From Formwork to Form Freedom

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Abstract

The growing urgency of addressing environmental challenges in construction emphasizes the need for sustainable materials like timber. Wood, particularly in the form of engineered products such as Glulam, offers unparalleled advantages for architecture due to its structural efficiency, aesthetic appeal, and significantly lower environmental impact compared to conventional materials like steel and concrete.

Despite these advantages, significant challenges remain in the production of curved timber elements. Traditional approaches rely heavily on labor-intensive processes and custom molds, which result in limited design flexibility, material waste, and prohibitively high costs. These constraints hinder the widespread adoption of curved timber components, which hold potential for enhancing structural performance and architectural innovation.

This research presents a robotic fabrication workflow designed to overcome these limitations. By integrating computational design and robotic systems, the proposed method simplifies and accelerates the production of single and double-curved Glulam elements. This approach reduces the reliance on formwork, minimizes material waste, and enhances design freedom. The solution offers architects and engineers the ability to create more intricate and sustainable timber structures, paving the way for a broader application of curved timber in modern architecture.

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Introduction

Environmental Impact of Materials

In the construction industry, material selection has significant consequences for the environmental impact and sustainability factor of a project. Common materials such as timber, concrete, steel have different environmental impacts, based on the raw material extraction, manufacturing, and production processes inherent to their use as construction materials.This section examines the environmental impact of these three key construction materials by focusing on their raw material sourcing, manufacturing emissions, and end-of-life recycling potential. Exploring these aspects highlights both the challenges and opportunities for reducing the ecological footprint of construction. These three points of analysis are commonly referred to as Life Cycle Assessment (LCA), a systematic approach used to evaluate the environmental impacts of a product across its entire life cycle, from raw material extraction to disposal or recycling.

Since industrialization began, global temperatures have risen due to greenhouse gases (GHG) caused mainly by human activities (Leyder et al., 2021). This makes reducing GHG emissions and saving energy essential. Following the 2015 Paris Climate Agreement, Switzerland pledged to cut its GHG emissions in half by 2030 (compared to 1990 levels) and reach net-zero emissions by 2050 (Leyder et al.). Reaching net-zero emissions means the country will manage to balance the amount of GHGs emitted with an equivalent amount removed from the atmosphere, through methods such as reforestation for example. In Switzerland, buildings are responsible for about 25% of all GHG emissions and 45% of energy use (Leyder et al.). While most emissions stem from the operation phase of buildings, ongoing advancements in energy efficiency are reducing emissions during this phase. As operational emissions decline, the relative significance of embo-

died emissions, those associated with the production of construction materials and the construction process itself, is increasing. A study estimates that the contribution of construction materials to the total life cycle emissions of residential buildings in Switzerland is projected to rise from 19% in 2015 to 39% by 2050 (Allan et al., 2022). As a result, the environmental impact of producing building materials and constructing buildings is becoming more important.

Raw Material Sourcing

Timber in Switzerland is mainly sourced from managed forests, which cover 32% of the country's land area (Forest and Wood: In Brief, 2022). Managed forests are areas where timber harvesting is regulated to maintain ecological balance. As multifunctional ecosystems, they offer vital services. They supply timber, protect against natural hazards, maintain healthy soils, and positively impact drinking water supplies. Additionally, they store CO_2, provide spaces for recreation, and help cool urban areas during hot weather. The Swiss Forest Act makes reforestation after logging mandatory and prohibits clear-cutting (Federal Act on Forest, 1991). As a result, Swiss forests sequester an estimated 3 million tons of CO_2 annually (Annuaire La forêt, 2023).

Unlike timber, steel is more difficult to find in the Swiss landscape. Steel used in Switzerland is predominantly imported due to limited domestic production capacity. The environmental impact of steel raw material sourcing is largely driven by the extraction of iron ore and the mining of scrap metal. Iron ore mining, in particular, can result in habitat destruction, soil erosion, and significant CO_2 emissions from the use of heavy machinery and transportation. The transportation of raw materials, especially over long

distances, also contributes to greenhouse gas emissions.

As for concrete, it relies on locally sourced aggregates and cement, which helps minimize transportation emissions. In fact, 86% of the cement used is sourced domestically (swisstopo, 2020). In Switzerland, limestone quarries, a primary source for cement production, are subject to stringent environmental impact assessments to mitigate land degradation and ensure sustainable extraction practices. These assessments help to minimize habitat destruction, soil erosion, and other environmental concerns associated with quarrying. However, the sourcing of raw materials, particularly limestone, still carries environmental risks, including the disturbance of ecosystems and the consumption of energy during extraction and transportation.

Manufacturing Emissions

The global warming potential emissions from material production for timber buildings are almost fully balanced by the carbon stored in the wood products (Buchanan et al., 2013). When compared to concrete or steel buildings, the material production and disposal of timber buildings result in only half to two-thirds of the carbon dioxide equivalent emissions, regardless of the end-of-life scenario (Buchanan et al.).

Steel manufacturing is a significant contributor to global greenhouse gas emissions. In 2019, the production of each ton of steel on average resulted in the emission of 1.851 tons of CO2 (World Steel Association, 2021). In 2020, global steel production amounted to approximately 1.86 billion tons, contributing to total direct emissions of around 2.6 billion tons of CO2 (World Steel Association). This accounted for between 7% and 9% of global hu-

man-caused CO2 emissions, highlighting the significant environmental impact of the steel industry (World Steel Association).

In 2017, Switzerland emitted over 47 million tons of CO2 equivalent, with 2.51 million tons originating from cement production, representing 5.3% of the total emissions (swisstopo, 2020). In cement manufacturing, one-third of the CO2 emissions are attributed to the combustion of fuels needed to reach the calcination temperature of 1450°C. The remaining two-thirds are due to the calcination of the raw mix containing limestone, which is essential for producing clinker.

End-of-Life and Recycling Potential

Timber has considerable recycling potential at the end of its life cycle, supporting sustainable construction practices. When buildings are deconstructed, timber elements can be repurposed for new structures, extending their usability and reducing the demand for new raw materials (Hafner et al., 2014). Solid and engineered wood products can be reclaimed and reused in construction, furniture making, or as raw materials for composite products like particleboard. Recycling timber also helps maintain the carbon stored within the wood, minimizing its environmental impact. Designing timber structures with reuse in mind can further enhance their sustainability by facilitating easier material recovery.

Steel is one of the most recyclable materials, capable of being melted and reused indefinitely without significant quality loss (World Steel Association, 2021). Recycling steel involves collecting and processing scrap, then melting it in furnaces to produce new products. This process requires considerably less energy and generates lower

CO_2 emissions compared to producing steel from raw iron ore. Improving scrap steel collection and processing efficiency can further reduce the industry's environmental impact.

As for concrete, recycling plays a vital role in minimizing its environmental impact by reusing materials from demolished structures. The process involves crushing and processing old concrete into recycled concrete aggregates, which can replace natural aggregates in new construction projects. This reduces the demand for raw materials and lowers the energy consumption and CO_2 emissions associated with quarrying and transporting virgin aggregates (Estévez et al., 2006).

Context: Timber Construction

In Switzerland, timber construction is being widely discussed and has started to be prioritized over other construction materials for sustainable reasons. Under the 2015 Paris Climate Agreement, Switzerland has committed to achieving net-zero greenhouse gas emissions by 2050, and timber structures are recognized as a key solution due to their low embodied energy and emissions. The use of timber in construction is steadily increasing: in 2018, 14 percent of building permits for new single-family houses and 7.5 percent for multi-family houses were for timber structures, compared to 12.6 percent and 6 percent, respectively, in 2011 (Leyder et al., 2021).
Swiss forests have significant potential to support this trend sustainably. Of the estimated 6.1 million m^3 of timber that can be sustainably harvested annually, only 5.2 million m^3 were harvested in 2022 (Annuaire La forêt, 2023). This highlights the untapped capacity of Swiss forests to support the increasing demand for timber in construction. This chapter delves into three important aspects of timber construction: the growing adoption of mass timber products, the potential of prefabrication in controlled environments using advanced technologies, and the integration of digital and robotic methods for fabrication and assembly. These elements together underscore timber's potential to revolutionize sustainable building practices.

Mass Timber Products

Concrete and steel have dominated the construction industry for centuries due to their strength, durability, and versatility (Abed et al., 2022). However, their production processes are highly energy-intensive. In response to this challenge, mass timber construction has emerged as a sustainable alternative that offers structural, environmental, and aesthetic benefits. Mass timber is a family of engineered wood products designed to be used as primary structural materials in mid- to high-rise buildings. Products such as Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), Nail Laminated Timber (NLT), Dowel Laminated Timber (DLT), and Structural Composite Lumber (SCL) demonstrate timber's potential to replace conventional materials like concrete and steel in many applications.

- Cross-Laminated Timber (CLT) is one of the most innovative and widely adopted mass timber products. Developed in Europe during the 1990s, CLT consists of layers of lumber boards arranged perpendicularly to one another and bonded using structural adhesives (Abed et al.). This cross-lamination process imparts dimensional stability, exceptional strength, and stiffness to the panels, making them ideal for prefabricated wall, floor, and roof elements. Additionally, the precision manufacturing process, which uses Computer Numerical Control (CNC) machinery, reduces material waste and ensures tight tolerances.

