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REIMAGINING TIMBER: AN INTEGRATED APPROACH OF RESOURCE EFFICIENT FABRICATION PROCESS FOR TOPOLOGICALLY OPTIMISED CROSS-LAMINATED TIMBER SLABS

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ABSTRACT: Timber, recognised for its sustainable properties including renewability, carbon sequestration, and low embodied energy, plays a vital role in modern construction. This project focuses on using a standard timber product to make structurally optimised irregular slabs in a resource-efficient manner. This research develops an innovative computational workflow integrating architecture, computational design, structural engineering, and advanced manufacturing technologies to create complex laminated timber form with both structural and resource efficiency. The methodology combines topology optimisation, discrete assembly, and bin-packing algorithms within a comprehensive framework. Through prototype development and testing, the research demonstrates very high (>95) material efficiency through production, while maintaining structural integrity and design flexibility. The research establishes new pathways for sustainable timber construction, contributing to improved resource efficiency and environmental sustainability in architectural practice.

KEYWORDS: *Circular construction, Bidirectional evolutionary structural optimisation, Bin packing algorithm, Heuristic algorithm, Mixed-integer linear programming, Material efficiency*

1 INTRODUCTION

Timber plays a pivotal role in low-carbon construction, offering renewability, high strength-to-weight ratios, and carbon sequestration potential [1,2]. However, large volumes of under-utilised wood are generated throughout forestry, processing, and demolition activities, possessing irregular shapes and dimensions that fall outside standardised material systems [3,4]. These irregular waste wood streams often retain structural and aesthetic value but are typically down-cycled or discarded due to fabrication and design limitations [4,5].

This preliminary study investigates a computational workflow for generating structurally efficient and materially expressive timber assemblies composed of highly irregular forms. Using standard, regularised timber feedstock, the research focuses on integrating structural optimisation, material-packing algorithms, and discrete assembly logic. While this study does not yet engage directly with irregular waste wood, it establishes key computational and fabrication strategies necessary for future applications involving such materials. The project contributes to sustainable construction and computational design by developing methods that can support greater geometrical adaptability with both structural and resource efficiency.

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2 BACKGROUND

2.1 Potential and Challenges in Using Irregular Waste Wood

Construction and demolition (C&D) activities generate substantial quantities of wood waste, a significant portion of which is either down-cycled into low-value applications such as mulch and biomass or ends up in landfill [6]. Many of these discarded elements retain structural potential but are excluded from mainstream construction due to non-standard shapes and dimensions.

Wood forms that are irregular in shape, such as reclaimed branches, offcuts, and forked members, present unique opportunities for reuse in construction [2,7,8]. Despite their mechanical integrity and rich visual texture, these materials are rarely integrated into engineered wood products due to their incompatibility with conventional fabrication and design systems [9,10]. Recent research [2,6,11] has explored reuse strategies ranging from algorithmic arrangement of offcuts [12] to heuristic matching of forked branches [10] for load-bearing joints.

While these studies demonstrate the feasibility and appeal of irregular wood in architectural applications, challenges remain in achieving repeatability, scalability, and efficient structural integration [13,14]. Automating the arrangement of irregular components into defined modules could bridge this gap and enable wider use of non-standard timber in construction.

2.2 Packing Algorithms and Layout Optimisation in Timber Design

Packing algorithms, widely used in manufacturing and logistics, offer an effective method for arranging irregular objects to optimise space usage and minimise waste [15,16]. These strategies have been adapted for architectural applications where irregular material assemblies are required. Recent developments include the use of reinforcement learning [17–19], heuristic algorithms [16] and integer planning [9,20] to determine optimal layouts, cut plans, and assembly sequences.

In timber construction, such algorithms can enable precise placement of elements within modular assemblies, supporting efficient fabrication and design flexibility [21]. When coupled with structural optimisation techniques, these methods offer a pathway to combine formal complexity with material responsibility [22].

