Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich, Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Enabling the circular use of Cross-Laminated Timber by upcycling production waste

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Abstract

Over the past two decades, the use of Cross-Laminated Timber (CLT) has significantly increased in the building construction sector. The low-efficient production process of CLT requires $1.21\,\mathrm{m}^3$ of lamellae per $1\,\mathrm{m}^3$ of CLT, creating waste which is typically burnt and releases biogenic carbon. This paper presents a state-of-the-art literature review of the circularity of the CLT industry regarding production waste. First, despite a project-based variation, the level of waste generated is consistent between the Northern American and Danish contexts. However, the lack of information on its properties is a primary bottleneck in the structural reuse of this waste. Recent literature on the structural reuse of those CLT offcuts is presented and other possible applications are proposed. Finally, computational methods and tools supporting stock-constrained design are reviewed. None of the publicly available tools are suited for stocks of CLT offcuts. Based on an example found in the literature, we present a computational method for designing flat reciprocal frame structures from reclaimed timber and propose conceptual modifications to adapt it to the specific requirements of CLT offcuts.

Keywords: Cross-Laminated Timber (CLT), production waste, reuse, circular economy, computational method, combinatorial design, stock-constraint design tool

1 Introduction

The global construction sector is an important contributor to the current climate crisis and one of the biggest consumers of resources as well as waste producers. The manufacturing of traditional construction materials such as steel, concrete and glass is responsible for 6% of the global energy consumption and 11% of the carbon dioxide (CO_2) emissions in 2018 [1]. While 60% of the global Construction and Demolition (C&D) wastes are disposed of in landfills [2], in Europe, C&D waste represents 35% of the waste generation [3]. Alternative construction materials with lower environmental impact exist in the form of bio-based materials such as timber and more specifically Engineered Wood Products (EWP). Due to its mechanical properties, Cross-Laminated Timber (CLT) is considered a high-value alternative to mineral-based construction materials [4].

The atmospheric carbon absorbed by timber during its growth is sequestrated in the CLT during its lifespan [5]. Contrary to fossil fuels-intensive traditional building materials (concrete, steel) whose associated emissions happen in their production stage the total impact of bio-based materials heavily depends on the End-of-Life (EoL) scenario which defines if the biogenic carbon will be transferred to other storing units or emitted back to the atmosphere.

Being a relatively new construction material, there is an absence of information and best practices regarding the actual end-of-life scenarios for CLT. Suppose the landfill practices currently in place in the C&D waste management are applied to timber material. In that case, the biogenic carbon will be released into the atmosphere and the positive impact of such material will be cancelled. Additionally, with only 37% of the round wood without bark into CLT, it is the least resource-efficient Engineered Wood Product (EWP) while being the most widely used [6]. This suggests the need to focus more on the resource efficiency of the CLT industry. To maximise resource utilisation and reduce waste generation, different end-of-life scenarios than the ones currently in practice are required for dealing with CLT. This would also contribute to preserving the environmental benefits obtained by the biogenic carbon.

The concept of Circular Economy (CE), as defined in Leising et al. [7], provides a framework for alternative end-of-life scenarios where the timber can cross over from the technosphere cycle to the biosphere cycles, where cascading can be implemented [8]. The CLT industry is not yet fully integrated into the Circular Economy because it does not currently support end-of-life scenarios which would allow for maximum material use and preserve the biogenic carbon sequestrated. The end-of-life scenarios apply to the CLT elements after their first life cycle and by extension apply to the production waste which are regarded as waste as soon as they exit the manufacturing lines.

This paper addresses three main topics: the investigation of offcut production, the proposition of a structural use for those offcuts and the tools and methods for designing from a stock of elements. *Section 2* presents the results of the literature review on the three topics. *Section 3* contains the results of the analysis of the data obtained by the industrial partner. Dimensions, surface area and weight of the CLT panels are sorted, clustered, identified and analysed per project. Finally, based on the knowledge gained by the literature review on computational methods and CLT offcut specificity, concept development is used to propose modifications to an existing computational method. The modifications are presented conceptually and illustrated in *Section 4*. The limitations of this paper are discussed before it is concluded in *Section 5*.

