Exploring the Potential of Funicular Timber Floors

blindfold
blindfold

ABSTRACT: This research investigates funicular timber floor systems to reduce timber volume and employ re-assembly through detachable connectors and modules. The research began with visits to Swiss timber manufacturers. Observations from these companies reveal well-developed systems that often overlook optimal material use. In timber floor fabrication, the process plays a major role in relation to structural analysis, acoustical properties, and mass automation timber. Current market solutions lack two-directional spanning timber floor slabs, highlighting a research opportunity. Structural shaping must address manufacturing challenges, either through bending or angled cutting, both of which are costly processes. The study explores two primary approaches: Panelized CLT Timber Vaulted Floors and Triangulated Boxed Timber Floors. The first approach uses detachable connectors for tight interfaces between CLT panels, while the second employs non-industrial timber and minimizes glue usage. This study aims to advance timber floor construction by addressing these challenges and opportunities.

Keywords: Funicular geometry, Timber floors, Circular floor systems, Timber Earth

1 STATE-OF-THE-ART

Two methods were used to learn from existing timber floors: a) Swiss-German timber companies interviews, b) an academic literature review. The visits have been documented in short videos [Blinded]. The following companies were visited: Balteschwiler, Schilliger Holz, Tschopp, Lignatur, Schneider (Germany), Rematter (Hortus building), and Blumer Lehmann (modular and free-form construction) as seen in Figure 1.

Figure 1. Visited companies: A - Schilliger Holz, B - Tschopp Holz, C - Rematter and Blumer Lehmann, D - Lignatur, E - Schneider Best Wood, F - Erne, G - Blumer Lehmann. Key processes include heat pressing, gluing, and cutting, with minor exceptions for dowel lamination and transitions between earth and concrete.

1.1 *Swiss Timber Companies Floor Production*

Timber floor-production is often the final step in the wood-production chain. Schilliger Holz states that at least five other applications are needed for timber commercial viability: 1) structurally graded timber, 2) non-structural uses like EUR-pallets, 3) agricultural uses like pressed pellets, 4) energy production by burning, and 5) post-production waste like insulation panels. High automation is necessary to compete with other construction materials while producing self-similar, repeatable elements.

In Switzerland, freshly cut trees cost around 100-200 CHF/m^3, increasing to 400-600 CHF/m^3 for regular rectangular beams and 1200-1400 CHF/m^3 for processed timber like CLT or LVL, up to 2000-9000 CHF/m^3 for doubly curved beams [Vestartas, 2021, p. 7]. The cost of timber floors varies between 150-250 CHF/m^2 for timber-only and timber-concrete hybrids. Swiss-only timber floors range around 250-350 CHF/m^2. The primary factor is the level of automation and the higher volume of wood available in Austria, Germany or Nordic countries. Timber floors are mostly one-direction elements with square sections up to 5-6 m spans. Larger spans require glued timber products, box or T-sections, to fit a common 0.40 m floor height. According to Blumer Lehmann, curved panels remain labor-intensive and expensive. Their modular timber construction with divided spans of up to 5 meters offers rational section sizes with glue laminated beams. Costs depend on whether a system is old or pioneering, requiring additional work to understand factors not present in current norms. Timber is lighter than other materials, resulting in smaller overall loads and similar costs to other construction methods. It is more economical to produce timber elements outside Switzerland. However, Swiss regulations forbid the construction of public buildings that do not use Swiss timber. In Switzerland, you must prove that you cannot build schools and other public buildings in timber before using other materials. Previously, the legislative focus was on the cheapest option, but now it aims at the best option. These incentives and support are necessary for timber advancements.