2.3 Structural Optimisation in Digital Design and Fabrication

Topology optimisation, initially developed within the fields of mechanical and aerospace engineering, has become an influential tool in architectural and structural design, enabling the creation of materially efficient, performance-driven forms. Among various methods, Bidirectional Evolutionary Structural Optimisation (BESO) has proven particularly effective in architectural contexts due to its simplicity, robustness, and suitability for irregular design domains [23]. BESO operates by iteratively removing inefficient material and adding it in regions of high stress, producing optimised structural topologies that align with load paths.

Recent developments have extended BESO-based methods beyond conceptual design, incorporating detail control strategies to support buildable and fabrication-aware geometries [24]. These workflows have been integrated into parametric environments and digital fabrication pipelines, enabling high-resolution control over edge conditions, openings, and support logic. In parallel, performance-driven design approaches have been proposed that integrate topology optimisation with multi-agent systems, allowing adaptive form-finding processes that respond to both structural feedback and fabrication constraints [25]. When combined with robotic fabrication and material-aware constraints, topology optimisation supports the generation of free-form structures that align formal complexity with structural clarity and sustainable construction goals.

3 PROJECT DESCRIPTION

This project presents a preliminary investigation into the integration of structural and spatial optimisation for laminated timber assemblies with complex geometries. The study employs regular, standardised timber components to simulate highly irregular forms, Figure 1, allowing the research team to test the effectiveness of a combined computational workflow that includes:

a) bidirectional evolutionary structural optimisation (BESO) to generate structurally efficient topologies;

b) a material-packing algorithm to arrange discrete timber elements within target geometries while minimising waste; and

c) discrete assembly methods to ensure constructability and modularity of the generated forms.

While this initial study is based on regular feedstock, it establishes the computational and fabrication framework required for future applications involving irregular waste wood. By benchmarking the workflow in a controlled material environment, the project identifies core challenges and performance benchmarks before extending to more variable input sources.

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Figure 1. Design rendering.

The outcomes of this phase include a digital design-to-fabrication pipeline, the production of small-scale prototypes, and preliminary performance assessments in terms of material efficiency and structural viability. This research contributes to ongoing developments in computational timber construction and provides a foundation for further studies aimed at reintegrating irregular wood resources into high-value architectural applications.

4 DESIGN PROCESS

A novel computational workflow is proposed to design and fabrication highly irregular, yet structurally optimal, laminated timber forms from standard timber components with minimum waste. The workflow integrates two main methods: a structural optimisation and form generation method using BESO techniques, and a material-packing algorithm to arrange cutting parts withing discrete timber elements with minimum waste.

4.1 BESO-Based Form-Finding for Timber Slabs

Topology optimisation has emerged as a powerful tool in architectural design, especially for generating structurally efficient and materially responsive forms. In this project, topology optimisation was applied to the form-finding of a timber floor slab, Figure 1. Leveraging the Bidirectional Evolutionary Structural Optimisation (BESO) method, the design process integrated material performance, structural feedback, and fabrication constraints, aiming to develop an expressive yet efficient free-form structure.

The floor slab in this study was designed using a modified BESO method, building upon prior research from the X-Form 3.0 project, where BESO was successfully applied to spatial skeletal frameworks [26]. The resulting slab geometry is a centrally symmetric, free-form configuration with approximate dimensions of 3000 mm × 3000 mm × 500 mm (width × length × height). The primary design goal was to achieve a lightweight yet structurally robust system that articulates the flow of internal forces.

The underlying Finite Element Analysis (FEA) model comprised 450,000 quadrilateral shell elements, each 10 mm thick. The timber material was defined with a Young's Modulus of 11,000 MPa and a Poisson's Ratio of 0.3, while the optimisation was driven by a minimum radius filter (Rmin) of 20 mm, an evolutionary rate (ER) of 2%, and a local volume fraction constraint of 50%.

Over 45 iterative cycles, the BESO algorithm gradually eliminated inefficient material regions and evolved an organic network of structural paths. The final topology exhibits a strong correspondence with the principal stress trajectories, enabling substantial material reduction while maintaining structural integrity and suitability for digital timber fabrication.