- Glued Laminated Timber (Glulam) is composed of layers of lumber bonded with adhesives. The laminations are aligned with the grain running parallel to the member's length, resulting in a product that combines strength, durability, and design flexibility. Glulam members can be manufactured in custom sizes and complex shapes, making them suitable for beams, columns, and architectural elements (Abed et al.).

- Nail Laminated Timber (NLT) is one of the oldest mass timber products, used historically in warehouses and factories. NLT is created by placing dimensional lumber edgewise and fastening them together with nails,

resulting in a solid, structural element suitable for floors, walls, and roofs (Abed et al.).

- Dowel Laminated Timber (DLT) is a relatively new innovation in the mass timber industry and offers a fully mechanical alternative to other engineered wood products. DLT panels are made by stacking dimensional lumber and connecting them with hardwood dowels. This method eliminates the need for adhesives or nails, resulting in a non-toxic, fully recyclable product that aligns well with the principles of circular construction (Abed et al.).

- Structural Composite Lumber (SCL) represents a family of engineered wood products that include Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), and Laminated Strand Lumber (LSL). by gluing together smaller pieces of wood to create one solid structural member. SCL products are known for their high strength and reliability, making them suitable for demanding structural applications such as beams, headers, and columns (Abed et al.).

Mass timber's growing adoption extends beyond its environmental benefits. Recent research has demonstrated its reliable fire performance through predictable charring behavior, allowing safe use in tall buildings (Michael Green, 2017). Studies have also shown that exposed wood in buildings significantly enhances occupant well-being by reducing stress levels and improving cognitive performance (Strobel et al., 2017). These proven advantages in both safety and human health have helped drive mass timber's increasing acceptance in construction.

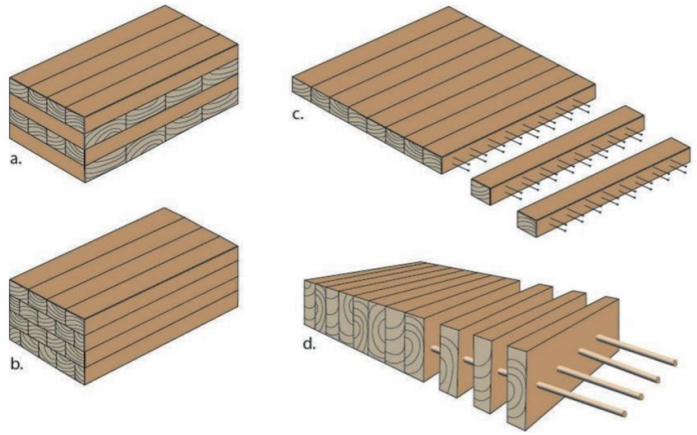

Figure 1
The main mass timber types: Cross-Laminated Timber (A); Glued Laminated Timber (B); Nail Laminated Timber (C); Dowel Laminated Timber (D)
(Abed et al.)

Prefabrication

Another key advantage of mass timber construction lies in its prefabrication potential, which offers numerous benefits over traditional building methods. One of the most significant is the remarkable speed of construction it enables. Mass timber buildings can be erected at an impressive rate of 3-4 days per story, compared to the 28 days per story typically required for reinforced concrete construction (Abed et al., 2022). Prefabrication in timber construction ensures high-quality production in controlled environments, significantly reducing the likelihood of errors and additional costs during on-site assembly. Timber structures are quickly made weather-tight, allowing interior work to commence without delays, further streamlining the construction process. The dry construction method inherent to timber eliminates waiting times, enabling quicker project completion and allowing occupants to move in immediately after finishing.

This method requires detailed planning, particularly for integrating building systems and services. However, this upfront effort ensures efficient prefabrication, precise assembly, and high construction standards. Computational design and robotic fabrication enhance this process by enabling an integrated design-production workflow, improving material efficiency, optimizing resources, and facilitating the creation of structurally complex designs.

Robotics also reduces or eliminates the need for formwork, simplifying manufacturing and broadening design possibilities. These innovations, explored further in subsequent sections, make timber prefabrication a reliable and attractive option for modern construction.

Figure 2
Truck loaded with prefabricated timber elements at JPF-Ducret, Orges. Photo taken during site visit on December 11, 2024.

Digital and Robotic Innovations

The final aspect of timber construction explored in this section is the integration of digital and robotic methods for fabrication and assembly. These advancements are transforming the way timber components are designed, manufactured, and assembled, offering unprecedented efficiency and precision (Krieg & Lang, 2019). The widespread use of Computer Numerical Control (CNC) machinery is at the forefront of these methods, which has become a standard tool in the timber industry. CNC systems enable highly accurate cutting, drilling, and shaping of timber components based on digital designs, ensuring consistent quality while minimizing material waste. They are particularly well-suited for producing mass timber products like Cross-Laminated Timber (CLT) and Glulam. During my visit to the JPF-Ducret facilities in Orges, a leading timber construction expert in French-speaking Switzerland, I observed that every element leaving the factory undergoes processing through one of their multiple CNC machines.

Building on the capabilities of CNC, robotic systems are increasingly being used to extend the possibilities of digital timber fabrication. Robots add versatility to the fabrication process by automating not only cutting and shaping but also the assembly of components into larger, more intricate structures. A prominent example is the robotic fabrication of timber trusses, as demonstrated by ETH Zurich. Using industrial robots, complex timber trusses are assembled with precision and efficiency, allowing for customized geometries that would be difficult to achieve through traditional methods.

Figure 3
Robotic assembly of large timber trusses for the ETH Zürich Arch_Tec_Lab. (Krieg & Lang, 2019)

Context: Glulam

Glulam, short for glued laminated timber, is a composite material that offers greater mechanical uniformity and superior strength compared to solid wood. It is constructed by arranging thin wooden laminates with their grains aligned parallel and bonding them with structural adhesives. The origins of Glulam date back to the early 20th century, when advances in industrial fabrication and timber construction methods began to emerge (Rinke & Haddadi, 2021). Otto Hetzer's invention in Germany in 1906 laid the foundation for modern Glulam technology, which quickly spread to other countries, including Switzerland. Swiss engineers Bernhard Terner and Charles Chopard acquired the rights to Hetzer's patent in 1909, pioneering numerous glulam structures for industrial, cultural, and public purposes (Rinke & Haddadi). Over time, the versatility and economic efficiency of Glulam made it a preferred choice for large-span structures, especially in periods when steel and other materials were scarce or expensive. This chapter explores Glulam's technical performance, its production process, and the architectural potential of curved elements. These aspects demonstrate why Glulam is essential for sustainable and versatile construction.

Technical Performance of Glulam

Glulam's technical properties make it an outstanding alternative to traditional materials such as concrete and steel in modern construction. The Constructive Quality Ratio (CQR), a metric that evaluates the efficiency of materials by comparing their structural performance relative to weight, highlights Glulam's superiority. Glulam achieves a CQR of 2.2, outperforming steel (0.55) and concrete (0.06), indicating its exceptional efficiency in providing structural strength without excessive weight (Zhuravlev & Zhuravleva, 2020).

	Concrete	Steel	Glulam	Wood
Lifetime (years)	100	50	100	100
Density (Kg/m3)	2500	7800	330-400	330-900
Constructive Quality Ratio (CQR)	0.06	0.55	2.2	<2.2

Table 1
Properties of main construction materials (Zhuravlev & Zhuravleva).

Glulam's density ranges from 330 to 400 kg/m³, in comparison, concrete has a density of 2,500 kg/m³, and steel reaches 7,800 kg/m³ (Zhuravlev & Zhuravleva, 2020). This lower density not only makes Glulam easier to work with but also contributes to its effectiveness in load-bearing applications, particularly in large-span structures where weight reduction is critical (Kuzman et al., 2010).

Additionally, Glulam offers remarkable durability. Its lifespan of approximately 100 years ensures long-term structural integrity, comparable to traditional wood and exceeding that of untreated steel, which typically lasts around 50 years. Its ability to remain structurally sound over time adds to its value as a sustainable and reliable construction material (Zhuravlev & Zhuravleva, 2020).

Glulam's technical performance enables architects and engineers to design innovative structures that are both functional and environmentally responsible, solidifying its role as a cornerstone of modern architectural and structural design.

The Glulam Production Process

The production process for glue laminated timber may vary slightly from one country to another but most of the time it will follow the same sequence of operations.

The typical production site is divided into five main steps organized in five different areas of the factory.

- Area A – Preparation of the planks
- Area B – Finger jointing
- Area C – Gluing process
- Area D – Finishing/post-processing
- Area E – Preparation of the adhesives

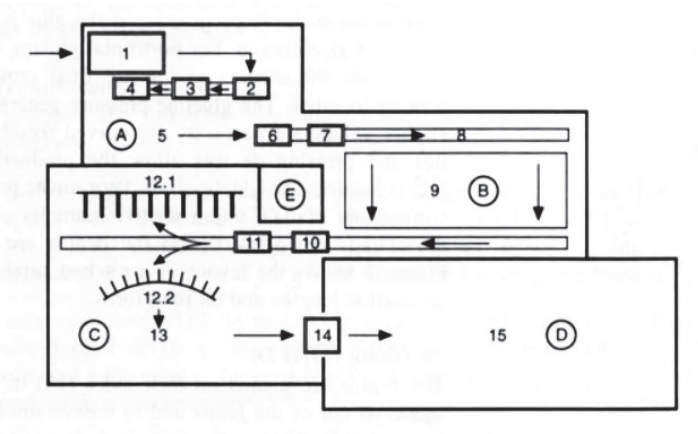

Figure 4
Typical production process for glulam.
(Colling, 1995)

Area A - Preparation of the Planks

Usually, the factory buys the planks directly from a sawmill that provide them with a timber according to the factory requirements. All the planks have a constant thickness of maximum 50mm and lengths ranging from about 1.5m to 5m (Colling, 1995). The choice of the thickness depends on the final product that must be produced, for example a straight glulam beam will be made with much thicker planks than a curved element with a small radius. According to the European Standard EN 14080:2013 the thickness of lamellas in curved glulam beams is limited to 1/200th of the minimum radius of curvature to ensure the wood can bend smoothly without cracking or delamination (Svilans, 2021). This guideline helps maintain structural safety and durability in curved timber applications.