Highly automated timber floor systems are well developed and technologically advanced. For example, Lignatur boxes are produced in less than half an hour, and Schneider CLT boxes in 20 minutes. Key production techniques include a) heat-press with fast curing times, b) glued or dowel-laminated beams or boards, c) custom fabrication for punctual connections and building services, and d) hybrid timber with concrete or earth composites. Companies demonstrated hardwood applications for smaller sections and higher load capacity, such as the Hortus building by Rematter, Erne Headquarters, and Rocket and Tigerli. Industrialized timber products like CLT panels are fabricated on demand for specific dimensions. CLT, BauBuche, spruce Kerto, and Glulam use simple cuts to maximize rectilinear geometry. Waste is minimized as one pays for a rectangular element. Manual fabrication is often cheaper than automated CNC fabrication, allowing for corrections to draftsperson's mistakes even in automated processes.

There are two types of acoustical measurements in floor systems: a) impact sound insulation and b) airborne sound insulation. Timber can more easily reduce airborne sound insulation through linear cuts or point pattern, but it is weaker in impact sound insulation, which is related to the mass of a floor. Heavy infill can be addressed using construction waste, as seen in Hortus with compressed earth or crushed brick sand. Concrete is often used for its higher density.

Several potential research lines were identified from the visited companies: a) automating hybrid earth-timber composites for small spans, as their fabrication is still semi-manual and slow, b) structural shaping for spans over 8 meters when conventional timber sections exceed common heights, and c) implementing a digital configurator for modeling existing timber floor systems, as detailed knowledge remains with privately owned companies and is rarely open-sourced Tavares Pini and Olga [2024].

1.2 *Research in Vaulted and Flat Timber Floors*

Existing vaulted timber floors could: a) reduce embodied carbon emissions by more than half compared to flat timber floors Hossell [2023], Groenewolt [2023], b) improve acoustic performance due to their geometry and dry-assembled heavy infill Méndez Echenagucia and Block [2015], ReMatter [2023], c) utilize a compression-dominant geometry with simpler connections, avoiding bending-dominant steel Noda and Kimura [2022] or glued timber connections Robeller and Von Haaren [2020], Manahl and Wiltsche [2012], d) be competitive with standard floors due to the repetitive nature of load-bearing grids Bechert [2021], Gollwitzer and Linse [2019], and e) increase spans of hybrid earth systems, currently limited to approximately 5x0.5 m dense beam placement if non-glued elements are used. The lack of commercialization of timber-vaulted floors is due to the absence of standardized design and production workflows, as well as cost analysis and feasibility studies.

Researchers have analyzed existing timber building layouts, primarily regular grids or linear arrays Svatoš-Ražnjević [2022], Salvadori [2023]. In the last three decades, multi-storey timber buildings have re-emerged due to advancements in mass-production of engineered timber, yet they remain niche in the construction market. The DACH region, with its strong timber building market, sees innovation mainly from fabricators, focusing on CLT, box floors, and box-beam elements Orozco [2023]. Timber is marketed primarily for its inherent qualities, with limited innovation in both structure and application. Column-beam frame systems are commonly used for regular grids, while panels are utilized in linear arrays. Timber is generally assumed to be strong in tension and therefore mostly used as beam elements. However, longer spans require significantly oversize timber sections, often using mass timber or highly processed timber (LVL, MPP, Kerto, GLT). Larger spans are common in open-office spaces and other non-residential functions. A study Krtschil [2022] shows that flexibility in these spaces is key, rather than having small-span grids. Therefore, alternative methods need to be explored besides merely sizing the timber sections.

Joinery within floor and beam-column elements plays a significant role, most commonly using standardized steel connections, with a few exceptions in timber such as X-Fix Robeller and Von Haaren [2020] or concrete as demonstrated by Erne Holzbau. For modeling the connections and stacked timber elements, individual companies often have in-house configurators Epp. However, open-source solutions are not available, nor is the documentation of the numerical data. Such digital tools would also benefit the design of novel timber floor systems. More transparent translations from Eurocode or Swiss norms would help in early-stage architectural and structural design. Individual initiatives have already addressed life cycle assessments from Swiss regulations into an online accessible tool EcoTool. Several authors have started developing CAD plugins while initially focusing on specific project needs Tavares Pini and Olga [2024]. Open-sourcing such tools would benefit the industry and academia but requires greater experience from practice. Accurately assessing such details is still a challenge. Therefore, detailing connections across various materials and providing an open-source tool that different parties could contribute to would be beneficial.