A visualisation of the optimisation sequence from iteration 1 to 45 is provided in Figure 2, illustrating the step-by-step evolution toward an efficient structural layout. A rendering of the final geometry is shown in Figure 1.

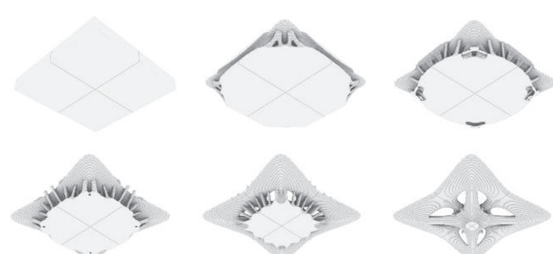

Figure 2. Iteration process.

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4.1.1 Morphological Control Strategies in Architectural Optimisation

Despite the elegance and efficiency of BESO-generated forms, practical architectural applications often demand further morphological conditioning to meet multi-objective design criteria, including spatial function, construction feasibility, and aesthetic intent. To address these challenges, this project incorporated two key strategies for controlling form generation within the BESO process.

(1) Property-Based Influence
Material properties and boundary conditions were adjusted to influence local density distributions. For instance, by reinforcing the stiffness around the central support zone where a column is located beneath the slab, the optimisation process encouraged load transfer directly toward the column. This approach ensured efficient structural performance by aligning the topology with the actual support condition, Figure 3.

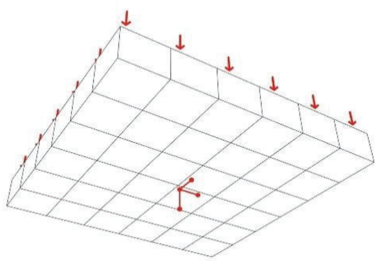

Figure 3. Loading and boundary conditions.

(2) Algorithmic Symmetry Control
To preserve geometric symmetry, often a desirable quality in architectural components for both aesthetic and fabrication reasons, an additional constraint was introduced into the BESO process. This constraint ensures that element pairs located symmetrically about the slab's central axis are updated simultaneously during each iteration, either both retained or both removed. Such intervention effectively mitigates the common issue of asymmetrical drift observed in standard BESO outputs, which typically arises when void elements are removed unevenly due to non-divisible quantities or sensitivity fluctuations across the domain.

By incorporating this algorithmic control, the optimisation process becomes more aligned with architectural design intentions, enabling the generation of structurally rational yet formally coherent outcomes. More broadly, these and other adaptive strategies demonstrate how computational optimisation can extend beyond conventional structural performance metrics to address spatial logic, fabrication feasibility, and visual clarity. Through the integration of geometric, material, and algorithmic constraints within the BESO workflow, the resulting timber slab achieves a holistic synthesis of performance, expression, and constructability.

4.2 Packing Algorithm

The developed timber form is proposed to be made as a cross-laminated timber slab. If decomposed into constituent layers, Figure 4, it is composed for irregular shapes and varying timber lengths. This could correspond to the characteristics of reclaimed of out-of-grade wood, or enforcing such correspondence could be introduced as an additional optimisation constraint. However, for the present study, the form is instead proposed to be fabricated from timber stock with size and grade to benchmark the efficiency with which a complex CLT profile can be fabricated.

Key to achieving material efficiency is material *packing*, comprised of placing individual parts used in the CLT lamination within larger pieces of stock material, so they can be cut with minimal waste. Packing workflows may also consider minimising the number and dispersion of cuts to reduce processing costs and improve the value proposition of working with irregular materials.

For packing problems, a difficulty is encountered in the complex topologically optimised forms investigated in the present study. The generated forms demand high numbers of short length parts, with no length regularisation. This increases the number of possible packing combinations, making brute-force enumeration computationally infeasible. As such, an efficient and constraint-aware packing strategy is required that both limits combinatorial growth and aligns with fabrication objectives. To address these problem requirements, the packing operation is implemented as a two-stage process combining recursive pattern generation with discrete optimisation.

