JSACE 2/35

ELEMENTerial – Construction System Study for CLT Offcuts

Received 2023/11/13

Accepted after revision 2024/02/26

ELEMENTerial – Construction System Study for CLT Offcuts

Siim Tuksam*, Sille Pihlak

Estonian Academy of Arts, Faculty of Architecture, Timber Architecture Research Center PAKK, Põhja pst 7, Tallinn, Estonia

*Corresponding author: **siim.tuksam@artun.ee**

https://doi.org/10.5755/j01.sace.35.2.35559

Abstract

The ELEMENTerial research project focuses on the development of an innovative design and construction system for Cross-Laminated Timber (CLT) offcuts. CLT construction, while offering advantages for automation, raises concerns about offcut waste, which constitute 5-10% of the material production in Estonian CLT timber industry. This research highlights the importance of aligning timber construction with circular economy principles by effectively utilising offcuts. The study focuses on the development of a design method, creating a versatile and holistic construction system that breaks away from traditional orthogonal designs. Algorithmic tools are employed to streamline the design process and to help manage the complexities of working with smaller elements. The outcomes include a geometric strategy, offering variable configurations for assembly in walls, floors, ceilings and openings. The research demonstrates the potential to automate and pre-rationalise the design process, providing design freedom beyond orthogonal constraints and shell structures. The applications range from shelters to facade systems, building extensions to potentially large-scale construction systems. This study offers environmental benefits and design flexibility in the construction industry. It holds a potential to guide the sector towards reduced waste and increased material efficiency, fostering sustainability and economic value from waste materials. The prospects for future research include further automation, refinement of connection details, and efficiency in production and material usage.
Keywords: algorithmic design; CLT offcuts; modular construction; upcycling; timber prefabrication; circular design.

Introduction

CLT construction can be considered less environmentally friendly than timber frame construction (Passarelli, 2018). At the same time it has many advantages for the automation of construction and a potential cascade use (Dammer et al., 2016). Its main advantages include the possibility of reducing elements, i.e. producing full wall sections, as well as constructing linear structural members, while being able to take loads in- and out-of-plane (Kurzinski, 2022; Popovski et al., 2014; Schenk et al., 2022). This makes the material very versatile. Yet due to the possibility of producing entire wall and floor sections in a single piece 10-20% of offcuts can be produced during fabrication already (Graf, 2017). According to the project partner for this study – Arcwood by Peetri Puit – the offcut percentage fluctuates between 5-10%, yet their statistics are not comprehensive (Table 1). Two main directions can be identified in up-cycling CLT offcuts: the production of new stock materials by cutting and joining, or using the material as-is for smaller scale construction elements.

Producing new stock material, meaning cutting offcuts down even further into more standardised pieces and joining them together into larger linear elements or producing new full sized plates, is

Journal of Sustainable Architecture and Civil Engineering
Vol. 2 / No. 35 / 2024
pp. 34-42
DOI 10.5755/j01.sace.35.2.35559

a commonly used approach (Casagrande et al., 2021; Graf et al., 2020; Recycled CLT 2022; Vessby et al. 2023). This process helps to reduce the environmental impact by creating new products from waste. Their economic value is only granted by the policy of moving towards more sustainable construction.

Using the material as-is for smaller scale construction elements creates more challenges. Self-builders can use offcuts to construct one-off structures as avoiding production cost makes the lower price of the secondary material economically attractive. Looking at a wider applicability some studies have been made looking into automation and design for manufacture (DfM) for structures that take advantage of smaller panel sizes. Here value is created through design in addition to lowering the environmental impact. These studies are still mainly concentrated on one-off designs for domes and other types of single enclosure systems (Adelzadeh et al., 2023; Menges et al., 2015; Robeller and Von Haaren 2020). This study set as its aim to develop a design method that makes use of the small scale of the offcut elements to produce a holistic construction system with a formal flexibility beyond the orthogonal in a systematic way that is mass producible – maximising formal flexibility and adaptability of the structure while minimising the complexity on the element level. Customisation has to happen in the configuration of elements, not the elements themselves. To manage the increased complexity of constructing with smaller elements, algorithmic tools were developed to automate the DfM process

Methods

This is a creative research study using methods common to contemporary architectural research and practice. It consists of literature surveys on research into CLT construction, more specifically into the use of CLT offcuts, standardisation and automation in the architectural design process, with the focus on methods for systematically structuring spatial aggregations, space filling geometries and lattice structures as well as algorithmic tools for design automation. The potential of CLT offcuts was mapped in the Estonian timber industry by analysing the offcut ratio to overall CLT production and the geometric characteristics of the offcuts.