2 METHODS

The methodology is prototype-driven to understand the fabrication workflow needed to create a vaulted timber floor, including: a) Study 01 - Panelized CLT Timber Vaulted Floor, and b) Study 02 - Triangulated Boxed Timber Floor. We consider an 8x8 meter vault, as shown in Table 2. We focus on larger spans, as typical 5-6 meter spans are well automated even using non-graded timber, such as Dowel-laminated-timber (DLT) or traditional Beam-Panel floors without infill or earth-based hybrids. The vault rise is constrained to less than 1 meter. The shell must be discretized for transport, with the shortest edge not exceeding 3-3.5 meters. Ideally, the vault should approximate a catenary geometry, followed by static loads defined by Eurocode. We use flat elements of 4.8 kN/m^3 with a safety factor of 1.35. For office spaces, we consider 1.5-2 kN/m^2 live loads and 2-3 kN asymmetrical loads without a safety factor of 1.5. Floor leveling is achieved using heavy infill of earth-based products within 15-16 kN/m^3.

2.1 *Study 01: Panelized CLT Timber Vaulted Floor*

The first study employs: a) two-direction timber, b) minimal fabrication with saw-blade, c) punctual non-glued detachable connections. These connections ensure a tight fit between panels with resistance to moment forces due to asymmetrical loads. Structural calculations indicate that connections are sufficient in the middle of the vault, but the edges must resist forces twice as high as the connection capacity as seen in Figure 3. For self-load, 120 mm CLT panels are adequate. However, for asymmetrical loads, the static height must be increased to up to 250 mm panels, or the vault geometry must be altered. These structural calculations are based on preliminary 2D Graphic Statics and finite element analysis using Abaqus (Dassault Systemes, 2019) as seen in

Table 1. Summary of Structural Design Attributes

Property	Description
Vault Dimensions	8 x 8 m
Vault Rise	Less than 1 m
Transport Constraints	Shortest edge must not exceed 3-3.5 meters
Timber Density	C35 4.8 kN/m^3 (Study 01: Spruce CLT, Study 02: Boards)
Safety Factor (Material)	Material: 1.35, Loads: 1.5
Live and Asymmetrical Loads	1.5-2.0 kN/m^2, 2-3 kN
Floor Leveling	Heavy infill of earth-based products (15-16 kN/m^3)

Figure 3. Further physical tests are recommended to validate the results. The fabrication of how the shell is joined with a flat surface is a subject of future research.

2.1.1 *In-plane Connections*

The connector requires a 240 x 90 x 93 mm cutout as seen in Figure 2. The LVL timber element is sized as 128 x 78.5 x 90 mm, and the inner thin part is 27.7 x 40 x 90 mm. The angles are set at 45°. The distance between two connectors ranges 300 mm - 3000 mm. Within 120 mm CLT, joint can withstand tensile forces of up to 35 kN and shear forces of up to 40 kN. The joint is integrated into the `compas_wood` package Vestartas [2021]. Asymmetrical and buckling loading require a moment-resistant connection, which suggests joinery acting from both the bottom and top of the panel. If necessary, the thick steel bolt can be replaced by two smaller ones positioned at the top and bottom of the joint. 30 mm of timber is left from the bottom of the panel for fire safety. The development was supported thanks to collaboration with Hilti and Balteschwiler AG.

Table 2. Connection Properties

Mechanical resistance and stability	Level / Class
Tensile – strength ($R_{t,k}$), Tensile – slip modulus ($K_{ser,t}$)	35 kN, 10 kN/mm
Shear – strength ($R_{v,k}$), Shear – slip modulus ($K_{ser,v}$)	40 kN, 10 kN/mm
Reaction to fire for Plywood, min. density 400 kg/m^3 (EN 13501-1)	D-s2-d0

Figure 2. Detachable joint made from Laminated-Veneer-Lumbner (LVL) and steel bolt.

