeholder inputs. It adopts a convergent design strategy by integrating spatial requirements from architects, structural performance input from engineers, service integration needs from MEP designers, and manufacturing constraints and capabilities from manufacturers and fabricators. While the methodology and part of the workflow are developed and presented in this paper, a thorough validation of the proposed approach is still pending due to ongoing analysis.

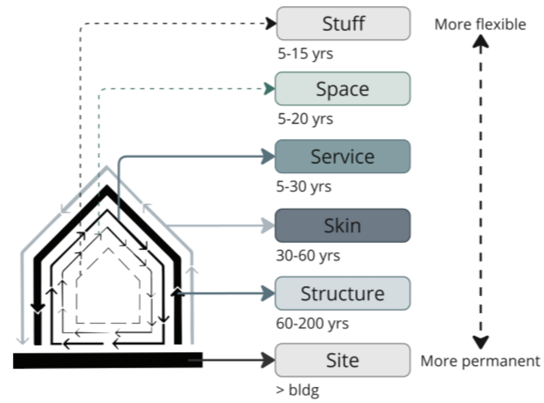

Figure 2: *Building shearing layers, their approximate expected physical lifespan, and level of flexibility and adaptability in layers [4].*

2 – BACKGROUND

Design for adaptability and flexibility stands out as a key approach for extending the functional lifespan of buildings by focusing on decisions made in the early design phase. Therefore, this approach is crucial for enhancing the sustainability of MT buildings and contributing to the circular economy by "slowing the loop", i.e., postponing the flow of resources at the end of a building's service life. Unlike strategies aimed at recovering and reusing building materials at the end of a building's life, adaptability targets modifications that may arise throughout a building's operational lifespan. Adaptability is defined as a design characteristic that incorporates spatial, structural, and service strategies, allowing the physical artifact to possess a level of malleability in response to users' needs over time [12].

Despite the development of flexible design strategies and their documentation in literature, there remains a significant gap in the practical application of these strategies in the Architecture, Engineering, and Construction (AEC) industry. Buildings that are supposed to be flexible during their lifespan often do not meet the ease of modification expected by users. This is partly because the lifespan of a building cannot be viewed as a single entity. A widely referenced concept in this context, introduced by Brand (1995), is the separation of shearing layers [13]. This concept divides a building into six layers: site, structure, skin, services, space plan, and stuff, suggesting each layer has a distinct lifespan, as presented in Figure 2.

Building on the concept of separating buildings' shearing layers, it is important to recognize that design decisions related to one layer may affect the service life and adaptability of others. For example, the structural layer is typically designed and constructed to have the longest service life. However, if modifications to spatial planning, which has a shorter lifespan, are not adequately supported by the structure, the adaptability of the spatial layer may be significantly constrained. For instance, in a MT panelized system, comprised of timber walls and floors, the walls serve as vertical load-bearing elements. The need for a continuous load path from one storey to another restricts changes to the floor layout of an individual level. Therefore, a convergent design approach is essential for creating a building structure that enhances the adaptability of shorter-lived layers, such as services, spatial planning, and furniture.

Convergence refers to two or more things coming together, joining together, or evolving into one. In architecture and engineering, it is characterized by the blurring of boundaries between disciplines and roles, facilitated by interdisciplinary collaboration [14]. This approach often involves the harmonization of various building systems. Convergent design is particularly valuable in projects that require balancing diverse and potentially competing objectives, as it streamlines decision-making. For instance, it may be used to develop design solutions that integrate structural and manufacturing considerations, factors that are often addressed only after the architectural space planning phase. Figure 3 illustrates the input and data flow in traditional design and convergent design workflow for prefabricated building systems such as MT structures [15].