2 Previous work

The CLT industry is a relatively young and exponentially growing industry, with an annual global output of 1.44 million m^3 in 2019 [9]. In 2019, 60 production lines were present in all habitable continents but with a high concentration in Europe and more specifically the DACH+I+C region (Germany, Austria, Switzerland + Italy + Czech Republic) producing alone 70% of the output volume. About one-third (32%) of production is for multi-family housing, 29% is for medium-sized public buildings and 22% for medium-sized industrial buildings [10]. Large-scale projects represent only 7% as of 2015 due to high constrained imposed by building codes.

2.1. Waste

Three waste categories can be identified in CLT manufacturing: Shavings, Finger-joint cutoff and CNC waste, and end cuts, corresponding to the three steps of the manufacturing process [11]. Shavings, finger-joints cutoffs and CNC wastes are dust-like or relatively small elements of little to no structural value. The rest of the waste is generated by the customisation of the master panel for the specific project. The adaptations can be opening for doors and windows (mainly in wall panels) and opening for staircases and technical shafts (mainly in floor panels) creating ‘cut-out’ elements. Angle cuts for wall panels under slanted roofs or left-over due to the imperfect nesting of panels in the master panels are referred to as ‘offcuts’. Finally, the ‘trim-offs’ result from adjusting the invoicing width to the required dimension of the panels.

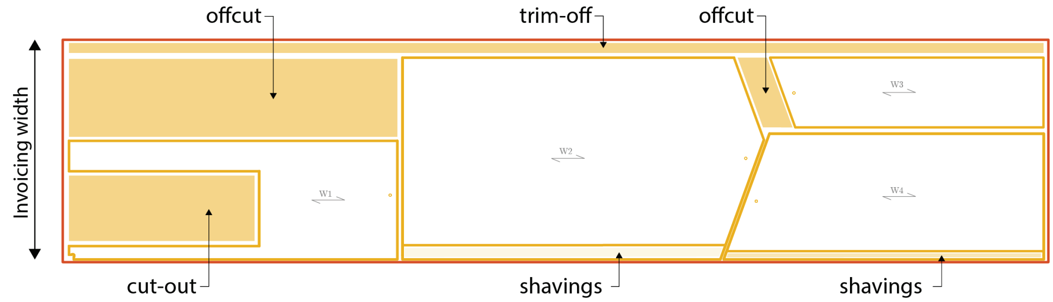

Figure 1: Illustration of the waste type generated from producing four wall panels out of a Master Panel. Based on [12]

In the literature on the Life-Cycle-Analysis (LCA) of CLT production, the waste level, all sorts combined, ranges from 17.4% odkg [11] in Canada to 20.5% odkg [13] in the USA (Oregon). The proportion drops between 12.7% odkg [14] and 14.1% odkg [13] for structurally useable offcuts. In literature about the structural use of offcuts, Vamza et al. [15] put forward the value of $0.128\,\mathrm{m}^3$ of waste per $1\,\mathrm{m}^3$ of produced CLT.

2.2. Structural applications proposed in literature

Several papers in the past decade have proposed applications. Robeller et al. [16] reshaped 5-ply CLT offcuts into hexagonal for a segmented shell. The compression-only structure reduces the complexity required for fastening all stock elements. Resnais et al. [17] proposes to make finger joints at the end of the elements and reassemble them in larger (master) panels showing structural capacities equivalent to C18, C24 and C28 timber. Vamza et al. [15] implicitly uses the proposition of Resnais et al. [17] and shows that 70% of the offcuts generated from a single-family house can be reused in a structural application. Mangliár and Hudert [18] [19]) proposed a modular construction system where offcuts are connected by interlocking and notched connections. The system is suitable both for robotic assembly and disassembly. Finally, Vessby et al. [20] illustrates three uses of offcuts: 1) finger-joined on their top and bottom surface, they create plates used for cross-layers in new CLT. 2) As a replacement for the horizontal sawn-timber rail in timber framing (also proposed by Casagrande et al. [21]). 3) As a local reinforcement of GLT beams at the support location.