2.1.2 *Planar Quad Geometry with Constant Conic Offset*

The planar quad geometry with constant planar edge offset is developed and open-sourced via COMPAS framework and the publicly available package `compas_timbervaultedfloor`. First, a sphere is created from three points defining the vault dimensions. The square boundary is then subdivided, and frames are created, while orienting from the lowest sphere point to the U and V edges of predefined vault distances. A grid of intersection points is computed. Planar polygons and their normals are stored, followed by the generation of the vertex offset method. Normal computation is necessary for planar extrusion of edges and planar offset polygons. Finally, border polygons are cut with vertical planes to obtain flat side edges as shown in Figure 4. The results of these geometrical operations are serialized to transfer data from the

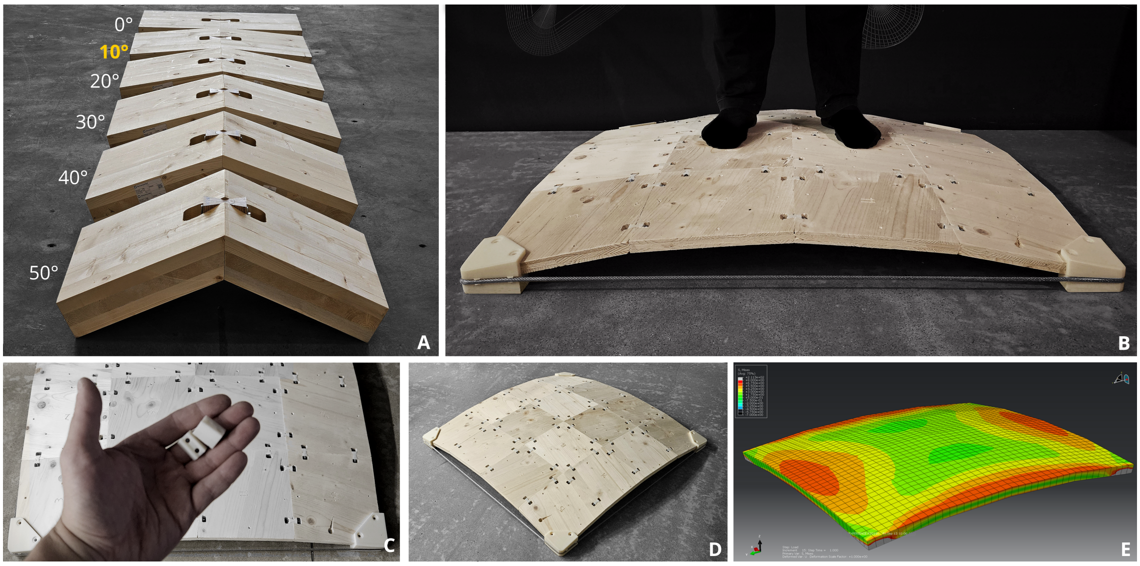

Figure 3. A - 120 mm CLT and joinery angle check, B - plate and cable, C - printed 19 mm joints, D - vault di-hedral angles are within 10°, E - stress analysis showing concentration of forces on shell edges twice to joint capacity.

`compas_timbervaultedfloor` package to the `compas_wood` package. The later generates connections for display and fabrication. Fabrication was performed using CNC machines: larger two-panel connection samples were cut with a 5-axis Techno-Wood CNC machine, and a small-scale panel prototype was made with a 3-axis CNC machine by incrementally cutting inclined corners.

2.2 *Study 02: Triangulation of linear Timber boards*

Wood, predominantly available as straight beams, exhibits clear anisotropic properties, with significantly greater strength in the longitudinal direction of the fibers than orthogonal to them. This property should be exploited similarly to classic beam-based, one-directional spanned timber floor slab systems. Investigations of current timber systems have revealed various methods for constructing short-span structures. For longer spans, the hollow box system by "Lignatur" represents an optimized solution within our group of investigated systems. It uses raw material with minimal glue and reduces material usage through its geometric form. Despite their advantages, these systems are typically limited to one-directional spans. The only exception is CLT, which also has primary and secondary axes. In a two-way span system, the top and bottom layers must span in the same direction to absorb the greatest stress moments. Therefore, we aim to develop a new two-way span system as an alternative to high glue and timber ratio CLT floor systems and single-direction boxed systems.