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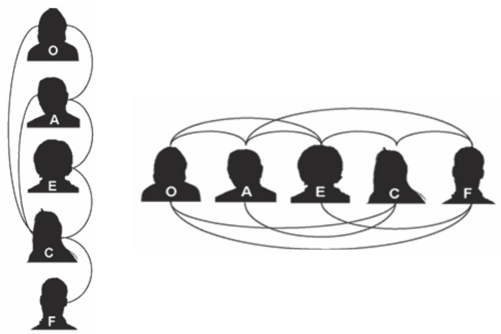

Figure 3: Traditional design flow (left) and convergent design flow (right) in prefabricated design [15]. O: owner, A: Architect, E: Engineer, C: Contractor, F: Fabricator

3 – PROJECT DESCRIPTION

This study aims to implement the optimization of MT 3D structural grids to support flexible spatial layouts and MEP routing. A range of early-stage design requirements, including occupancy needs, building code constraints, and material capabilities, influence this process. Different occupancy classes require different organizations of the space and, therefore, grid layout. Fire resistance requirements impact member sizing (e.g., increasing cross-sections to account for charring) and can limit the number and location of allowable MEP penetrations. Additionally, the grid layout influences beam depth and available space for integrating MEP systems. When these factors are not considered in an integrated manner, the design process tends to become fragmented and inefficient, leading to missed opportunities for optimization. For instance, attempting to force a MT solution on a grid initially laid out for steel or concrete can result in design conflict or inefficiencies and may overlook opportunities related to manufacturer capabilities [16]. Therefore, incorporating MT-specific considerations early in the grid design, such as accounting for span ranges suited to MT floor panels, supports cost efficiency and reduces waste. Manufacturing capabilities primarily impact the dimensions of MT elements, while strength and stiffness are more closely tied to wood species and layup configurations used during the manufacturing process. Therefore, a Design for Manufacturing (DfM) approach is imperative, aligning the design process with the manufacturing process to make buildings that are cost-effective and efficiently use available products in their standard form, avoiding ad-hoc modifications.

This study employs a parametric design approach to incorporate input from multiple disciplines in a convergent design process and a generative design approach to find an optimum structural solution for greater flexibility. Parametric design refers to a process that involves setting rules and adjusting parameters to control the design, whereas generative design utilizes algorithms to autonomously explore and generate optimal designs based on defined goals and constraints. What distinguishes computational design from conventional methods, where the designer typically interacts with digital drawings or models, is that the user instead engages with the digital environment and the mechanisms that generate those representations. The architect can visualize and interact with the design in real time, where changes are immediately reflected in the model [17].

Figure 4 represents a design optimization process that begins with the identification of constraints. These constraints include project-specific requirements such as program needs, relevant codes and regulations, and building type, as well as technological factors like MT elements and connection devices. Once the constraints are established, the process proceeds to the generation of multiple design alternatives that comply with these constraints. Each alternative is then evaluated against a set of predefined criteria, such as certain flexibility, structural integrity, energy efficiency, and cost-effectiveness, to assess how well it aligns with the project's goals. Following evaluation, the designs undergo refinement through an iterative process where poorly performing alternatives are adjusted or discarded, and promising ones are further evolved and reintroduced into the generation cycle. This continuous loop of generation, evaluation, and refinement ensures that designs are iteratively improved until the optimal solution is achieved, all while adhering to the initial constraints.

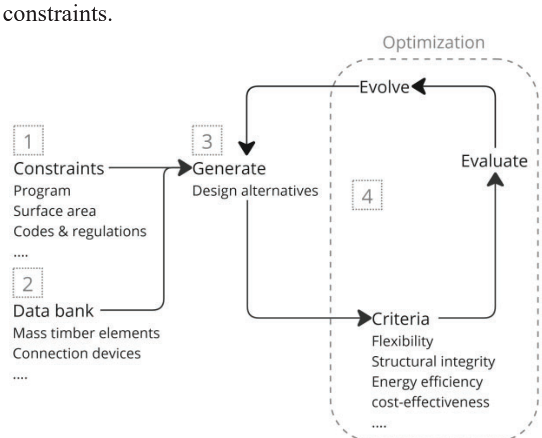

Figure 4: Generative design workflow that gets design constraints and input, generates alternatives, and iterates to evolve options based on optimization criteria (objectives).