2.3. Other structural applications

Certain structures are developed and researched without the primary aim of reusing CLT offcuts but are suitable for doing so. Hyperbolic paraboloids (hypars) show the potential as they can be meshed with flat quadrangles [22]. Hypars' structural behaviour depends on the orientation of their rise relative to the loading direction [23], developing membrane force and work in shell action or as walls Reciprocal frame (RF) structures are characterised by each element being both supporting and being supported by other elements making them able to span distances greater than the length of their components [24]). Reciprocal frames are described by the length, engagement length and eccentricity of the elements and the valence, style (rotation orientation), and end disposition (top/bottom of supporting element) of the fans (assembly of elements) [25]. While a large eccentricity will lead to mainly axial forces, a small eccentricity will create primarily shear and bending [26]. The connection is located along the span of the members creating only T-shape connections. The connection detailing of reciprocal structures makes them a perfect target structure for timber [27]. Despite most buildings using reciprocal frames spanning 3 to 12 meters [24], some examples of large structures using this structural principle exist such as the Serpentine Gallery 2005 by Alvaro Siza.

2.4. Computational method

The reuse of structural elements brings a paradigm shift in the design process, going from an unconstrained design where materials are manufactured accordingly to the outcome towards a process where the structural geometry and topology depend on element stock characteristics [28] [29]. Two main approaches are taken in developing computational methods supporting the design from stock.

The bottom-up approach relies on aggregating the discrete available stock elements via rules. It is based on shape grammar developed in the 1970s by Stiny et al. [30] and uses stock variables as input to generate a final form, structural layout, and design. The top-down approach starts from a given design and aims at fitting the stock to it, in an optimisation logic. The stock elements are screened and the best matching one is selected to be placed at each location needed. This process usually requires the adaptation of the stock elements to fit their allocated position but can ensure an outcome close to the original targeted design [29].

Table 1, inspired by [29], gathers papers solving an inventory matching problem. The type of algorithm used does not seem to be correlated to the type of stock, the approach, or the target structure. Despite the increase in the past five years in research on computational methods for designing with element stock the implementation in practice is difficult due to the lack of design tools based on the developed methods.

Table 1: Overview of publication on computational method for material reuse

Source	Stock	Structure	Approach	Algorithm	Language	Publicly Available
Fujitani and Fujii 2000	Linear	Frame	Top-down	GA [1]	-	×
Mollica and Self 2017	Fork	Truss	Top-down	Greedy	gh [2]	×
Bukauskas et al. 2017	Linear	Truss	Top-down	Greedy	-	×
Brütting et al. 2018	Linear	Truss	Top-down	MILP [3]	MATLAB	×
Lokhandwala 2018	Polygons	Funicular	Top-down	Dynamic Relaxation	gh	×
Larsson et al. 2019	Linear	RF	Top-down	Hungarian Algorithm	-	×
Allner et al. 2020	Fork	Grid shell	Bottom-up	Greedy	gh + Wasp	×
Baber et al. 2020	Linear	Funicular	Top-down	Greedy + Dynamic relaxation	-	×
Brütting et al. 2020	Linear	Truss	Top-down	MILP	-	×
Brütting et al. 2021	Linear	Truss	Top-down	CEM [4] + Greedy	-	×
Amtsberg et al. 2021	Fork	Grid shell	Top-down	Hungarian Algorithm	gh + C#	×
Huang et al. 2021	Linear	Grid shell	Top-down	Hungarian Algorithm	gh + C# + Julia	✓
Parigi 2021	Linear	RF	Top-down	SPEA 2 [5]	gh + MATLAB	×
Warmuth et al. 2021	Linear	Truss	Top-down	MILP / Greedy	gh + C#	✓
Kim and Kim 2021	Linear	Frame	Top-down	GA	-	×
Rahbek et al. 2022	Linear	Grid shell	Top-down	GA + TBR [6]	-	×
Ongenae 2022	Planar	Frame	Mixed	Greedy	gh	×
Reisach et al.2023	Cuboid	Arch	Top-down	-	gh + C#	✓
van Lookeren et al. 2023	Linear	Truss	Top-down	Grow algorithm	gh + Python	×
Cucuzza et al. 2023	Linear	Truss	Top-down	Greedy Search + GA	-	×
Tomczak et al. 2023	Linear	Timber framing	Top-down	Greedy / Bipartite graph / MILP	Pyhton + gh	✓
Warmuth et al. 2023	Linear	Truss	Top-down	MILP / Greedy + GA	gh	×
van Marcke et al. 2023	Truss	Truss	Top-down	Growth + GA	-	×