Complex geometries made of wood are usually cut from standard wooden boards, resulting in considerable waste and additional financial outlay. The aim is to find geometries that minimize waste. By making a single diagonal cut through a rectangular board, triangular elements are obtained. These can be rearranged to create another rectangular surface, directing the wood fibers' forces to the four corners. Two identical triangles, glued together with vertical rectangular boards, create boxes similar to the Hollow Box system from Lignatur, but in this case, they are triangular. These triangular box elements are arranged so that the wood fibers correspond to the expected force flows within a panel spanning between four supports. This approach maximizes the structural properties of the material while minimizing processing steps, glue usage, and waste as seen in Figure 5.

The production of a vaulted wooden floor panel system requires precise bonding at specific angles to achieve the desired curved shape. The complexity of this system arises from the requirement that each triangular board must be fixed at an individual angle, which requires a complex manufacturing process: To accomplish this, the saw blade used in the cutting process would often need to be adjusted in angle to accommodate the variety of triangular components. Another factor,

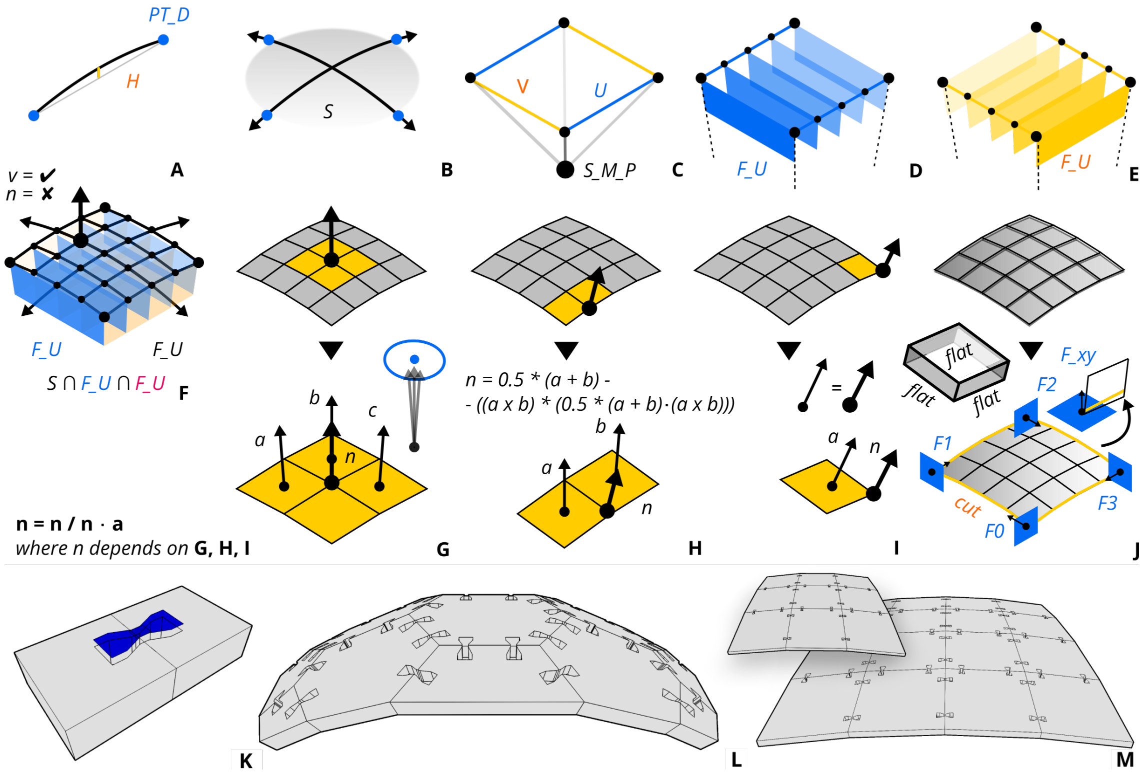

Figure 4. Planar quad mesh: A - circle from vault's opposite diagonal points and maximum rise, B - sphere from circle, C - four corner points of the vault and the sphere's bottom point, D - generate frames in the u and, E - v direction, F - sphere-frame intersections, G - inner vertex normal, H - boundary two-valence normals, I - corner normals, J - cut the boundaries, K - flat plates, L - planar 3-valence hex-subdivision, M - quad tesselation.