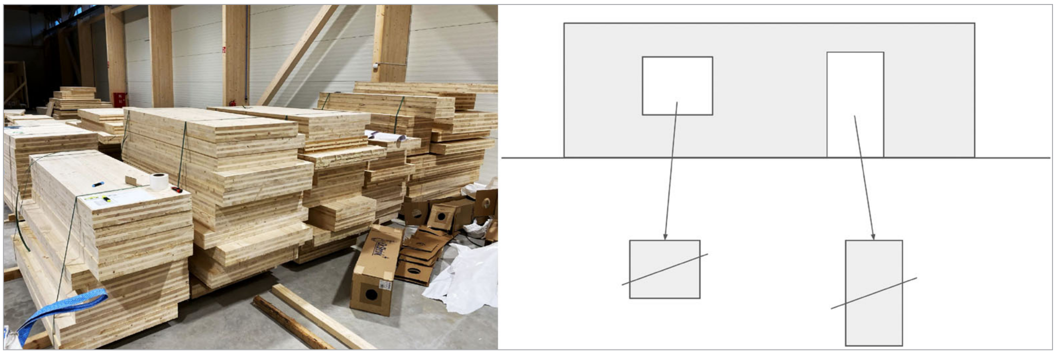
An experimental development was carried out based on the results of the surveys. An algorithmic tool was created to automate the design process and evaluate the outcomes on functionality, structural behaviour, and aesthetic appeal. The development was concluded with the construction of a demonstrator in the form of a small-scale shelter structure. Although as an object it is whole, it is considered as a construction system that can be extended and adapted to any regular spatial structure – creating moments of higher articulation in otherwise straight forward structural systems. In order to achieve this a geometric design method has been developed that is adaptable in scale and is endlessly space-filling in its topology. The method unifies the part and the whole into a coherent design system to incorporate the varying element size of offcuts and possibility to adapt to various spatial building grids. This way the proposed construction system can be used as standalone or in particular building elements in multi-storey buildings e.g. facade systems.

Mapping the potential of industry residues

Mass timber products, such as CLT, have broadened the possibilities and increased the amount of material used in large scale timber construction in recent decades. Even though offsite construction has made timber construction more precise, material efficient and faster, contemporary timber construction is currently not aligned with circular economy principles (Cristescu et al., 2020). The Estonian timber industry has developed greatly in recent decades, constituting the primary export commodity, with figures reaching up to 9,5 million cubic metres (Kobuszynska, 2016). As indicated by the largest Estonian CLT producer Arcwood, whose annual production is up to 17 000 cubic metres, the CLT offcuts make up 5-10% of the overall material production.

Lansink's ladder of waste hierarchy suggests a waste prevention and re-use of products as the highest rank of material use (Lansink, 2018). The current ELEMENTerial study proposes primarily a reuse method for the offcuts. The future outlook of this research is to arrive at a waste prevention, a zero-waste construction system for large scale multi storey buildings including a structural facade system (Jõpiselg 2022). The by-products of the CLT fabrication process are too small for regular timber construction applications (Adelzadeh et al., 2023), thus the construction system introduced in this research is intended for moments of higher articulation within building structures, exemplified by a shelter structure.

Fig. 1
Arcwood CLT offcuts in Põlva factory, the door shape offcuts in size of approximately 800*2000mm



The study at hand is based on the CLT offcuts, mostly in the scale of doors and windows, from Arcwood factory (Fig. 1). Mapping the Arcwood CLT industry, the analysis of leftovers compared 2 large scale buildings, taking into account the gross and net volumes of the used material (Table 1). The material thickness ranges from 60-140 mm, most commonly 100 and 120 mm and 5 layers. The most prevalent shape is rectangular, the offcut doors and windows, commonly in a size of approximately 800x2000 mm.