1. Genetic Algorithm — 2. Grasshopper environment in Rhino — 3. Mixed Integer Linear Programming — 4. Combinatorial Equilibrium Modeling — 5. Strength Pareto Evolutionary Algorithm 2 — 6. Team-Based Repair

2.5. Tools

Among the papers presented, only a few have made their method available as a usable tool. From research, it is found that Wasp [31], Fox, Spruce Beetle [32], Phoenix3D [33] and Algorithmic Circular Dome [29] are, to the knowledge of the authors, the only publicly available tools showing potential in supporting stock-constrained design. Additionally, Tomczak et al. [34] made some ready-to-use matching algorithms available in Python and for the Grasshopper environment. Those are meant to be adapted by designers for their specific needs. However, none of the tools reviewed above are directly suited for dealing with CLT offcuts. Wasp and Fox, performing aggregation, are limited by the type of stock they can take as input; either limited to a single element or requiring a manual input of each geometry. Those tools are based on shape grammar and thus have the inherent difficulty of creating valid rules and steering the design. The two tools integrating a structural analysis (Phoenix3D and ACD) are configured for bar elements. The CLT offcuts could still be input but their bending capacity would be neglected resulting in a sub-optimal use of resources. Finally, Spruce Beetle is made for stock elements whose three dimensions are within the same order of magnitude and requires a continuous curve as a target structure reducing the range of applications for CLT. No algorithm allows the adaptation of the stock in another direction than the length, as they deal with linear elements, which might be needed for CLT offcuts. Even though ACD mentions that the stock elements are pre-processed to give them a squared cross-section, this is not done computationally. Overall, the available tools to design for reuse have a large variation in scope, possibilities and goals ranging from explorative to generative, to design, assessment, and supporting digital fabrication.

3 Availability of waste

CLT production and/or delivery data for eleven recent projects, made available by CLT-Denmark and their supplier KLH Massivholz, are analysed to determine the quantity and quality of production waste. Production Drawings (PD) give a geometric representation of every master panel produced and their cutting/shaving/trimming into the panels used for construction. Delivery Data (DD) summarises in a tabular overview both the master panels and the elements delivered on the construction site but does not contain geometrical representations. The client bears the cost of the waste material. It is usually economically advantageous for a client to design elements in one piece and pay for cut-outs rather than connecting smaller elements [35]. The offcuts generated are generally disposed of directly exiting the production line and are not shipped to the clients, meaning that they are not given an ID or tag and do not appear in the production drawing or the delivery data while it is logistically possible. The production drawings contain the yield per master panel expressed as a percentage of the surface area $[m^2]$ and show a large variation, from 100% to as low as 58%. When aggregated per project, the waste level ranges from about 5% to 22%, within the range of values found in the literature. The waste level is correlated to the project type and thus structural systems. Small single-family housing projects generate more waste than medium multi-family housing and large office buildings respectively.

The geometry of each panel's waste is available as the difference between the gross and net area and ranges from 0 up to $8.4\,\mathrm{m}^2$. This value is however an overestimate of the actual waste as visual inspection of the production drawing shows that smaller elements are nested in the waste material. Their area is not subtracted from the information on the panel providing the waste. Thus, a visual inspection of the production drawings for individual panels is required to obtain the effective surface and geometry of the waste making it a cumbersome process. Processing the offcuts as regular elements in the logistic chain and thus making their properties traceable and accessible is an essential step toward the (re)use of production waste. This can easily be done as attested by the industry data. It is, however, of no use as the offcuts are currently of no economic value to the manufacturer in their primary form. The (re)use of

CLT waste also poses the issue of storage as currently, panels are produced on demand and are shipped with little to no buffer time.