4 – DESIGN PROCESS

To implement a multi-criteria optimization for balancing maximized grid span and maximized ceiling-to-floor clearance in MTC, this study develops an algorithm for a MT post-and-beam structural system using US glulam and CLT products, in compliance with Oregon building codes and regulations, as a case study. Architects can employ this tool to generate multiple design alternatives that have incorporated structural design constraints. The tool also enables users to select from a range of American products and manufacturers available for each design output. The following sections provide more details on the design and material inputs, the optimization process, and the outputs.

4.1 DESIGN CONSTRAINTS

The algorithm gets constraints and boundary conditions set by the architect and is preloaded with other input parameters, such as relevant codes and regulations and process formulas from architecture, structural, and MEP engineering domains. Figure 5 presents a preliminary version of the constraints and calculation inputs used in the framework, which is currently under development.

The constraint parameters that define the boundary conditions to be set by designers include building occupancy type, construction type, geometry, surface area, number of stories, position of the lateral force-resisting system, and connection systems.

The first group of Input parameters preloaded into the algorithm, such as height limits, lighting and ventilation requirements, and fire safety regulations, are grouped under "Architecture and MEP" in Figure 5 (green boxes). These are collected from the International Building Code (IBC) [19] and Oregon Structural Specialty Code (OSSC) [20].

The second group is structural input parameters and performance metrics, such as maximum allowable moment and adjustment factors, that are presented under "Engineering" constraints in Figure 5 (green boxes). They are sourced from the IBC, the National Design Specification (NDS) for Wood Construction [21], and the US CLT Handbook [22].

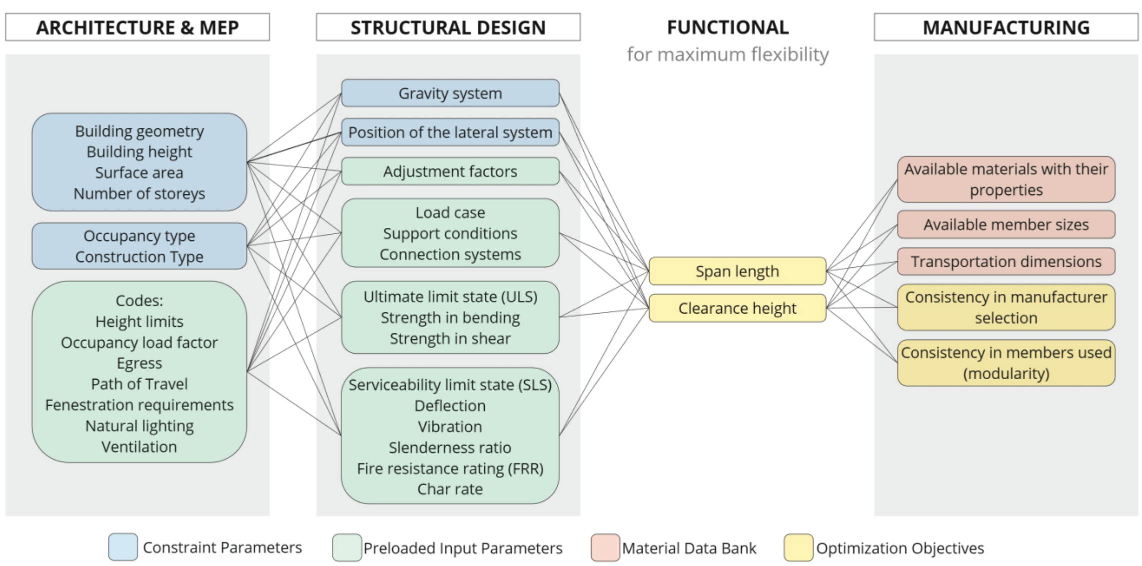

Figure 5: *Mass timber constraints and calculation inputs (Architecture, MEP, Structural design, and Manufacturing) for the framework, along with flexibility metrics (Functional) identified as optimization objectives.*

4.2 MATERIAL DATABANK

A material database has been created, incorporating glulam and CLT products from various US manufacturers, adhering to the DfM approach. The database includes product types, specific material properties, structural design values, and available dimensions. This information is sourced from product reports published by the Engineered Wood Association (APA) [23], organized in a spreadsheet, and linked to a customized GH component (Figure 6) as input parameters.