Table 1
Arcwood building projects, offcuts ranging from 6-7% of the overall CLT volume

Item	Gross volume (m^3)	Net volume (m^3)	Offcuts (%)
Rae Sportshall	698	656	6,0
Rae high school	1482	1383	6,7

Development of geometric strategy

The utilisation of small-scale CLT elements has been a subject of continuous exploration in recent years. When working with small scale building elements, a prevalent strand of inquiry is into geometrically complex shell structures, such as ICD/ITKE Research Pavilion 2011 (Knippers et al., 2015), folded-plate arch prototype (Robeller et al., 2015), Landesgartenschau Exhibition Hall (Menges et al. 2015), or Buga pavilion (Bechert et al., 2021). Mostly these projects abide by the digital industry ideology of mass customisation, neglecting the economy of scale. Furthermore, they mainly concentrate on double-curved shell structures.

The study at hand takes a different approach: looking at space-filling regular structures. Standardisation and automation of design in architecture often involves the utilisation of geometric grids, which facilitate precision and efficiency in the design process. Using orthogonal grids, the simplest way of distributing elements in space is translation and orientation. The aforementioned examples use more complex transformations, resulting in infinitesimal variation in elements. In design development these variations are often rationalised, reduced and simplified within some set tolerance to meet stock material sizes, fabrication limitations etc. The proposed method pre-rationalises sketch geometry to fit the developed construction system (Fig. 2).

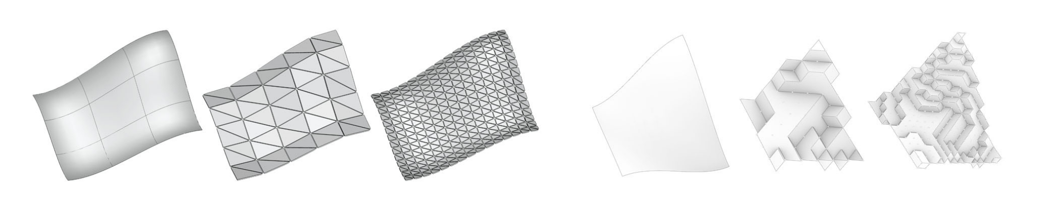


Fig. 2
Variable panelisation vs modular pre-rationalised panelisation on an undulating base geometry

Using grids to systematise the design process has a long history in architecture. In the context of this study some examples are of particular interest. Jean-Nicolas-Louis Durand with his devised method systematised architectural drawings turning architecture into a configurable modular typology (Picon, 2000). A similar rigour of abstraction can be seen in Konrad Wachsmann and Walter Gropius' General Panel System, where the systematic design of buildings was linked with the production of a specific construction system. Although the rationale of unifying design and manufacture is a positive development towards more efficiency in construction, the specificity and precision of the system was also one of the reasons for its economic failure (Gropius & Wachsmann, 2021). A step even further in generalising architectural design can be seen in Buckminster Fuller patented Octetruss – a mass producible construction system for any building. The system does not differentiate structural systems: walls, floors, enclosures, can all be constructed using the same elements (Fuller, 1970).

All regular space filling structures can be related to subdivisions of a cubic lattice. In crystallography cubic lattices are subdivided into base-centred, body-centred, and face-centred (Chanda, 1979). Space filling platonic solids add additional vertices to the system, but they are still what Eckhard Schulze-Fielitz calls intracubic (Fiel, 2020, p. 364). In a cube there are three possibilities for connecting vertices: along edges, along face diagonals or along the long diagonals. These vectors define three types of planes in the subdivision of the cube. These also correspond to the Miller indexes (Sun, 2020). The first ones are parallel to the faces in 3 directions, with a square intersection, the second type divides the cube into two equal triangular prisms in 6 directions (three orthogonal pairs) with a rectangular section, the third type divides the cube into three slices along the long diagonals in 4 directions with equilateral triangular intersections. Eckhard Schulze-Fielitz called these the α-, ɣ-, and β-positions respectively (Fiel, 2020, p. 374). Introducing these planes into the system increases the possibility of creating planes from 3 to 13, while retaining a cubic symmetry.