Additionally to applications, a market and a logistic chain are needed for CLT offcuts to be effectively (re)used. The simplest is for the material to remain within the manufacturer's logistic chain like with the REX-lam by Stora Enso mentioned in Vessby et al. [20], or NordicCLT and its commercially finger-joined RecycledCLT, similar to the method proposed by Resnais et al. [17]. Another alternative relies on third parties like Circular-CLT™, a recent initiative by NEY & Partner WOW [36]. The focus of Circular-CLT™ is on removing the main barriers for non-industrial parties to use the offcuts, the dimension and weight, by reprocessing waste into smaller elements by cutting them in their length but also thickness. While Circular-CLT™ does not focus on structural reuse of the CLT, thus reducing the value of the material, they argue that to save volumes of timber, offcuts have to be made more easily available and develop widespread applications [37].

4 Reciprocal stock-constrained design tool

The method presented in a previous section by Parigi [38] is promising in the context of CLT waste reuse for its type of stock and structure. This section briefly presents this method by Parigi [38], highlights its limitation for CLT and proposes conceptual modifications.

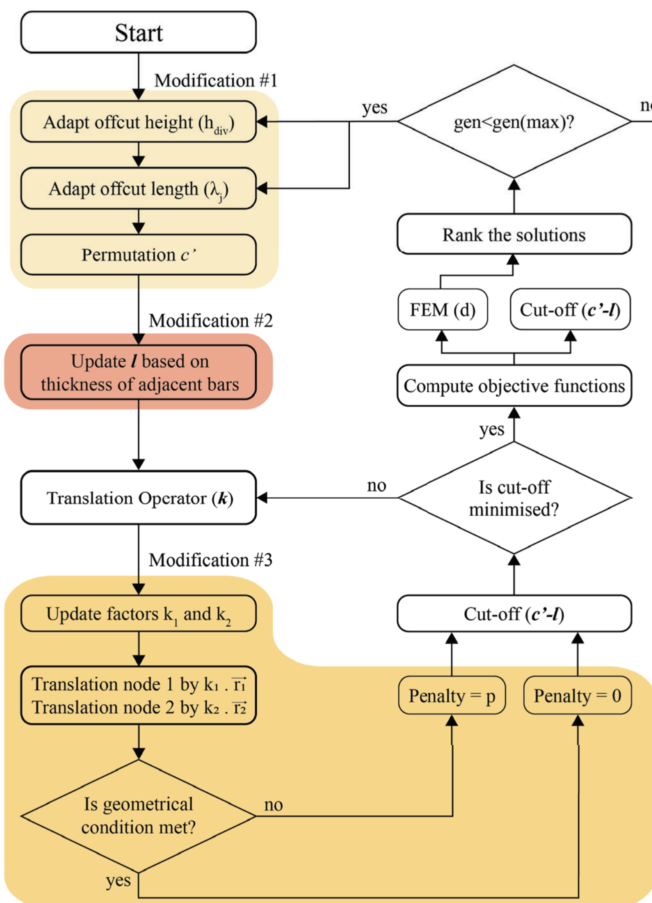

Figure 2: Organigram of the multi-objective optimization algorithm with additions and modifications implemented by the authors, based on previous work by [38] [12].

The computation method developed by Parigi [38] is a top-down approach, performing the assignment of stock elements to the members of a target structure. The solution to the assignment problem which minimises the unused length of the element and maximises the structure's global stiffness is found as the Pareto solution of an SPEA 2 procedure, using the engagement length and the permutation of the stock as variables. The original method is meant for reclaimed sawn timber and is tested on a virtual stock of consistent cross-sections. As observed from the industrial data, CLT offcuts have widely varying dimensions. The first conceptual modification is thus to include a stock preprocessing step in the assignment algorithm by performing an adaptation of the height and length and a permutation selection. A user-defined target beam height is used to perform the Euclidean division of the offcuts width. The offcuts are then split into sub-elements according to the nearest value creating no remainder. This step harmonises the beam height and thus moment capacity. The length of each sub-element is split along its length using the nearest value to $\lambda min(\ell)$ creating no remainder ($min(\ell)$: minimum length across all sub-elements). The target height and the factor λ are used as variables of the optimisation algorithm such that the cutting plan can be optimised. Finally, as the number of produced stock elements is likely to be larger than the number of structural members, a permutation is performed. A random permutation selection would turn the heuristic search into a stochastic search [39]. Instead, the stock elements are clustered by layer orientation and ranked by height such as to select the stiffest elements. The pre-processing could happen directly when the CLT panels are machined from the master panel to minimise the amount of handling operation as proposed by Potenchkin et al. [40].