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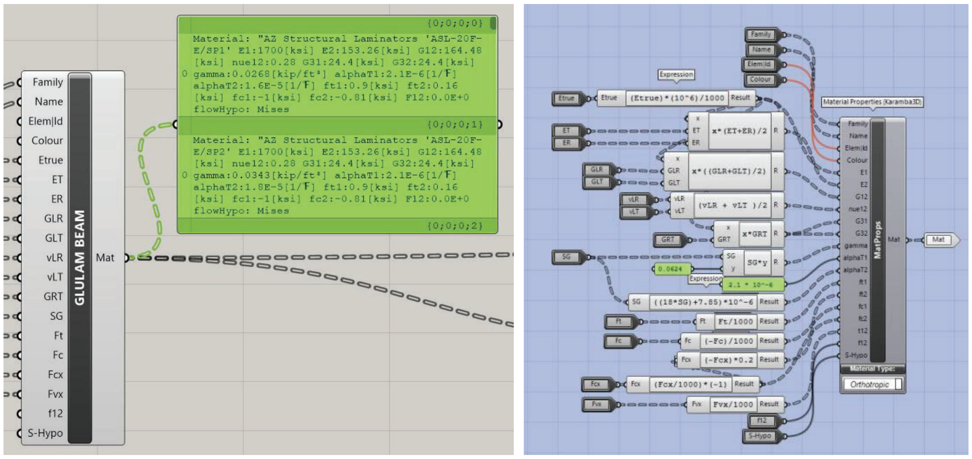

Figure 6: Screen capture of customized material component in Grasshopper for embedding mass timber material properties from APA reports into the algorithm, developed by Nastaran Hasani

4.3 GENERATE

Utilizing GH, the algorithm generates multiple three-dimensional structural grids (Figure 7) for the gravity load-bearing system by referencing the material databank and taking into account the design constraints and input parameters from various disciplines. In this step, they can explore different generated alternatives that meet the structural requirements and performance threshold defined in Karamba3D. The tool provides a list of available US glulam and CLT products, along with their respective manufacturers, that can be used for each alternative. Since MT products vary in available dimensions and properties, not all are compatible with every design. The tool allows users to explore the availability of local manufacturers for potential use in the project.

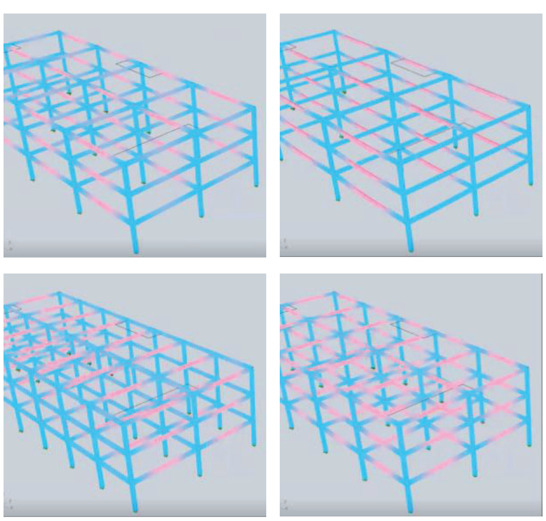

Figure 7: *Examples of generated three-dimensional grids for the gravity load-bearing system of a sample building in Grasshopper.*

4.4 ITERATE

A multi-objective optimization loop is employed to iteratively refine a three-dimensional grid, aiming to maximize beam length and ceiling-to-floor clearance, both serving as key fitness criteria in the evaluation process. Each selected configuration resulting from the iteration is then evaluated using Karamba3D to assess its performance based on calculated structural behaviour. The optimization result of a trial is presented in Figure 8.