For the shelter structure the β-position of the grid was used. Only the planes orthogonal to the long axes of the cube were used. This means all the elements of the system are multiples of equilateral triangles, with all edges being multiples of the triangle edge and panel widths corresponding to the height of the triangle. The height of the grid cell in the β-position is defined by the height of the tetrahedron. The base measure was derived from the plate thickness of 100 mm. At the moment of production the most common offcuts were 800x2000 mm. While the thickness of the material corresponds to the height of the tetrahedron, the width of the panel is determined by the height of the face:

$$h = \frac{3}{2\sqrt{2}}H \quad (1)$$

where: h - height of face, module for the panel with; H - height of tetrahedron, corresponding to panel thickness.

The module for the width therefore is approximately 106 mm, making the maximum panel width 742 mm. As the panel is cut at the dihedral angle of the tetrahedron (Fig. 3) to fit the grid geometry an additional 35 mm is added to the total panel width due to the thickness, making the total width 778 mm.

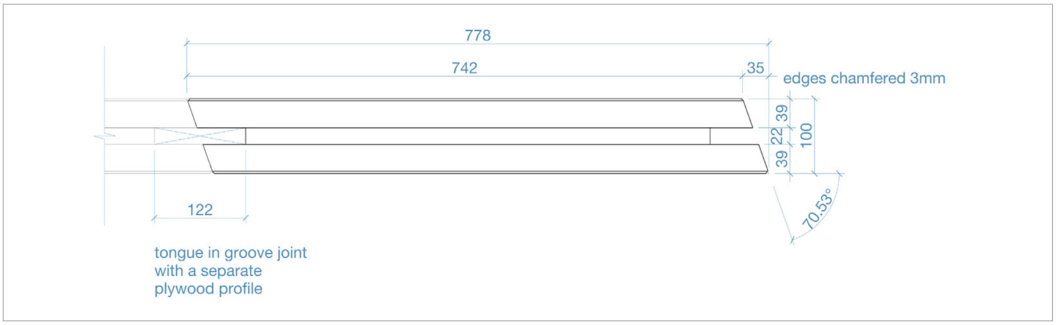


Fig. 3

The standard cross-section of the panel

The diagonal cut is performed in the middle of the offcuts and the panels rejoined along the perpendicular end. The resulting panel can be made into either a parallelogram or a trapezoid by rotating one of the pieces 180° along the longitudinal axis (Fig. 4).

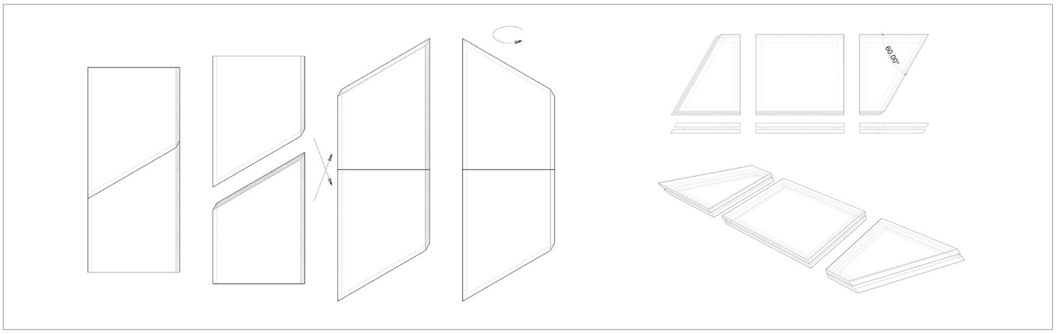


Fig. 4

Creating parallelogram and trapezoid shaped elements from most common offcuts

Design automation

The process of design is made intuitive by algorithmic tools developed on the visual programming platform Rhino Grasshopper. Based on the selected spatial structure, its scale and orientation in space, any 3D geometry can be approximated within the grid. This allows for quick 3D sketching, while simultaneously generating the pre-rationalised, modulated version of the geometry (Fig. 5). The orientation of the grid has a substantial effect on the articulation of the end result. Due to the fact that a cubic translation can be used for the aforementioned space filling geometries, voxelisation can be used as the initial approximation process instead of creating large amounts of tetrahedral solids from the start.