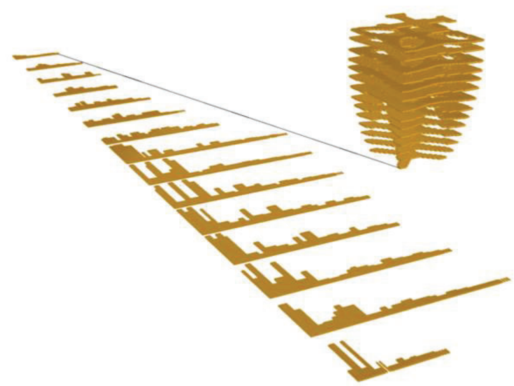

Fig 4. CLT layers (top right) and constituent parts (bottom left).

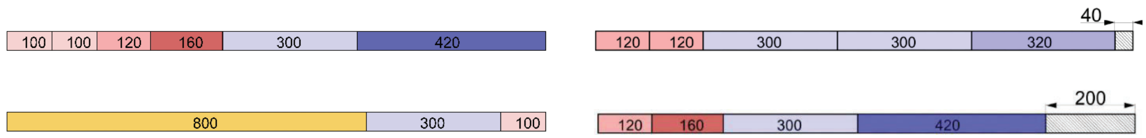

Figure 5. 1200mm stock with embedded parts. Left: no-waste part packing. Right: typical part packing (grey area is waste).

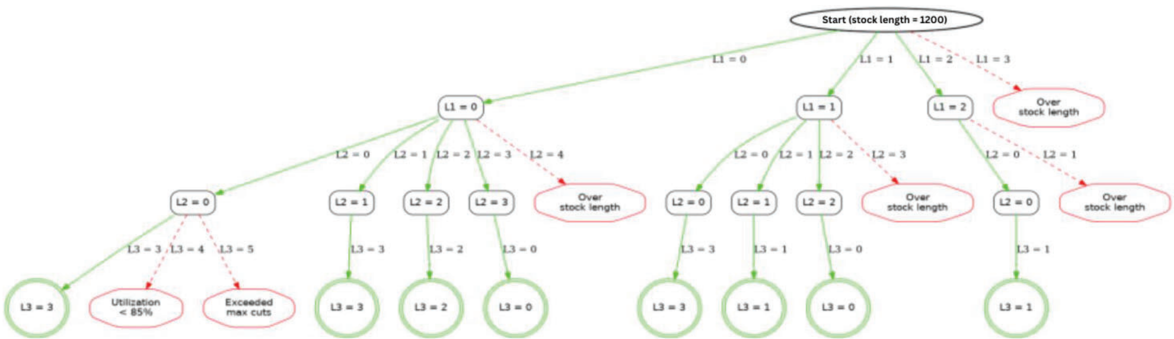

Figure 6. Recursive pattern generation with pruning.

4.2.1 Pattern Generation

To manage the combinatorial complexity introduced by varying element lengths, particularly where segments tend to be short and numerous, a constrained pattern generation strategy was developed. The objective is to generate cutting configurations that are both materially efficient and practically manageable in a workshop setting, Figure 5.

The pattern generation process is implemented as a recursive depth-first search algorithm, Figure 6, with embedded pruning criteria. Each level represents a chosen count for a particular timber length. For instance, Level 1 (L1) might be the longest piece type; the algorithm tries a chosen count of 0, 1, 2, etc, pieces of that length (branching out), then proceeds recursively to decide counts for the next length (L2), and so on.

Branches are terminated immediately when a constraint is violated. In Figure 6, green-highlighted nodes and arrows trace the successful patterns that meet all criteria. Three core constraints are applied at each recursive step:

- Segment count limit: Each pattern contains no more than 5-6 segments, reducing fabrication complexity and avoiding excessive fragmentation that could weaken the stock's structural coherence or complicate handling during fabrication.
- Minimum utilisation: To prevent unusable leftovers, each pattern must use at least 85% of the stock length. In this study, a target material utilisation rate of >95% was defined as a benchmark for efficient reuse which reflecting practical reuse considerations.
- Stock length conformity: The total length of all segments must remain within the available stock (e.g. 1200 mm), ensuring that patterns are physically realisable and fabrication ready.