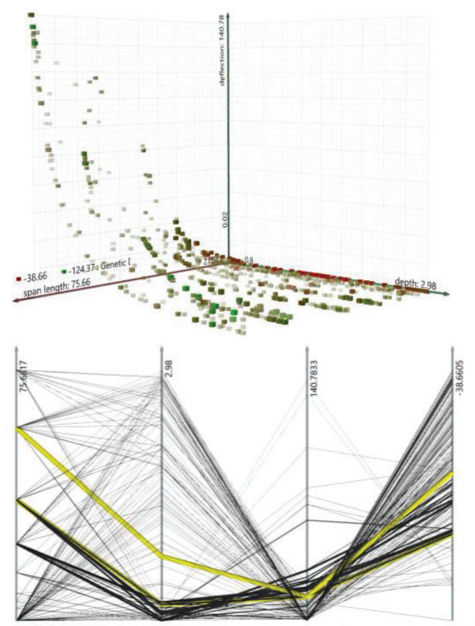

Figure 8: *Screen capture of Octopus' Pareto front approximation for a multi-objective optimization problem involving span length, clearance height, and deflection, after 13 generations, population size 200. The yellow lines in the parallel coordinates plot (bottom) indicate a subset of high-performing trade-offs among the objectives.*

5 – OUTCOMES AND REFLECTIONS

The primary outcome of this study is the development of a multi-objective optimization workflow and the validation of its feasibility for post-and-beam MT structures, offering valuable insights to inform the design process. The current version of the algorithm, presented in Figure 9, works with US glulam and CLT products and complies with relevant building codes in the state of Oregon. While still under development, the initial results demonstrate the potential to achieve extended grid spans and increase under-the-beam clearance while adhering to structural performance criteria. Additionally, the use-agnostic approach to structural configuration allows the system to support various occupancy types, enhancing overall adaptability and versatility.

Implications for industry:

This tool is intended to provide practical applications of adaptable design strategies, focusing on one of the most frequently cited criteria in MTC, and streamline collaborative workflows. It is designed to assist architects during the schematic design phase by incorporating input from various stakeholders early in the process. By addressing key factors upfront, rather than after architectural space planning, this approach has the potential to reduce the need for iterative changes in later design and construction stages. Although emerging MTC design tools, alongside generic specification, are increasingly incorporating available MT products from partner suppliers during the validation of finalized designs, an innovative aspect of this research is that it integrates those products and associated manufacturing capabilities directly into early-stage design optimization to generate constructable design alternatives from the outset. This strategy aligns with the research objective to minimize bespoke design and custom manufacturing for a more efficient and scalable project delivery.

Challenges, limitations, and future work:

A key challenge in the process is that the horizontal distribution of the service paths is directly influenced by the location and spread of vertical service shafts. While a single central core may allow for a more open floor plan, multiple clustered service shafts reduce the distance that horizontal service paths need to travel, thereby lowering the required clearance under the beams. This layout minimizes the need for penetrations or concealed cavities in MT members and enhances accessibility for future modifications. Therefore, the location of building service shafts is another critical design input parameter that will be included in future versions of the algorithm. This parameter must also be coordinated with the placement of vertical structural lateral elements, as both will inform architectural space planning.

The current algorithm's structural analysis relies on Karamba3D, which models structures using linear elements connected at nodes and does not natively distinguish between connection details in platform and balloon framing systems. In platform framing, each floor is stacked on the one below, with continuous horizontal elements included in the vertical load path, whereas balloon framing excludes horizontal elements from the vertical load path. These connection detail affects the beam length, and therefore, must be considered early in the process. To accurately reflect structural behavior, the construction logic should be integrated into the geometry script before the model is fed into Karamba3D. Figure 10 presents the different details at connections to be considered in the algorithm.