The topology of the target structure is adapted through the optimisation process by allowing displacement of each member perpendicular to its supports. The alternation of clockwise and counterclockwise fans means that a change in the member's position will increase or decrease the length of both members supported by the moving members. If only one type of fan typology is used, one supported member would increase in length while the other would decrease.

Those add additional fictitious constraints on the required length of the supported elements. To relax this constraint, the mobility range of the members is increased by decoupling the motion of each of the member's nodes. To prevent the collision of members, geometric conditions are enforced by a penalty on the unused-length objective value. The mobility range should take into account the thickness of the stock element assigned to the adjacent members.

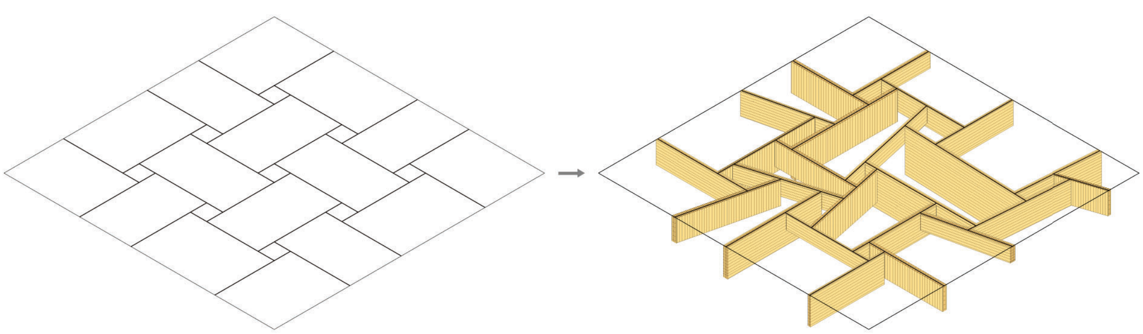

Figure 3: Illustration of a flat reciprocal frame with CLT offcuts. Based on [12].

5 Conclusion

This work promotes the circularity of the CLT industry by tackling waste generation in the production process. The paper is organised around two axes, the supply of material by analysing the availability of offcuts and its use through a tool to design from a stock of elements. The waste generation, ranging from around 5% to 22%, shows a large project-based variation mainly attributed to building typology and structural systems. Currently, the industry does not support the (re)use of production waste as offcut properties are not made readily available. Generalising the practice of recording waste properties can easily be implemented by the industry which needs an economic incentive to do so. Issues related to storing, handling and designing with those waste elements in large quantities are more limiting. Several applications for the recovered elements are found in the research that has emerged in the past five years. Despite showing potential for (re)using CLT offcuts, applications in relatively known structures such as segmented shells or reciprocal structures have not been investigated. Designing from a stock of elements is supported by several diverse computational methods. However, from the review of existing stock-constrained design tools, none are currently able to deal with the specificity of CLT stock. An existing computational method for fitting timber into reciprocal structures is modified accordingly.

To make the CLT industry fully circular, further work is needed focusing on topics such as the economic model and market for offcuts as briefly brushed upon in this work. The research should naturally expand toward the reuse of CLT building components. In addition to the questions relevant to offcuts, technical questions regarding connections and mechanical properties of reclaimed elements, financial questions on the costs and feasibility of reuse, legal aspects, and environmental benefits should be considered.

Acknowledgments

The authors would like to thank: Per Thomas Dahl, Andreas Juul Larsen and their colleagues at CLT-Denmark who provided delivery data of their projects and useful insights into the CLT industry. Johannes Habenbacher from KLH Massivholz for providing production drawings and key aspects of the manufacturing process. Oliver Dass and his colleagues at HolzKurier for access to their economic and production surveys. Benoît Hargot from NEY Partner WOW / Circular CLT™ for sharing his vision and work on the reuse of CLT offcuts. Dario Parigi, Associate Professor at Aalborg University, for providing insights on his methodology for a combinatorial approach based on structural reciprocity.

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