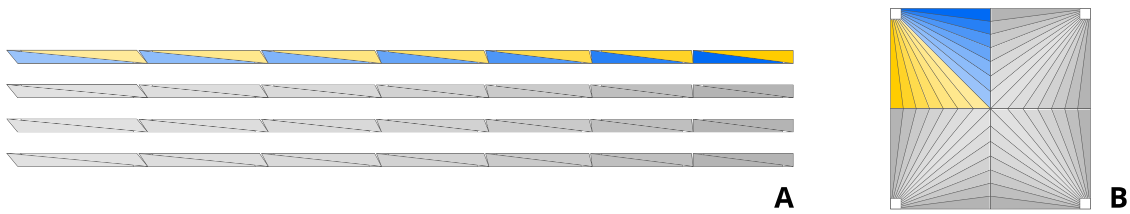

Figure 5. Rearranging Timber: A - linear boards, cut diagonally, B - Rearrangement of sawn timber elements.

that complexities this is the movement of the natural material. When using unglued wood, such necessary precision is almost impossible to realize, as the wood can distort considerably if there is no glue to prevent this. In order to develop a system that is based on a fabrication process that is as reduced as possible, an important goal is to minimize the number of incisions required in order to simplify production. In this case, the number of angled edges should be minimized, especially along the longitudinal edges. To optimally transfer the loads in a curved ceiling to the four supports, the boards can be positioned vertically instead of horizontally. They can be aligned so that a 90° angled corner on the top forms a flat surface that can be covered with additional boards and floor structures. The diagonal cuts correspond to the expected force paths and transfer the loads to the four supports. Figure 6 illustrates this vertical integration of the boards and shows how the realignment enables a more efficient force distribution path while reducing the complexity of the manufacturing process. The heavy infill of the floor can be placed directly on top of the floor surface or created by forming a flat bottom layer and adding the infill directly within the triangular boxes.