The adhesives used in the next steps of the production require the moisture content of the wood to be under 15% (Colling, 1995). Therefore, the first step (1) is to dry the planks using either air drying or kiln drying. By placing wood in a specialized chamber, known as a kiln, and applying heat and controlling humidity, the natural drying process is significantly accelerated compared to traditional air drying. This method focuses on removing moisture evenly and consistently, which helps prevent issues like warping, cracking, or other distortions that can arise from uneven or rapid drying of wood.

Once the planks are correctly dried, they are pre-planned (2) using a planer machine, a tool used to smooth and flatten the surfaces of the wooden boards while reducing their thickness to a precise dimension. It works by shaving off thin layers of wood using rotating blades or cutting knives set at a specific height.

After exiting the planer machine, the planks pass immediately through an X-ray machine (3) to map their density. This process evaluates the strength of each plank, verifies overall quality, and identifies the placement of possible knots. This process will later enable the optimal arrangement of the planks to ensure consistent quality throughout the length of the final product.

Then, each plank's ends are cut off in preparation for the finger jointing (4) and the planks are stock piled (5).

Area B – Finger Jointing

At this stage, all planks are a maximum of 5 meters long. To extend their length, finger joints are cut into the end grain (6), allowing the planks to be glued together seamlessly to form longer elements. The planks are then pressed together for at least two seconds (7) such that the friction between the fingers of the joints keeps the planks together during handling (Colling, 1995). The continuous section is then cut (8) into the laminations of the required lengths depending on the size of the final product. Finally, the planks must be stored (9) for a minimum of eight hours to ensure the curing of the glue in the joints (Colling, 1995).

Figure 5
Machine for Joining Planks End-to-End with Finger Joints at the JPF-Ducret Facility in Orges.
Photo taken during site visit on December 11, 2024.

Area C – Gluing Process

All the planks are planed again (10) to ensure the removal of any remaining rough surfaces, inconsistencies at the finger joints, and excess. After planning, the planks pass through a glue curtain (11), where they are evenly coated with adhesive. Once coated, the planks are rotated 90 degrees to stand on their sides and are carefully aligned and placed one after another between large clamps, which apply consistent pressure to bond them together securely.
The positioning of the jigs in the clamps determines the production of either straight elements (12.1) or curved elements (12.2), depending on the design requirements. To ensure optimal results, the clamps create a pressure ranging from 0.4 to 1.2 N/mm², sufficient for forming a strong and durable bond (Colling, 1995). The glued laminations must remain clamped for a minimum of six hours under controlled conditions of 20°C temperature and 65% relative humidity (Colling). This curing period allows the glue to set properly and achieve maximum strength.
After the curing time, the clamps are released, and the bonded beams are stacked (13) in preparation for the final finishing process, ensuring they are ready for their intended application.

Figure 6
Planks Passing Through a Glue Curtain at JPF-Ducret Facility in Orges. Photo taken during site visit on December 11, 2024.

Area D – Finishing / Post-Processing

The beams are planned on their sides (14) in order to remove residual adhesive squeezed out of the joints and to ensure smooth surfaces. Finally, the beams are finished (15). The finishing process can be either fully manual or fully automated, depending on the factory setup and the complexity of the parts being processed. In manual operations, workers use large circular saws to trim the beam ends, ensuring they are neat and clean. Additionally, holes may be drilled manually for future mechanical connections. Alternatively, the same tasks can be performed entirely automatically using large-scale CNC machines equipped with 3 to 5 axes and various milling and drilling tools. These machines offer significantly faster and more precise results, particularly beneficial when working on beams with complex geometries.
Finally, the beams are wrapped to protect them from damage and dirt during transportation, whether they are being sent to another factory for further processing or directly to the construction site for assembly.

Area E – Preparation of the Adhesives

A dedicated area in the factory must be set aside for storing and preparing adhesive compounds, typically consisting of a resin and hardener. This space also holds essential tools like precision scales for mixing, cleaning supplies, and safety equipment to ensure proper handling. Maintaining appropriate environmental conditions in this area is crucial for ensuring the quality and effectiveness of the adhesives.

The fifteen steps outlined in this chapter are standard in most factories producing glue-laminated products. This method has remained largely unchanged for over 50 years, demonstrating its robustness and effectiveness, although it faces some challenges discussed in the next chapter. The process described here theoretically enables the production of beams with unlimited dimensions. Glulam beams with depths of up to 2.0 meters and lengths of 30 to 40 meters are technically feasible and not uncommon.

However, practical limitations arise due to factors such as the open time of the adhesive, the capacities of planning machines, production hall dimensions, and architectural requirements. Transportation also imposes significant constraints, as glulam beams exceeding 16 meters in length, 2.5 meters in width, or 3.5 meters in height require special arrangements, such as police escorts (Colling, 1995). Additionally, the transport route may include low bridges, tunnels, or tight curves, making it impossible to deliver overly long elements.
This glulam manufacturing process accommodates a wide variety of beam shapes. Producing curved beams, however, requires adjustments to jigs and pressing devices for each new geometry, leading to longer production times compared to straight beams.

Architectural and Structural Possibilities with Curved Glulam

One key architectural feature of Glulam is its ability to be manufactured into curved elements, made possible by its unique production process. Thin timber layers, known as lamellae, are bonded with strong adhesives, allowing the material to take on complex shapes beyond traditional straight beams and columns. Unlike the labor-intensive and expensive process of bending finished steel, Glulam's anisotropic, fibrous structure makes it naturally suited for crafting curved elements and surfaces with minimal effort during production. This method not only simplifies fabrication but also optimizes material distribution, reducing overall dimensions and weight, which results in significant material savings (Zhuravlev & Zhuravleva, 2020).

Beyond its structural benefits, Glulam's natural color and texture add considerable aesthetic value. While synthetic materials can replicate various finishes, the authentic texture and unique fiber patterns of natural wood set Glulam apart. Its intrinsic beauty eliminates the need for additional artificial decoration, offering a high aesthetic quality that enhances architectural expressiveness.

Reflecting Vitruvius's principles of architecture: firmitas (strength), utilitas (function), and venustas (beauty), Glulam excels in all three (Zhuravlev & Zhuravleva). Its strength ensures structural reliability, its adaptability allows for diverse functional uses, and its natural warmth and ability to form elegant curved shapes enrich the visual impact of architectural designs.

Figure 7
- Central Mosque, Cambridge, (Marks Barfield Architects, 2019)
- Swatch/Omega Factory, Bienne, (Shigeru Ban, 2019)
- Pompidou-Metz Center, Metz, (Shigeru Ban, 2010)

These three examples beautifully illustrate how curved Glulam embodies Vitruvius's principles. In the Cambridge Mosque, the bent Glulam elements serve ornamental purposes, enhancing the spiritual and aesthetic atmosphere. The curved structures at the Swatch Group Headquarters enable large spans, demonstrating their functional efficiency. Meanwhile, the Centre Pompidou-Metz showcases Glulam's ability to achieve complex geometries, merging structural innovation with architectural elegance. These projects highlight the versatility and elegance of curved Glulam in modern architecture.

State of the Art

The field of curved Glulam manufacturing has been the subject of several research projects, resulting in a range of innovative techniques designed to push the boundaries of timber construction. The applied methods aim to enhance precision, efficiency, and adaptability in producing both single and double-curved Glulam elements. In this chapter, existing research on curved Glulam manufacturing is reviewed and compared to the methods currently employed in the construction industry. This comparison provides insight into how advancements in the controlled research environment might influence practical applications in industry.

The discussion is structured into three key categories: double curvature via cutting and subtraction, gantry systems for single and double curvatures, and the formwork-free approach. Each method represents a distinct strategy for achieving curved Glulam forms, reflecting the evolving techniques and technologies in this field. This chapter aims to provide a comprehensive overview of the current state of the art in curved Glulam manufacturing.

Double Curvature via Cutting and Subtraction

The Standard Industry Approach

In the construction industry, double-curved Glulam elements are primarily produced using milling tools, a subtractive manufacturing method. This process involves carving complex geometries from larger timber blocks, starting with single-curved components. While milling tools offer high precision and are capable of achieving intricate shapes, the method comes with significant drawbacks. The most notable is the substantial material waste, often exceeding twice the volume of the final product

(Chai, So, et al., 2021). This inefficiency contributes to higher production costs in terms of material consumption and time required for manufacturing. Moreover, when a single-curved beam is milled into a double-curved element, the wood fibers remain aligned with the original single curvature. This mismatch between the fiber orientation and the new geometry results in a final product that is not structurally optimized. The fibers are no longer aligned with the direction of applied stresses in the double-curved form, leading to a reduction in the material's load-bearing capacity (Chai, So, et al.).