These constraints drastically reduce the number of viable combinations, making the enumeration of patterns computationally tractable even when the input set contains many small or diverse lengths. To ensure completeness, base patterns (e.g., repeating a single length) are explicitly included for each demand type. The resulting pattern set is then sorted by residual waste and retained up to a maximum size (typically 500–5000 entries), balancing solution quality and solver performance.

4.2.2 Mixed-Integer Optimisation of Pattern Usage

Once a filtered set of feasible cutting patterns is established, the system determines the optimal number of times each pattern should be used to satisfy material demands. This is achieved through a mixed-integer linear programming (MILP) model, which balances total waste, overproduction, and the number of stock units used.

The objective function minimises a weighted sum of these factors:

$$\min \sum_j x_j \cdot \left(waste_j + \alpha\right) + \beta \sum_i over_i + \gamma \sum_j w_j \quad (1)$$

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Here, x_j denotes the number of times pattern j is used, and the weights α, β, γ are design parameters that allow the model to shift priority between *minimising* waste, avoiding surplus, and consolidating offcuts.

The model incorporates three key constraints:

- All demand types must be fulfilled within a small overproduction margin (e.g. 1%).
- The total number of stock pieces used must not exceed available inventory.
- The number of distinct waste-generating patterns is limited, encouraging waste concentration.

To support rapid iteration within design workflows, a time limit (e.g. 30 seconds) is imposed on the solver. If the optimal result is not reached within this window, the best feasible solution is returned.

Importantly, the optimisation is not performed over all possible cutting combinations, but rather over a pre-filtered library of patterns that already respect fabrication constraints, such as segment limits and minimum utilisation thresholds. This strategy ensures that the outputs are not only efficient but also immediately actionable in a workshop setting.

The output of this process is a set of feasible cutting patterns, each represented as a list of segment counts and associated waste. These patterns form the geometric basis for discrete assembly logic introduced in the CLT fabrication section.

5 RESULTS AND DISCUSSION

The proposed workflow generated structurally optimised geometries and corresponding cut plans for a CLT floor slab prototype. Due to spatial limitations in the fabrication environment, the floor slab was fabricated at a 1:3 scale to verify part packing efficiency. For the present preliminary study, packing and cutting was computed separately for each CLT layer and mapped to a corresponding stock layout plan for fabrication, Figure 7. Layers were aggregated in post-processing to evaluate the total stock demand and fabrication efficiency.

The 1:3 scale model used 43×19×1200mm pine as the stock material and required 20 layers in total. Material utilisation for the first seven layers (other layers similar) and in total is summarised in Table 1. The final material utilisation reached 97.28%, confirming the effectiveness of the pattern-based optimisation under real fabrication constraints.

Table 1. 43×19×1200mm Stock Material Usage

Layers	Stock Count	Total Waste (mm)	Material Efficiency
01	14	40	99.76%
02	16	320	98.33%
03	18	1240	94.26%
04	19	1240	94.56%
05	19	740	96.75%
06	18	40	99.81%
07	18	540	97.50%
...			
Sum	178	6830	97.28%

a) b)