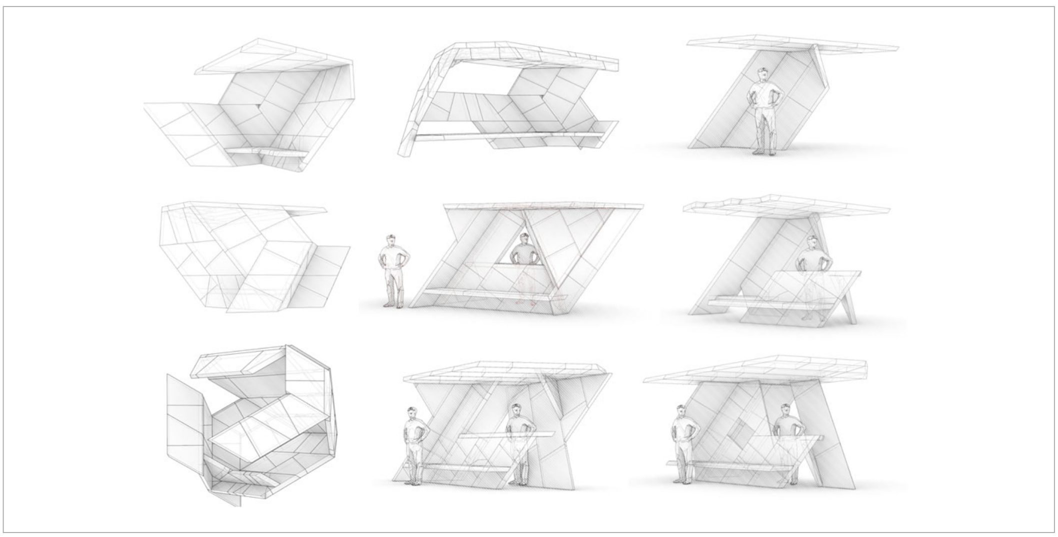


Fig. 5

Design exploration for variable assemblies of the designed panels from offcuts

While the first part of the algorithm produces the overall geometry, additional levels of organisation are built upon the basic structure. To create construction elements or panelisations, rule sets are developed to sort and group grid cells to produce panels. The simplest proof of concept for this type of variable based sorting is the longest linear element script, that looks for longest straight axes within the grid and joins the intersecting cells into a linear member. Doing this iteratively for all the cells results in a hierarchical structure (Fig. 6). Structural evaluation could be used to create a similar sorting based on structural performance, but has not been tested yet.

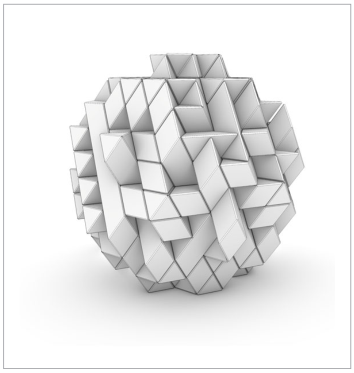


Fig. 6

Modulation of a sphere using the Tetrahedral-octahedral grid in the β-position and the longest linear element algorithm to join cells into linear volumes

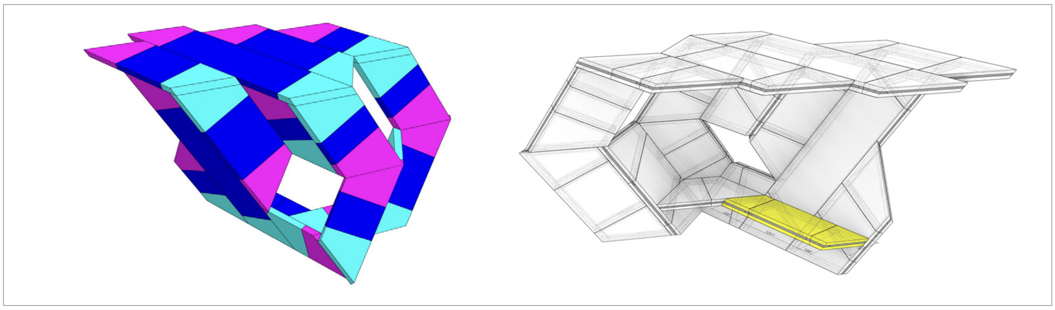


Fig. 7

Initial schematic design. As the edge-to-edge connections work similar to hinges, cantilevers had to be avoided