During my visit to the JPF Ducret factory in Orges, I asked how they produce double-curved beams. The engineers explained that designing custom presses or gantry systems for such beams would be too complex and costly for them. Instead, they create a thicker single-curved beam and then use a CNC machine to mill the top and bottom faces to achieve the desired double curvature. Although this approach results in significant material waste, they noted it is still more practical and efficient than developing bespoke presses for each unique geometry. This highlights the challenges the industry faces in producing double-curved Glulam elements and why subtractive methods remain prevalent, despite their inefficiencies.

Research on Robotic Bandsaw Cutting

Robotic bandsaw cutting has emerged as a groundbreaking technique for producing double-curved Glulam elements, addressing key inefficiencies of traditional CNC milling. Two notable studies by Hua Chai and Philip Yuan delve into the development and application of this innovative method, showcasing its potential to transform timber fabrication. These studies focus on improving material efficiency and reducing production time.

The first study, Investigations on Potentials of Robotic Band-Saw Cutting in Complex Wood Structures (Chai & Yuan, 2019), explores the feasibility of robotic bandsaw cutting for creating both planar and spatially curved timber beams. Initial studies by Greyshed and Princeton University have highlighted the potential of this technique (Chai & Yuan). Further advancements by RMIT University have improved its application, concentrating on speed, precision, and material finish for customized designs. This research demonstrates how robots equipped with bandsaw end-effectors, can overcome the limitations of traditional CNC milling by achieving smoother cuts, reducing kerf width, and minimizing material waste.

The manufacturing of the curved beams for this project commenced in a manner consistent with the production of any conventional glulam element. A collection of lamellas was adhered together and positioned within a CNC formwork to establish the curvature of the timber beams. This segment of the process predominantly necessitates manual labor and lacks a guarantee of a high degree of precision.

After the individual curved beams were fabricated using traditional methods, a second stage utilizing a robotic system was employed for post-processing. A special bandsaw end-effector was installed on a KUKA KR120 robot, allowing a working range of 11 m x 6 m x 3.6 m, providing many possibilities for fabrication (Chai & Yuan, 2019). The previously manufactured beam is placed on a movable table equipped with woodworking clips to maintain it. After measuring the beam's position relative to the robot, a tool path is designed and simulated, as shown in the figure above. Each beam is cut four times, respectively top and bottom surfaces, and two end surfaces. The initial cross-sections of the beams were 100 x 100 mm and were reduced according to the different longitudinal cuts.

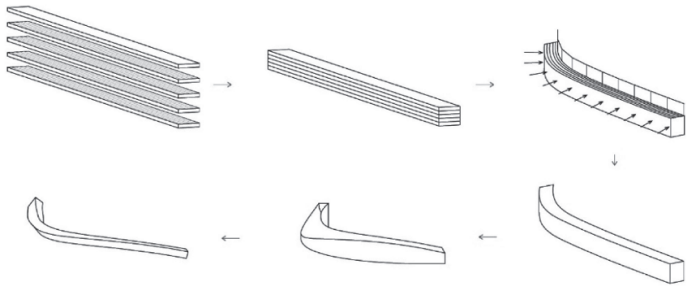

Figure 8
Diagram of raw beams production and cutting.
(Chai & Yuan, 2019)

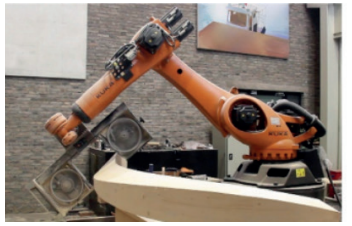

Figure 9
Robotic cutting simulation in KUKAlprc.
(Chai & Yuan, 2019)

A key application of this technique was showcased in a large-scale grid shell project. It consists of 16 beams, all plane curves with lengths ranging from 5.8 m to 7.5 m. Viewed from the top, it is an oblique quadrilateral grid system. The structure was designed in Grasshopper using the Millipede plugin to introduce structural performance-based design. Thanks to this novel fabrication method, complex three-dimensional ruled surfaces managed to be cut through the continuous rotation of the blades. It has demonstrated great efficiency and precision in producing three-dimensional curved wood surfaces. It achieves smoother and more continuous cuts than traditional CNC milling while reducing material waste, thanks to its minimal kerf.

Figure 10
Final structure.
(Chai & Yuan, 2019)

Following the groundwork established by the earlier study, Manufacturing double-curved glulam with robotic band saw cutting technique (Chai, So, et al., 2021) takes the research further by presenting a comprehensive framework for fabricating complex glulam geometries. This study addresses the challenges of double curvature by segmenting large beams into smaller, simpler sections. These manageable segments closely approximate the desired forms, reducing material waste and simplifying the production process.

The researchers utilized a dual-robot gantry system, with one robot dedicated to bandsaw cutting and another performing milling for interlocking joints. This collaborative approach eliminated the need for metallic connectors, emphasizing material efficiency and streamlined assembly. Each beam underwent a six-step process, including cuts along its top, bottom, and side surfaces, followed by precision joint preparation.
Parametric design tools played a crucial role in optimizing cutting paths and ensuring adaptability to varying geometries. The segmentation strategy not only improved production efficiency but also maintained the integrity of the final structure. The study's approach demonstrated the potential of robotic bandsaws to balance customization with industrial scalability, making it a viable alternative to CNC milling in modern timber construction.

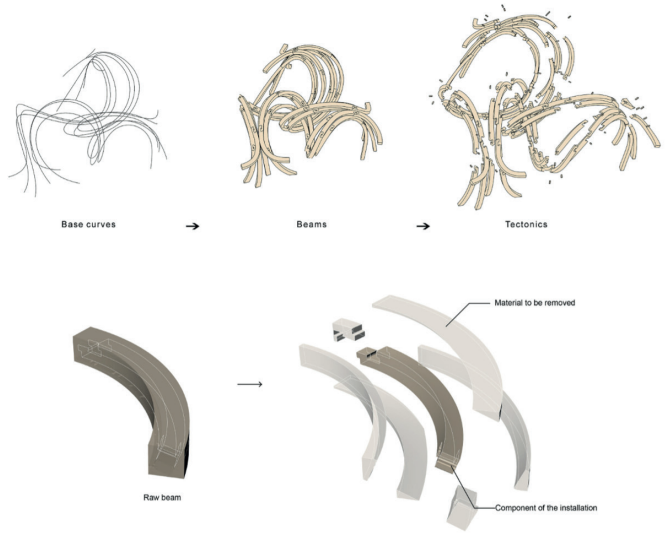

Figure 11
Curvature-based subdivision and beams cutting strategy design of the installation.
(Chai, So, et al., 2021)

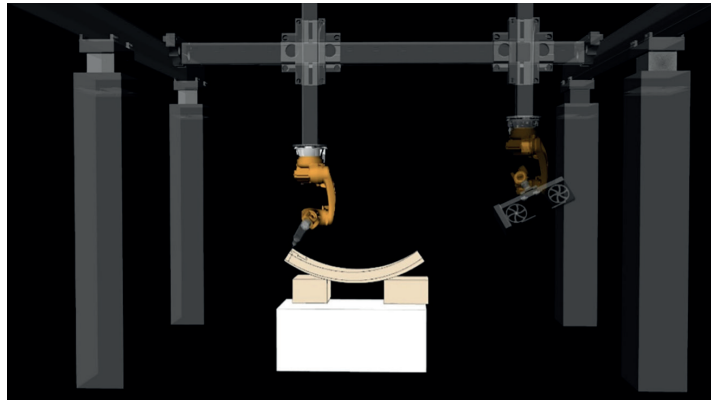

Figure 12
The robotic fabrication process method design and simulation.
(Chai, So, et al., 2021)

Gantry System for Single and Double Curvatures

This section investigates the use of gantry systems in fabricating single and double-curved Glulam elements, focusing on both industry practices and academic advancements. It is divided into two parts. The first part, Gantry Systems for Single Curves, explores how these systems are utilized in industry for simpler geometries and examines innovations from academic research. The second part, Gantry Systems for Double Curves, delves into the complexities of producing double-curved elements, highlighting the challenges faced in industry and the cutting-edge solutions proposed in academia.

Gantry Systems for Single Curves

In the timber industry, gantry systems are commonly used to produce single-curved Glulam elements, employing traditional jigs and formworks. The process closely resembles the production of straight beams, with the key distinction being that the clamps are arranged along a curved path rather than a linear one. Adhesives are applied to the lamellae as usual before they are positioned in the gantry. Pressure is then exerted by the gantry system to ensure proper bonding and precise alignment. Once the adhesive has cured, the curved Glulam element is removed from the mold, ready for further processing or installation.

Figure 13
Gantry system at JPF-Ducret, Orges, designed for producing single-curved beams. Photo taken during site visit on December 11, 2024.

While this approach is well-established, it presents two significant limitations. The first is the extended curing time required, with the pressed lamellae needing to remain in the gantry press for up to six hours. During this period, the gantry cannot be used for other beams, creating a bottleneck in production. The second limitation lies in the complexity and labor-intensive nature of fabricating the gantry itself. The process begins with drawing the desired beam's curve on the workshop floor to guide the placement of each clamp. Following this, the entire gantry setup, including clamps and supports, is assembled manually. This system must be rebuilt from scratch for every new beam design, as a single gantry can produce only one specific shape. These challenges highlight the inefficiencies of traditional gantry systems, particularly for projects requiring a wide variety of curved elements.