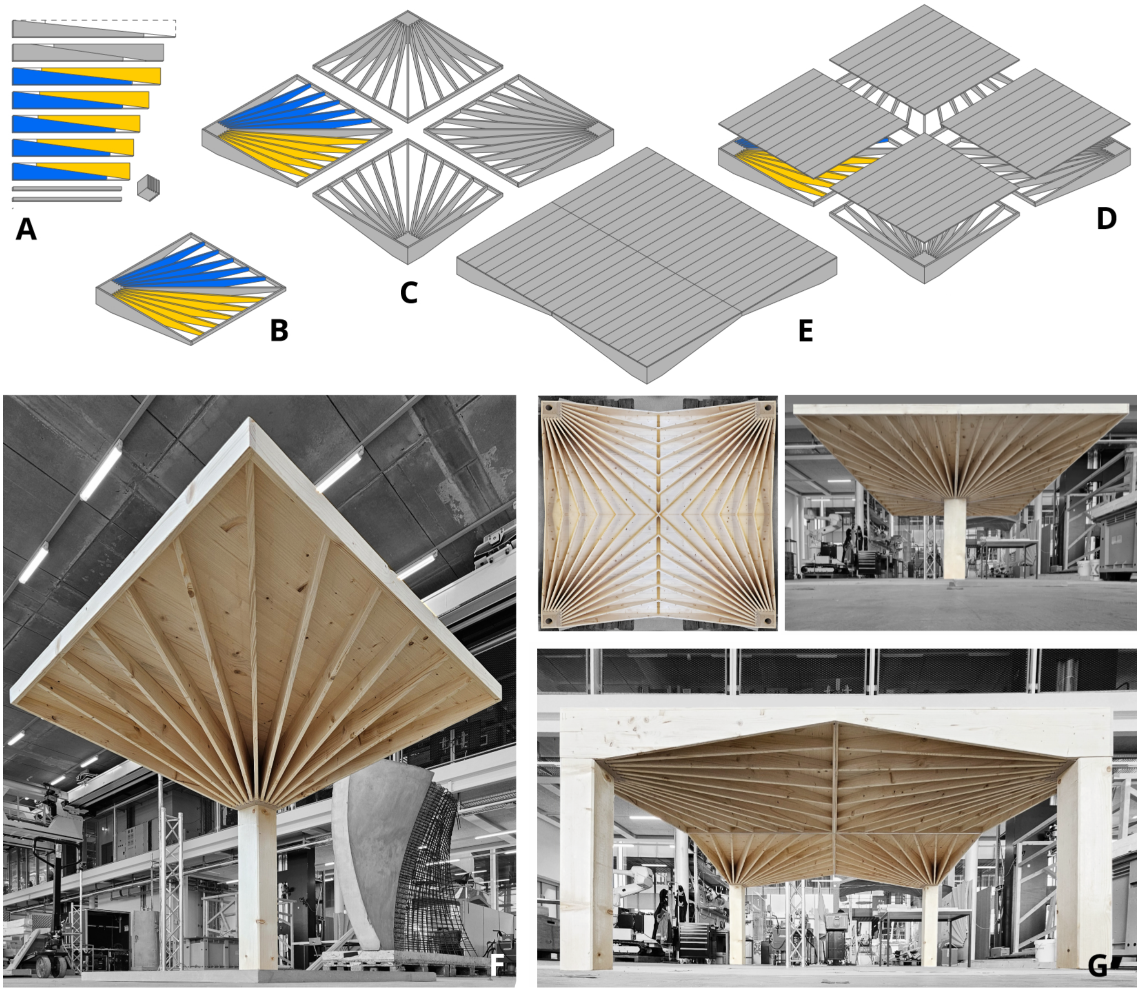

Figure 6. Rearranging Timber: A - linear boards, cut diagonally, B - one quarter of floor, C - four modules, D - added flat boards on top, E - final floor slab, F - one quarter prototype, G - four quarters.

3 OUTLOOK AND CONCLUSION

The research began with a review of papers on timber floor systems, followed by visits to multiple timber companies. These companies have well-developed floor systems but often do not prioritize optimal material use and are frequently oversized. Some exceptions focus on sustainable solutions, such as earth-timber hybrids. Timber solutions are priced similarly to other materials due to lower structural loads and high automation. The automation in timber companies includes grading timber in production, reusing structural by-products, custom pressing and cutting methods, and various glue or friction-based techniques. Several interviewees explained that timber floor can be optimized further and novel could be developed together with highly automated fabrication processes. Material reduction as a sustainable solution is often lacking in timber practices but needs to be addressed, especially for highly repeatable, large-scale applications.

Based on observations, two studies were initiated: a) Panelized CLT Timber Vaulted Floor, and b) Triangulated Boxed Timber Floor. The first study explored detachable connectors for tight interfaces between CLT panels, starting with existing two-direction industrialized timber products. The second study focused on minimal timber and glue use. Engineers provided insights that vault boundary conditions are critical due to stress concentrations, requiring stiffening by a) boundary beam elements, b) folding edges, or c) increasing static height with ribbed or box systems. Further studies are needed to understand the structural behavior and environmental impact of these floors. Emphasis will be given for detailing including column-head connections, joinery between slab elements and heavy infill. A third option could involve bending timber into cylindrical segments, but its economic feasibility needs to be proven.

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