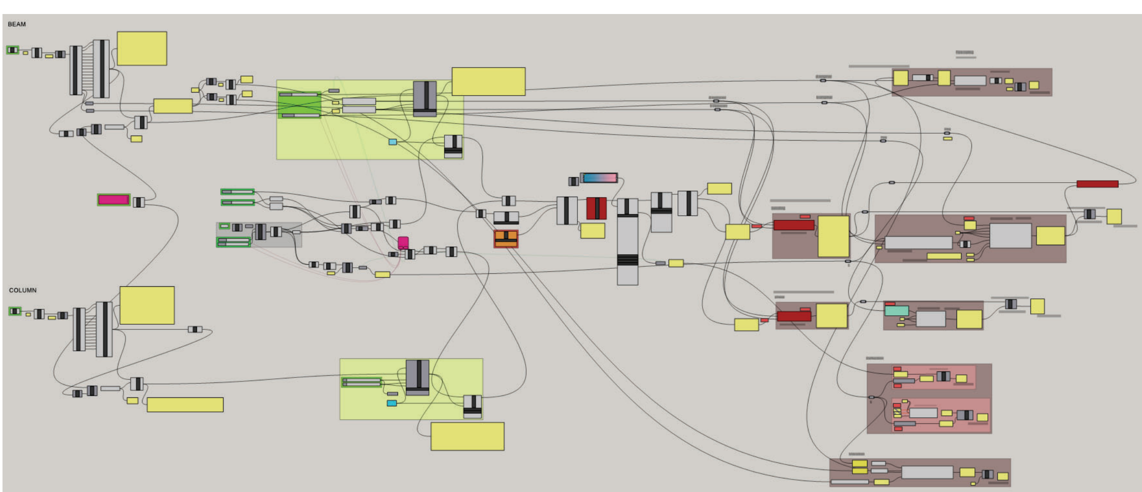

Figure 9: *Screen capture of the developed algorithm in Grasshopper for mass timber post-and-beam systems, created by Nastaran Hasani.*

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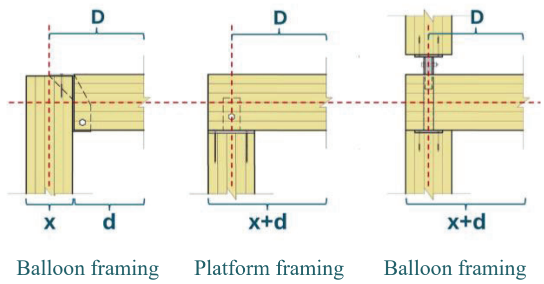

Figure 10: *The difference in beam length in different connection details (d and x+d) vs the same length (D) in node-based connections used in Karamba3D.*

6 – CONCLUSIONS AND RECOMMENDATIONS

This research aspires to address significant gaps in the multidisciplinary integration of adaptability strategies, particularly in the design stage of MT buildings, as well as in the multi-objective coordination of these strategies. It presents preliminary results toward developing a convergent, industry-informed process for early-stage design that supports the adaptability of MT buildings. Unlike existing studies that tend to focus on individual aspects, such as either spatial adaptability or structural optimization, this work seeks to integrate architectural, structural, and manufacturing considerations into a cohesive approach.

The design tool developed through this research demonstrates that a range of variable options can be generated by using this method and allows architects to select products from various manufacturers. This has been validated through preliminary trials of the tool on a sample building outline. Necessary adjustments and further data inputs for the next development phase have also been identified.

Given that parametric design facilitates the exploration of various design possibilities across different structural systems and fitness functions, the proposed methodology can be replicated and extended. The precented workflow can be scaled up and developed into a GH plug-in by including a more diverse post-and-beam material database, expanding to include MT post-and-plate and panelised systems, and adapting to different building codes. This would enable designers in various locations to work within their regional code requirements and with local suppliers. In this case, the material databank should be regularly updated with current product properties and dimensions. An additional enhancement to the database could be integrating cost estimation for different products and systems, enabling designers to assess the cost-effectiveness of each generated alternative.

Finally, the inclusion of real-world case studies is recommended to benchmark outcomes against the results from traditional methods, which will help validate and refine the process.

We acknowledge that other MT systems have been developed with the specific aim of supporting adaptability. For instance, certain systems offer alternative approaches to achieving the convergence of spatial and service adaptability, such as prefabricated boxed-type panels or CLT panels with pre-cut MEP chases that enable more flexible service routing through internal voids or integrated cavities. However, the methodology proposed in this study focuses on employing conventional MT linear elements and solid panels commonly produced by most manufacturers, allowing greater applicability at scale and across a broad range of projects.

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