Despite these challenges, traditional gantry systems remain widely used in the industry due to their reliability and effectiveness in producing repetitive, uniform curved elements. Recent academic advancements aim to reduce reliance on traditional jigs and presses by leveraging actuator-based systems to directly bend timber into precise curvatures. One notable example is the work by Bhooshan et al. (2024), which presents a formwork-free method for creating spatial curved laminated timber structures.

In this method, the lamellae are bent directly into their desired shape during the fabrication process, guided by computationally controlled actuators. These actuators apply localized forces to the timber, allowing precise control over the curvature and alignment of each lamella. Unlike traditional methods that rely on fixed jigs, this approach dynamically adjusts the forming process in real-time, enabling a high degree of customization and adaptability for different designs (Bhooshan et al., 2024).

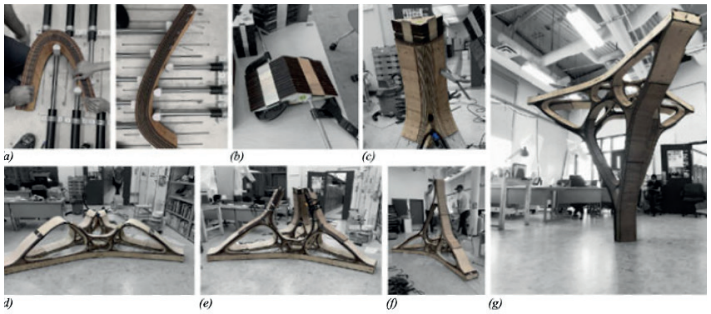

Figure 14
a) bent laminates
b) glued connectors
c) assembly of a connector on a node
d) phase 1 assemblage
e) phase 2 assemblage
f) phase 3 assemblage
g) final product
(Bhooshan et al., 2024)

By eliminating the need for bespoke jigs and formworks, the setup time is significantly reduced. Additionally, the actuator-based system minimizes manual intervention, streamlining the production process and allowing for faster fabrication of complex geometries. Bhooshan et al. (2024) demonstrate the feasibility of this technique through experimental validation, producing curved laminated timber components with high precision and structural integrity. The method's use of computational design tools ensures seamless integration between digital models and physical production, bridging the gap between design intent and fabrication. While still in the research phase, the formwork-free approach represents a promising alternative for producing single curved timber elements.

While academic research has advanced formwork-free approaches for curved Glulam fabrication, the timber industry has already developed automated systems that closely resemble these concepts. One such system employs adjustable hydraulic actuators to shape and hold timber lamellae during the bonding process, eliminating the need for fixed molds or traditional jigs (Svilans, 2021). This flexibility allows for streamlined production of single-curved elements, reducing setup times and labor costs compared to traditional methods. This aligns with the academic goal of integrating computational design and fabrication workflows, demonstrating that the industry is already adopting technologies that mirror research-driven innovations. However, this system has notable limitations. Like traditional gantry setups, the lamellae must remain in the machine for several hours during the bonding and curing process. This extended curing time prevents the machine from being used for other elements. Additionally, while the system is effective for single-curved beams, it is not capable of producing double-curved geometries, limiting its applicability for more complex designs.

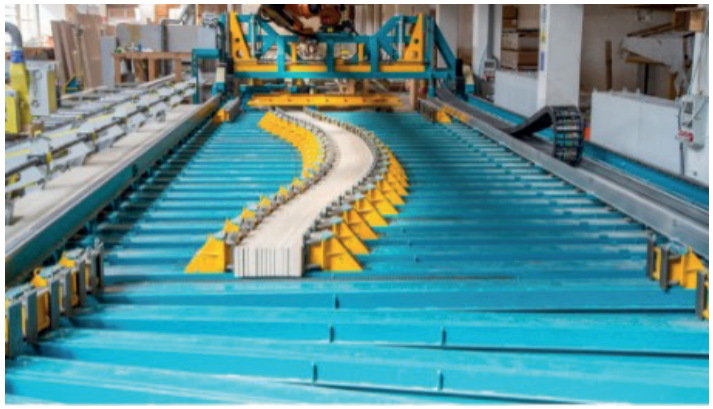

Figure 15
A single-curved glulam press.
Photo: Ledinek Polypress (https://www.ledinek.com/polypress)

Gantry Systems for Double Curves

At the beginning of this state-of-the-art review, we discussed the possibility of manufacturing double-curved elements from single-curved beams. However, a key issue arises due to the anisotropic nature of wood: cutting through the fibers during shaping directly impacts the final product's strength (Svilans, 2021). The only way to preserve the structural integrity of the material is to bend the fibers collectively to form the double-curved geometry. This approach, while necessary for maintaining fiber continuity, makes the production of double-curved Glulam elements in the timber industry a particularly complex and labor-intensive process, requiring a blend of traditional techniques and advanced manufacturing systems.

One challenge lies in the fact that a stack of lamellae, as commonly used in single-curved manufacturing, can only be bent along a single plane. As shown in the figure above, the width of the boards makes it impossible to bend them horizontally, highlighting a key limitation.

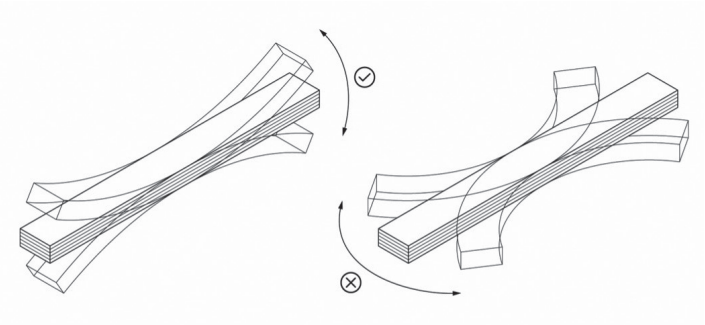

Figure 16
Possible bending orientations for stacked lamellas.

In industry, this challenge is overcome by beginning the process with a single-curved beam. Once the initial curvature is achieved, the beam is sliced perpendicular to the original lamellae (Strehlke & Hirschberg, 2021). These slices are then reassembled and glued in a new gantry, where the beam is bent a second time to achieve its final double-curved shape. This complex process requires two gluing sessions, two gantries and two cutting stages: first to form the single-curved beam and then to prepare the slices for the second bending stage.
As an alternative, thin square sticks can be used instead of traditional boards. Unlike boards, which can only bend along one plane due to their width, sticks are more flexible and can be bent in multiple directions. This property allows them to conform to complex double-curved geometries in a single operation. By gluing the sticks together and placing them in a multi-axis gantry, the desired final shape can be achieved in a single gluing session, simplifying the process and reducing the need for additional cutting and reassembly. However, this approach demands precise control to ensure both the structural integrity and accuracy of the final curvature.

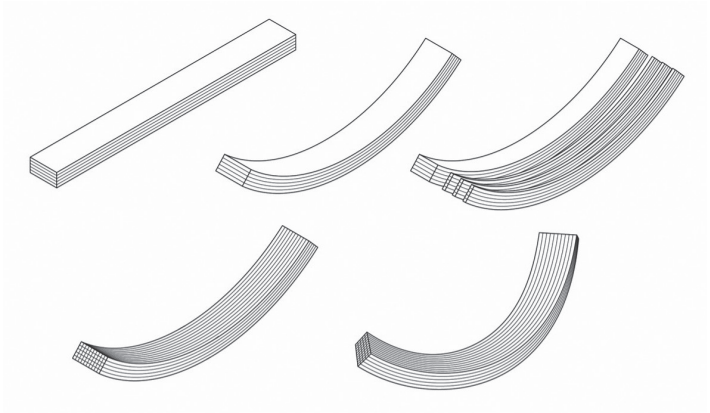

Figure 17
Double-Curved Beam Production Process.

Figure 18
The set-up for producing double-curved glulam beams.
(Strehlke & Hirschberg, 2021)

While the timber industry continues to face challenges in manufacturing double-curved Glulam beams using conventional methods, academic research has introduced promising alternatives to address these limitations. Chai, Guo, et al. (2021) propose a mold-free approach for fabricating complex glulam geometries, aiming to reduce material waste, time consumption, and structural weaknesses caused by traditional subtractive techniques. The system uses a mechanical gantry that spatially shapes timber into curved forms without relying on heavy molds or subtractive machining. This approach allows for efficient fabrication by directly translating digital design data into physical components, simplifying production while minimizing waste.

The paper's proposed system could be further enhanced by integrating Microsoft HoloLens, a mixed reality (MR) device, into the glulam production workflow. HoloLens enables real-time visualization of 3D models overlaid onto the physical workspace through augmented reality (AR). In the context of glulam fabrication, this technology could streamline the production process by projecting digital design models directly onto the workspace, guiding operators visually without requiring traditional 2D drawings or screens.

The paper also explores the use of depth cameras as a central component, focusing on their ability to capture 3D spatial data with high precision. Unlike mixed reality devices such as HoloLens, which provide an interactive augmented reality experience, depth cameras are used solely for environmental scanning and dimensional analysis. The system employs depth cameras to monitor the spatial position and geometry of the glulam beams during fabrication, enabling real-time feedback. This approach allows the system to detect deviations between the design model and the actual beam shape, ensuring production accuracy. The authors argue that while depth cameras lack AR capabilities, their precision, affordability, and compatibility with automated processes make them better suited for direct fabrication control, emphasizing efficiency and integration within an industrial setting Chai, Guo, et al. (2021).