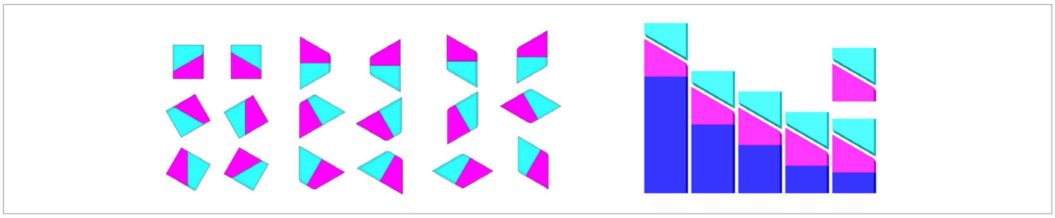


Fig. 8

The initial idea was to create standard end elements and incrementally variable extension elements resulting in 3 piece panels. In favour of structural rigidity a 2 piece solution was developed

Evaluation of structure and joinery

The characterisation of the CLT element modules had to allow for reconfiguration into various design solutions (Fig. 8), which necessitated the joint to be symmetrical. The connection system consists of grooves on all edges of the element and a concealed spline joint was introduced, which is a symmetrical alternative to the tongue-and-groove. The groove in the edge of the panel can be cut without needing to flip the panel over in the shop, and there is no reduction in effective panel width.(DeStefano, 2019). For fixings, plywood profiles were introduced, fastened with stainless steel screws (Fig 3).

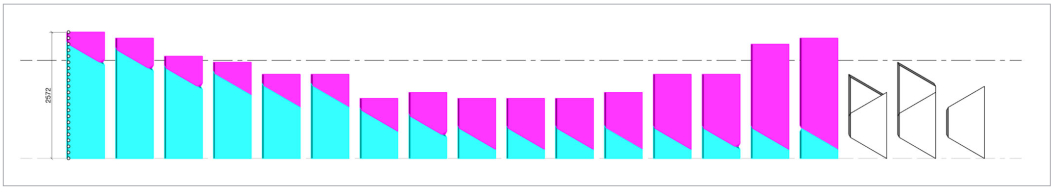
Results: Design and Construction System from CLT offcuts

As a result of this research an understanding of the amount and nature of CLT offcuts was achieved as well as an overview of the state-of-the-art in dealing with this secondary material resource. Based on the findings a strategy was developed to achieve a systemic approach for maximising value production to avoid offcuts' channelling into energy production and instead achieving long time carbon storage in a circular construction system.

Developing the geometric system for this study resulted in a method that can be extended from residues to design with new materials, as the system allows for systemic inclusion of additional orientation planes within a standardised construction system. Due to the versatility of CLT and contemporary ubiquitous automated production lines, the system is rather a description of a method than a panel system, hopefully avoiding the pitfalls of prominent predecessors like the General Panel System. Similar to the octetruss the system avoids the idiosyncrasies of structural elements like walls, floors and ceiling, treating everything the same. To deal with this complexity algorithmic tools for sorting, analysis and optimisation were used. Further design strategies need to be developed for it to become a comprehensive design tool. The experimental development component of the research was concluded with the construction of a demonstrator in the form of a small-scale shelter structure. The initial panelling was optimised, reducing the panel components from 3 pieces to 2. Additionally the structure was made more stiff by adding elements to remove cantilevers. The whole structure consists of 16 two part panels, 5 single part panels, and 3 additional narrower elements to construct the bench – 40 CLT parts in total (**Fig. 9**).

Fig. 9

The 37 elements laid out as pairs to be cut out from rectangular pieces. All elements with the standard width of 778 mm. Excluding the 3 non-standard elements for the bench



To illustrate the design for disassembly component of the research the shelter was initially constructed indoors (**Fig. 10**) and reassembled outdoors a few months later after treating it with colourless wood impregnation from the inside. The outside was charred and the joints filled with bitumen based sealant (**Fig. 11**).

Fig. 10

Case study for the Arcwood CLT cutoffs in the Estonian Academy of Arts gallery. Winter 2020. Photo: Johan Huimerind

Fig. 11

ELEMENTerial station in front of Estonian Academy of Arts. Winter 2021. Photo: Arno Mikkor

The results of the research allow to automate and pre-rationalise the design process of prefabricated timber buildings with articulations beyond the orthogonal. Possible application areas include facade systems, entrances, horizontal and vertical extensions, and larger gathering spaces in public buildings to name a few.