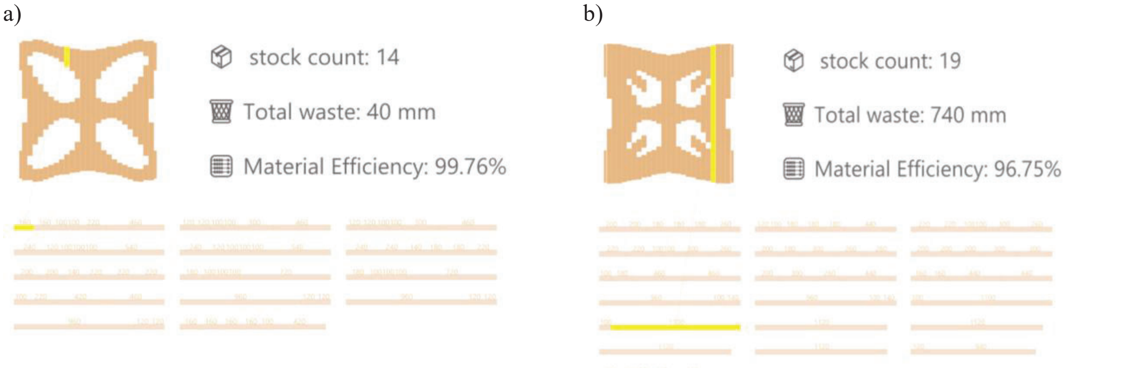

Figure 7. Layer-wise stock layout plan. Top: CLT layer and layer material efficiency measures. Bottom: cutting patterns per utilised stock (1200mm long). a) Layer 1 and b) Layer 5 shown as typical examples.

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Figure 8. The 1:3 scale prototype.

During testing, the recursive generator exhibited performance drops when demand exceeded 30 distinct element lengths, as pattern combinations scaled exponentially. To address this, a length grouping tolerance was introduced, significantly reducing complexity. Likewise, overly long stock (relative to required segments) led to excessive, low-efficiency pattern outputs. A length range of 1000–2000 mm was found optimal for the prototype scale, suggesting that longer reclaimed elements may require pre-cutting in future applications, or that additional algorithm stages are used to rationalise stock length relative to average or bounded part lengths.

The fabricated prototype is shown in Figure 8. The stock layout plan was sufficient to facilitate straightforward manual marking, cutting, and glueing of the CLT prototype, validating the feasibility of the proposed pipeline. A challenge was encountered in providing sufficient clamping pressure to the prototype for edge-bond and face-bond adhesion. This could be improved in future iterations with additional optimisation constraints or rationalisation of the BESO form to allow for compressive load paths (clamping) during partial assembly stages.

In summary, all key parameters, including segment count limits, utilisation thresholds, and length tolerances, are embedded within the developed workflow system and adjustable via an intuitive visual interface, allowing real-time tuning based on design and fabrication feedback. The outcomes demonstrate that the workflow can reconcile structural and material constraints, forming a foundation for future integration with out-of-grade timber in large-scale contexts.

6 CONCLUSIONS AND FUTURE WORK

This project presents an integrated computational workflow combining evolutionary structural optimisation, packing algorithms, and assembly methods to optimise timber usage when fabricating complex structural forms. Using topological structural optimisation, recursive packing, and MILP, we achieved structurally efficient designs with >95% material utilisation in small-scale prototypes. The workflow connects design, engineering, and fabrication constraints to demonstrate the feasible assembly of complex timber forms from standardised materials. The method balances design flexibility with material efficiency, ensuring practical workshop implementation.

By integrating packing constraints into the early design stage, the pipeline yielded stock cutting plans with high

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utilisation, reduced part variability, and waste concentrated in a minimal number of stock pieces. This supporting both ecological and operational objectives in timber use or reuse. It creates a possible framework for future extension into waste wood applications, promoting material circularity and reduced virgin material use.

Current limitations include using standardised timber instead of actual waste wood, computational complexity affecting large-scale implementation, and reduced-scale prototyping limiting full-scale insights. Future work should focus on applying the method to irregular waste wood, incorporating machine learning for potentially enhanced efficiency, scaling to full-size assemblies, and exploring automated fabrication. These improvements could accelerate adoption of waste-derived timber systems in sustainable construction.

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DECLARATION OF GENERATIVE AI

Artificial intelligence (AI) tools were used solely for grammar correction and language refinement in the preparation of this manuscript. No AI was involved in generating content, data analysis, or drawing scientific conclusions. All work has been reviewed and verified by the authors.

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