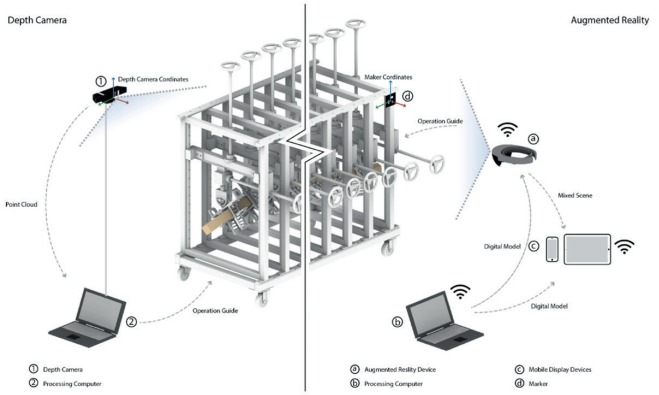

Figure 19
The composition of the Equipment.
(Chai, Guo, et al., 2021)

Formwork-Free Approach

This section explores the Formwork-Free Approach, an innovative fabrication method currently confined to academic research and experimental applications. Researchers from the University of Stuttgart have introduced a new method for producing curved laminated timber elements by combining bending-active techniques with robotic precision. This process harnesses the natural elasticity of wood to achieve both form and structural stability, eliminating the need for traditional formworks and clamps. By rethinking the relationship between material behavior and fabrication, this approach demonstrates significant potential for reducing production complexity and material waste in timber construction (Bahar et al., 2019).

The core of the method relies on bending a stack of wooden lamellae that are constrained at their endpoints, which causes different parts of the stack to either shorten or lengthen. This differential movement generates internal pressure between the lamellae, which is essential for bonding the layers together using glue. The bending process not only forms the curvature but also aligns predrilled holes in the lamellae for dowels, facilitating their assembly into a final structural element.

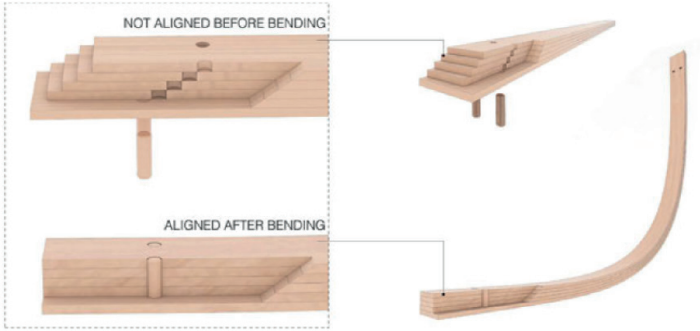

Figure 20
In the prefabricated straight lamellae, holes are initially not aligned. After bending the stack of lamellae, the holes do align and dowels can be inserted. (Bahar et al., 2019)

The fabrication is guided by computational design and simulations. Initially, the length and positions of each lamella are precalculated based on elastic curves, which dictate the bending process. These curves ensure that the wood's natural elastic properties are maximized for structural performance. The digital model allows for precise control over the bending path, ensuring that each lamella is bent to the correct shape while maintaining the alignment required for the bonding process. The precision of the robotic arm ensures that no sliding occurs at the endpoints, allowing the system to function without external clamps or formwork.

The first step of the fabrication is to cut the wooden lamellae to the correct lengths and drill them with alignment holes, the lamellae are then stacked and glued. The robotic arm bends the stack into the desired shape, and dowels are inserted to secure the alignment. The bending process generates the internal pressure needed for the glue to bond the lamellae together, and once set, the laminated element is a structurally curved piece, free from the need for traditional clamping methods. This method eliminates many of the labor-intensive and resource-heavy aspects of traditional glulam production, such as pressing and milling.

This process is adaptable, as the method allows for the creation of unique, complex shapes without adding extra cost or complexity. This makes it highly suitable for custom architectural projects where unique forms are often required. Moreover, because the bending process aligns the wood fibers with the force flow, the structural integrity of the timber elements is enhanced, ensuring their performance under load.

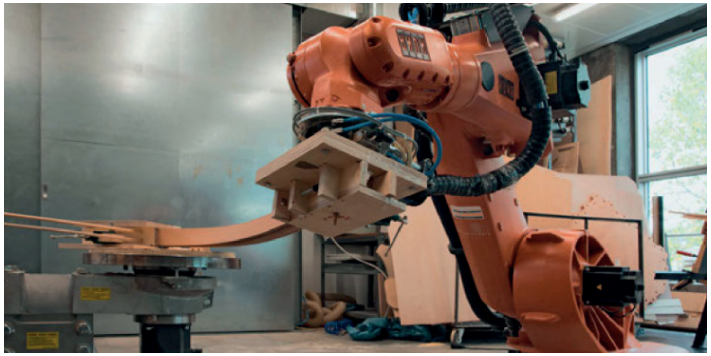

Figure 21
Fabrication setup consisting of a stationary clamp, a stack of lamellae, and a clamp that is attached to an industrial robot arm.
(Bahar et al., 2019)

Prototypes were developed to demonstrate the feasibility of this bending-active lamination process. These prototypes exhibited double-curved elements, showcasing the method's capability to create geometrically complex forms. The flexibility of the process allows for angles ranging from 10° to 120°, making it adaptable to a wide range of design requirements. The prototypes also validated the method's precision, as the measurements and pressure distributions were monitored and optimized during the fabrication process (Bahar et al., 2019).

In conclusion, the bending-active lamination process presented in this paper offers a promising innovation for the fabrication of curved laminated timber elements, combining the natural elasticity of wood with computational design and robotic precision. This method significantly enhances the efficiency and sustainability of timber construction by eliminating the need for traditional jigs, clamps, and extensive post-processing, while also enabling the creation of complex, custom geometries without added fabrication costs.

However, despite its potential, this approach has some limitations. One key challenge is that the timber elements must remain in the robotic system while the glue cures, which can be a constraint in terms of production time and scalability. Additionally, the method is best suited for the fabrication of relatively small timber elements. Larger structures may require adjustments or alternative processes.

Figure 22
Final prototypes of laminated elements.
(Bahar et al., 2019)

Problem Statement

Motivation

Timber is increasingly recognized as a material of the future, thanks to its exceptional sustainability and versatility. The demand for timber products, particularly glue-laminated timber, continues to grow due to its structural capabilities and adaptability in shaping. Among its many applications, curved Glulam is particularly valued for creating arches that enhance structural efficiency and aesthetic appeal.

The history of curved Glulam dates back to 1860, with the first arch constructed for the meeting room at King Edward's College in Southampton (Leloy, 2018). Remarkably, the fundamental methods used over a century ago are still prevalent in the production of curved elements today, despite significant advancements in technology.

Manufacturing single and double-curved Glulam remains a complicated and labor-intensive process. The complexity of these parts, particularly double-curved geometries, can lead to production costs being up to 15 times higher than those of straight Glulam (Strehlke & Hirschberg, 2021). This financial and technical challenge significantly limits the adoption of curved timber components in projects requiring custom or intricate designs.

This research seeks to address this gap by focusing on the following problem statement: ***How can robotic fabrication be applied to curved Glulam timber such that unique elements can be generated through one established workflow, minimizing formwork and enhancing design freedom?***

Research Questions

In response to the problem statement, three research questions have been developed. These questions are intended to guide the research proposal in the right direction.

- What opportunities does the bending of glulam offer to architecture in terms of design innovation and structural performance?

- What methods are currently used to manufacture curved glulam in the construction industry and explored in academic research, and how practical and effective are these methods in addressing challenges?

- What are the technical requirements for implementing robotic fabrication in the bending of curved glulam?

Figure 24
French glulam factory, 1965
(Leloy, 2018)

Figure 25
Gantry system at JPF-Ducret, Orges, designed for producing single-curved beams. Photo taken during site visit on December 11, 2024.

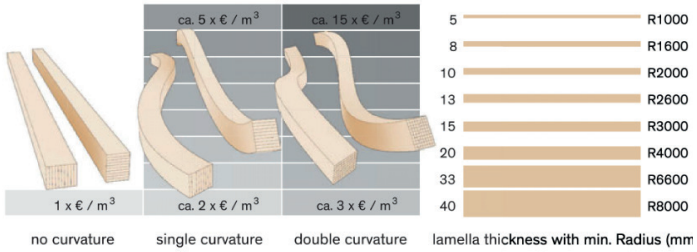

Figure 23
Geometry vs. Cost of Glue Laminated Timber.
(Strehlke & Hirschberg, 2021)

Research Proposal

Introduction

The integration of advanced technologies into timber construction presents opportunities to address persistent challenges in the production of curved Glulam elements. These components, valued for their structural efficiency and design adaptability, often rely on custom molds. This reliance limits design freedom, generates material waste, and slows production workflows. By exploring robotic fabrication, this research aims to develop a unified workflow that reduces dependence on formwork while expanding design possibilities. How can robotic fabrication be applied to curved Glulam timber to generate unique elements through a single established workflow that minimizes formwork and enhances design freedom ? This question directs the study toward bridging the gap between traditional practices and innovative advancements in timber construction.