Conclusions

The implications of this study on the environmental impact of CLT construction go beyond dealing with offcuts which, according to various sources constitute 5-20% of the produced material. The developed method can be used to produce building elements from standardised panels rather than creating offcuts by cutting out entire sections of walls. Just as well, this method can be used in combination, using the offcuts within the same project. Furthermore the standardised panels can be disassembled and reconfigured into new designs, contributing to the circular economy.

The economic implications could be realised on the side of the producer or the client likewise as the offcuts are already paid for by the client, making use of them, gets the client more for their money. Developing new products that make use of residues, could turn waste into resources at the same time. According to Arcwood by Peetri Puit export manager Raido Peedomaa CLT offcuts are sold at a quarter of the original price, which leaves ample room for additional processing cost to be economically viable.

The research outcomes can be applied in different scenarios, including standalone structures or building elements in multi-storey buildings, such as facade systems. Compared to previous studies, the proposed system has advantages in design freedom of the overall geometry, accompanied by automated algorithmic design and fabrication methods suitable for mass production.

The future challenges and limitations of this system lie in the further automation of the design and manufacturing process and further development of the connection details, in order to simplify assembly and improve rigidity. The research has a high potential for introducing zero-waste and circular economy methods into CLT construction while increasing design efficiency and freedom.

Acknowledgment

The research presented in this paper was supported by Enterprise Estonia (EAS) and Arcwood by Peetri Puit research project No. EU53849. This study was co-funded by the European Union and Estonian Research Council via project TEM-TA80.

References

Adelzadeh, A., Karimian-Aliabadi, H., Åhlund, K., & Robeller, C. (2023). ReciprocalShell: A hybrid timber system for robotically-fabricated lightweight shell structures. In Digital Design Reconsidered (Vol. 1, pp. 651-660). https://doi.org/10.52842/conf.ecaade.2023.1.651

Bechert, S., Sonntag, D., Aldinger, L., & Knippers, J. (2021). Integrative structural design and engineering methods for segmented timber shells-BUGA Wood Pavilion. In Structures (Vol. 34, pp. 4814-4833). Elsevier. https://doi.org/10.1016/j.istruc.2021.10.032

Casagrande, D., Sinito, E., Izzi, M., Pasetto, G., & Polastri, A. (2021). Structural performance of a hybrid timber wall system for emergency housing facilities. Journal of Building Engineering, 33, 101566. https://doi.org/10.1016/j.jobe.2020.101566

Chanda, M., & Chanda, M. (1979). Atomic Arrangements in Crystalline Solids. Science of Engineering Materials: Volume 1 Structure of Matter, 107-173. https://doi.org/10.1007/978-1-349-06051-1_4

Cristescu, C., Honfi, D., Sandberg, K., Sandin, Y., Shotton, E., Walsh, S. J., ... & Krofl, Ž. (2020). Design for deconstruction and reuse of timber structures-state of the art review.

Dammer, L., Bowyer, C., Breitmayer, E., Eder, A., Nanni, S., Allen, B., Carus, M., & Essel, R. (2016). Mapping study on cascading use of wood products. Gland: WWF, 1.

DeStefano, J. (2019). Detailing Cross-Laminated Timber Connections. Timber Frame Engineering Council (TFEC) Timber Design Guide 2019-15. www.timberframeengineeringcouncil.org

Graf, J., Krötsch, S., Poteschkin, V., & Shi W. (2020). Potentiale der Verwendung von Brettsperrholz-Produktionsabfällen zur Herstellung von Bauteilen im Holzbau - Recycling von Brettsperrholz-Produktionsabfällen. Fraunhofer IRB Verlag. https://tlab.architektur.rptu.de/forschungsprojekte/Potentiale-der-Verwendung-von-Brettsperrholz-Produktionsabfaellen

Gropius, W., & Wachsmann, K. (2021). 10. End of a Venture, End of a Dream? In The Dream of the Factory-Made House. https://doi.org/10.1162/a8667414.209f27d1

Fiel, W. (Ed.). (2010). Eckhard Schulze-Fielitz: Metasprache des Raums: Metalanguage of space. Springer-Verlag. https://doi.org/10.1007/978-3-211-99198-5

Fuller, R. B. (1970). Buckminster Fuller. CBC Learning Systems.