Research Methodology

Robot Capabilities

Building on the academic research presented in the state-of-the-art section, this proposal centers on the use of robotics as a core component for advancing the fabrication of curved Glulam elements. At the heart of this system are ABB articulated robots mounted on the ABB Track Motion system, providing the precision, strength, and adaptability required for handling complex geometries.
The IRB 6700 series, designed for industrial applications, can manage payloads of up to 300 kg with a reach of up to 3.2 meters (ABB Robotics, 2024). This payload capacity is crucial as the robots must not only carry the stack of timber lamellae but also apply the tension needed to bend the material into its final shape. The ability to exert controlled force while maintaining accuracy ensures that the bending process meets structural and design requirements.
The ABB Track Motion system enhances the robots' operational range by providing linear mobility, enabling them to fabricate large components.

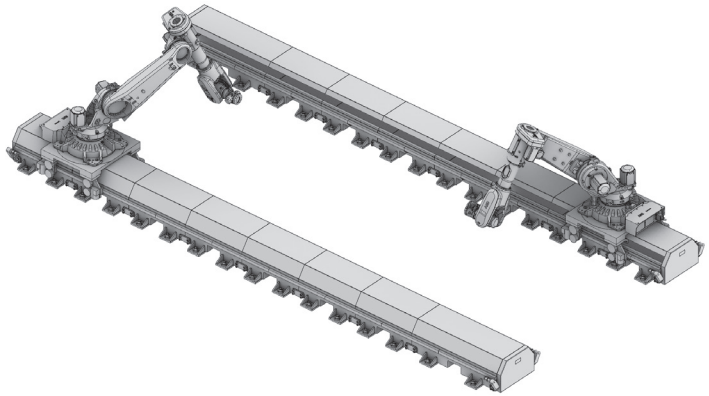

Figure 26
Initial setup featuring two robots mounted on rails.

New Production Workflow

Let's examine how the proposed production workflow operates. To simplify the explanation, this workflow will be illustrated through the example of producing one double-curved beam with a cross-section of 150 mm by 150 mm, composed of ten 15 mm-thick lamellae. The process is broken down into seven distinct steps, labeled A to H.

A) Preparation of the Planks

As in traditional manufacturing, the first step is to prepare the planks. This involves selecting the appropriate number of planks based on the required beams and lamellae. The planks must then be cut to precise dimensions—length, width, and thickness—to ensure compatibility in subsequent steps. This task can be performed using conventional tools, as the existing machinery is already well-optimized for this purpose.

B) Glue Application and Stacking

The next step is applying glue to the lamellae. This can be done using a glue curtain, a system where planks pass through a curtain of adhesive. In larger factories, this task is often fully automated with conveyor belts, while smaller factories may rely on manual application. Once glued, the lamellae are manually stacked on top of each other. This task typically requires two workers, each handling one end of the lamellae to ensure proper alignment.

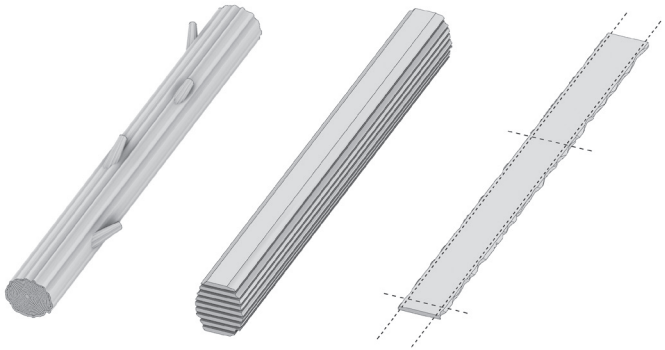

Figure 27
Preparation of the planks, cut to the required dimensions.

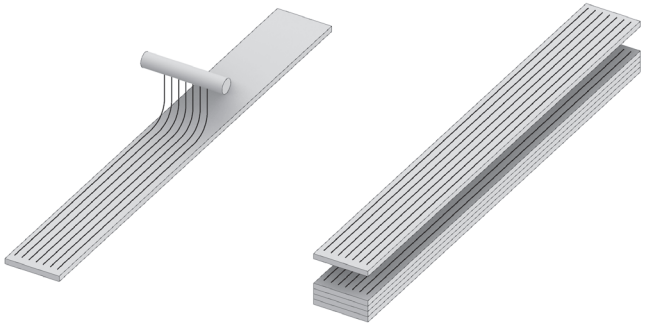

Figure 28
Applying glue to each plank to form a stack of Lamellae ready for bending.

C) Robot Preparation

Before proceeding, the robots must be equipped with their end effectors and positioned correctly. The initial setup involves placing the end effectors approximately 80 cm above the ground to facilitate the next step. The distance between the end effectors is adjusted to match the length of the beam before bending. This ensures that the robots are ready to handle the stack of lamellae effectively.

D) Placing the Lamellae in the End Effectors

Two workers place the stack of glued lamellae into the end effectors while the adhesive remains liquid. Their primary task is to ensure the lamellae are correctly aligned and stacked vertically within the end effectors, preparing them for the bending process.

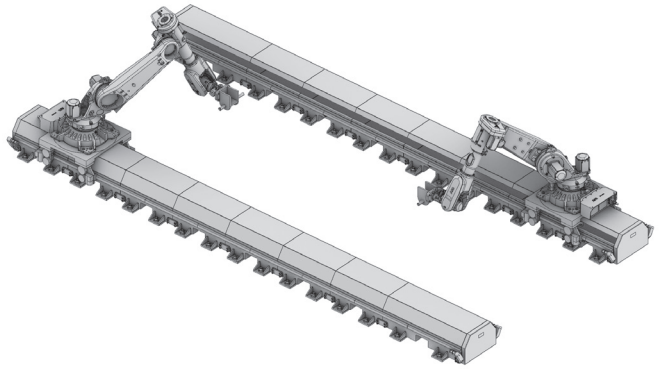

Figure 29
Robots equipped with custom end-effectors.

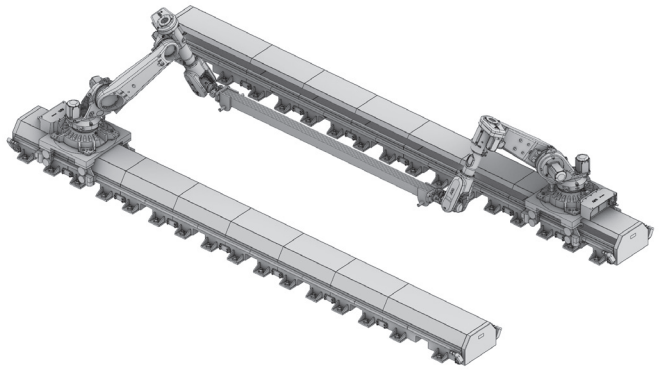

Figure 30
Positioning the stack of lamellae into the end-effectors.

E) Bending the Beam

The robots are activated to begin the bending process. This step is pre-calculated through virtual simulations to predict the behavior of the lamellae during bending. The end effectors apply controlled forces, respecting the natural elastic behavior of the timber to prevent misalignment or lamellae slipping out of place. This simulation-driven approach ensures a precise and consistent bending operation.

F) Locking the Beam

Once the bending is complete, the two workers return to secure a long metal tube between the two end effectors. This is achieved by tightening scaffolding clamps, which mechanically lock the end effectors together. This setup stabilizes the bent beam, allowing it to maintain its shape during the curing process.

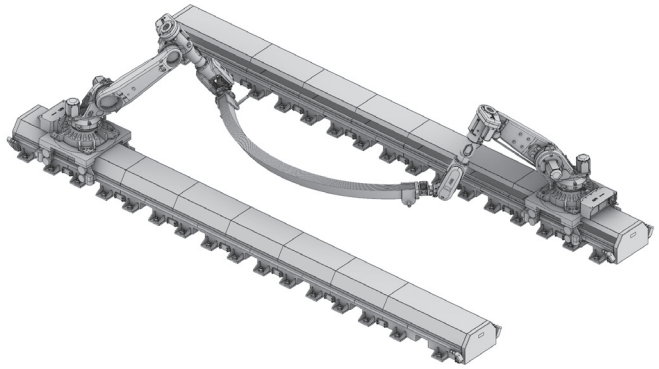

Figure 31
Bending the lamellae stack into the desired shape.

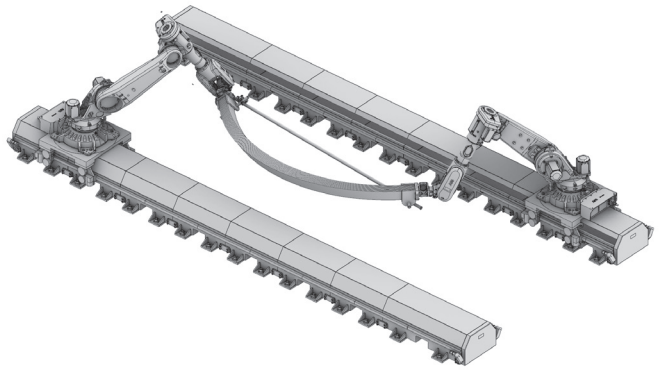

Figure 32
Securing the bent beam in position.

G) Detaching and Curing

In the final step, the workers detach the end effectors from the robots, leaving them attached to the beam along with the connecting metal tube. The beam is then moved to a designated curing area, where the adhesive can dry and set over the required time. During this curing period, the robots are freed for the production of the next beam. This workflow is consistent regardless of the beam's length, whether it involves a single curve, a double curve, or a twist. The uniformity of the process enhances efficiency and flexibility, making it adaptable to various geometries.