Jõpiselg, E. (2022). The Structural analysis of cross-laminated timber wall element for Slender house. TalTech, EAEI02/17

Knippers, J., La Magna, R., Menges, A., Reichert, S., Schwinn, T., & Waimer, F. (2015). ICD/ITKE research pavilion 2012: coreless filament winding based on the morphological principles of an arthropod exoskeleton. Architectural Design, 85(5), 48-53. https://doi.org/10.1002/ad.1953

Kobuszynska, M. (2016, December 20). Wood Sector in Estonia. USDA Foreign Agriculture Service. https://fas.usda.gov/data/estonia-wood-sector-estonia

Kurzinski, S., Crovella, P., & Kremer, P. (2022). Overview of cross-laminated timber (CLT) and timber structure standards across the world. Mass Timber Construction Journal, 5(1), 1-13.

Lansink, A. (2018). Challenging Changes - Connecting Waste Hierarchy and Circular Economy. Waste Management & Research, 36, 872-872. https://doi.org/10.1177/0734242X18795600

Menges, A., Schwinn, T., & Krieg, O. D. (2015). Landesgartenschau Exhibition Hall. Interlocking Digital and Material Cultures, 55-71

Passarelli, R. N. (2018). The environmental impact of reused CLT panels: study of a single-storey commercial building in Japan. In Proc. 2018 World Conf. on Timber Engineering (Seoul, Republic of Korea, 20-23 August 2018).

Picon, A. (2000). Précis of the Lectures on Architecture: with graphic portion of the lectures on architecture. Getty Publications.

Popovski, M., Pei, S., Van de Lindt, J. W., & Karacabeyli, E. (2014). Force modification factors for CLT structures for NBCC. In Materials and Joints in Timber Structures: Recent Developments of Technology (pp. 543-553). Springer Netherlands. https://doi.org/10.1007/978-94-007-7811-5_50

Recycled CLT. (2022). Recycled CLT. https://www.recycledclt.com/

Robeller C, Weinand Y. Interlocking Folded Plate - Integral Mechanical Attachment for Structural Wood Panels. International Journal of Space Structures. 2015;30(2):111-122. https://doi.org/10.1260/0266-3511.30.2.111

Robeller, C., & Von Haaren, N. (2020). Recycleshell: wood-only shell structures made from cross-laminated timber (CLT) production waste. Journal of the International Association for Shell and Spatial Structures, 61(2), 125-139. https://doi.org/10.20898/j.iass.2020.204.045

Schenk, M., Hübner, C., & Cabrero, J. M. (2022). Cross-Laminated timber: a survey on design methods and concepts in practice. CivilEng, 3(3), 610-629. https://doi.org/10.3390/civileng3030036

Sun, S., Zhang, X., Cui, J., & Liang, S. (2020). Identification of the Miller indices of a crystallographic plane: a tutorial and a comprehensive review on fundamental theory, universal methods based on different case studies and matters needing attention. Nanoscale, 12(32), 16657-16677. https://doi.org/10.1039/D0NR03637D

Vessby, J., Perstorper, M., DeMonte, F., & Eriksson, J. (2023). Structural use of cut-offs from clt-production-three examples that utilize the unique properties. In World Conference on Timber Engineering 19.-22. June, 2023, Oslo, Norway. https://doi.org/10.52202/069179-0019

About the Authors

SIIM TUKSAM

Researcher

Estonian Academy of Arts, Faculty of Architecture, Timber Architecture Research Center PAKK

Main research area

Algorithmic timber architecture, modular construction

Address

Põhja pst 7, Tallinn, Estonia
Tel. +3725084689
E-mail: siim.tuksam@artun.ee

SILLE PIHLAK

Researcher

Estonian Academy of Arts, Faculty of Architecture, Timber Architecture Research Center PAKK

Main research area

Algorithmic timber architecture, modular construction, somatic architecture, volumetric renovation

Address

Põhja pst 7, Tallinn, Estonia
Tel. +3725150065
E-mail: sille.pihlak@artun.ee

This article is an Open Access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 (CC BY 4.0) License (http://creativecommons.org/licenses/by/4.0/).