H) Curing Completion

Once the curing time is complete, the beam can finally be removed from the end effectors. The scaffolding clamps are unscrewed and detached, allowing the end effectors to be easily released from the beam. At this stage, the beam is ready for use, and all the tools—including the end effectors, clamps, and metal tubes—can be prepared for the production of another beam.

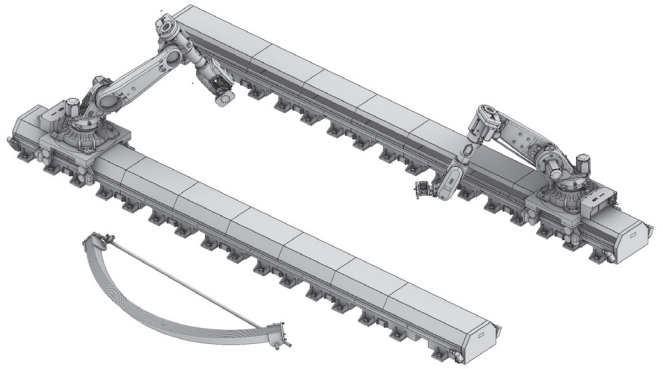

Figure 33
Removing the beam for the curing process.

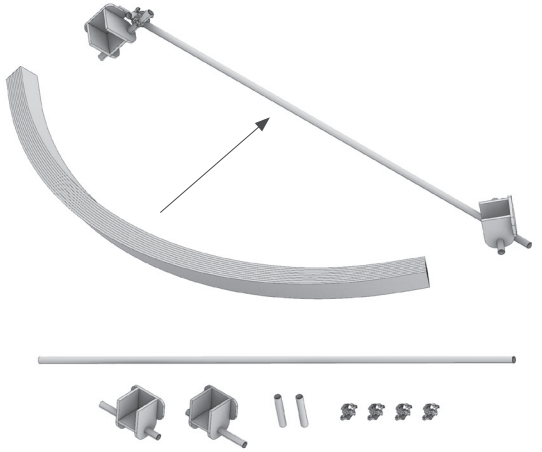

Figure 34
Curing completed and removal of end-effectors.

Custom End Effectors

To handle a stack of lamellae ready for bending, the robot must first be equipped with custom end effectors, specifically designed to manage this task efficiently. An end effector is a device attached to the end of a robotic arm, enabling it to interact with its environment. The design of the end effector depends on the application, and in this case, it must perform three key functions tailored to the bending workflow.

Firstly, the end effector must be detachable from the robot. It consists of two main components. The first is a base plate, securely mounted on the robotic arm with multiple bolts to ensure stability during operation. This base plate includes four precisely positioned holes to attach the detachable portion, providing flexibility for reconfiguration or maintenance.

The second component is the detachable section of the end effector, which plays the most critical role in this setup. It will be bolted to the base plate using four bolts, allowing for quick detachment while maintaining a robust connection when in use. This detachable part is essentially a static gripper, designed with a cavity to accommodate a stack of lamellae up to 150 mm thick. The gripper will also constrain the width of the lamellae to a maximum of 150 mm, ensuring consistent handling across all operations.
The cavity of the gripper should be sufficiently deep to accommodate the movement that occurs between the layers during the bending process. As shown in Figure 38, the lamellae do not all have the same length. This variation in length must be precisely calculated to account for the sliding of the layers. Proper calculations ensures that all the lamellae are correctly positioned once the beam is fully bent.

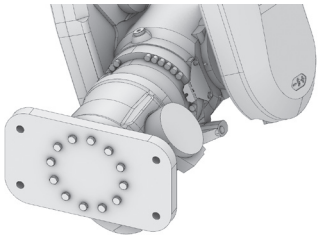

Figure 35
Fixation plate secured to the robot's end.

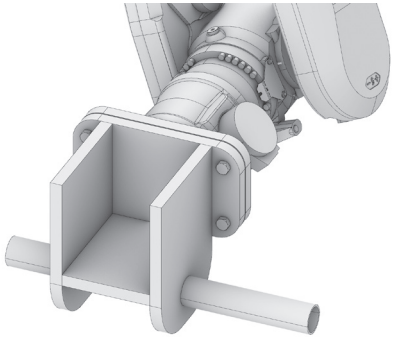

Figure 36
Custom end-effector for lamella handling.

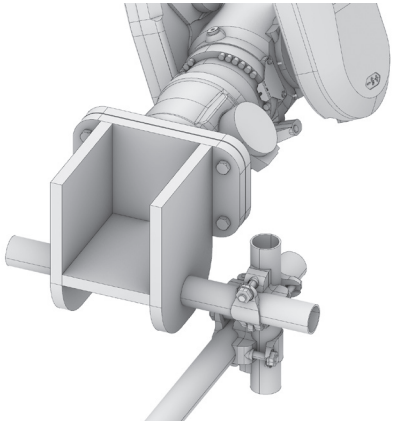

Figure 37
Attaching scaffolding clamps and tube to link with the opposite end-effector.

A pivotal element of the workflow is the ability to connect the end effector on one side of the beam to its counterpart on the opposite side, ensuring that their relative positions remain fixed even after they are detached from the robot. This is accomplished by incorporating a metal rod, similar to those used in scaffolding, into the detachable section. This rod acts as the central connection point for two scaffolding clamps mounted on each end effector. The same assembly is mirrored on the opposite end, enabling both ends to be joined with a long scaffolding tube. Once the tube is secured and the clamps tightened, the two end effectors are mechanically locked together. This configuration allows the end effectors to bear the tension exerted by the bent beam, making it possible to unbolt them from the base plates and move the beam to a separate location for curing, which may take several hours.

The design of the end effectors prioritizes simplicity and cost-effectiveness, ensuring they can be easily duplicated without excessive resource demands. This simplicity is crucial for optimizing production workflows and minimizing delays. To achieve this, the end effectors could be constructed from thick plywood, chosen for its strength and affordability, capable of resisting the forces encountered during bending. Additionally, the use of readily available metal tubes and scaffolding clamps further streamlines the construction process, reducing both costs and complexity while maintaining reliability and functionality. This approach not only ensures operational efficiency but also provides the flexibility needed for scaling the system to accommodate varying beam sizes.

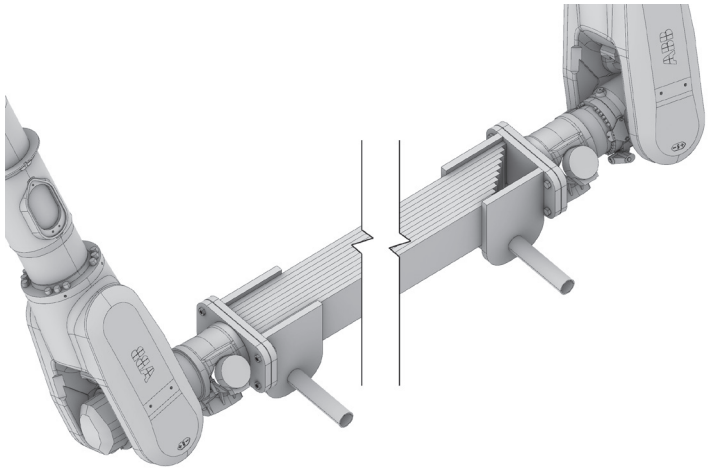

Figure 38
Lamellae positioned in end-effectors with varying lengths to compensate for sliding during the bending process.

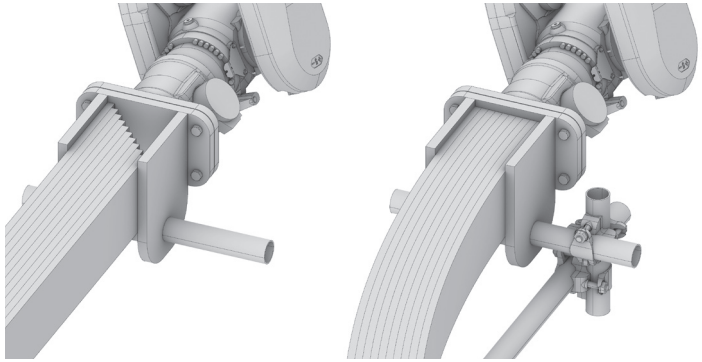

Figure 39
Comparison of lamellae alignment before and after bending.

Curved Beam Assembly

In traditional manufacturing processes for curved Glulam, once the stacked lamellae are glued and dried, post-processing is typically required. This step, particularly focused on milling the ends of the beams, is necessary because the lamellae often become misaligned during the bending process. However, the proposed solution offers a high level of control over the material and its alignment, significantly reducing or even eliminating the need for post-processing. This enables the production of beams that are ready for use immediately after the glue has dried, making the production process more efficient.

Post-processing curved elements, especially double-curved geometries, is notoriously challenging. These complex shapes are difficult to position with precision in multi-axis CNC machines. Since CNC tools cannot «see» the material during milling, achieving the required accuracy demands exact placement, which becomes increasingly problematic for double-curved elements. By contrast, this approach allows for the lamellae's ends to be milled before they are glued and stacked. This not only simplifies the workflow but also enables the integration of a variety of joint types directly into the beam during production.

For instance, beams could be designed with integrated mortises by stacking lamellae with pre-milled profiles. Similarly, finger joints, dovetail connections, or other advanced joinery techniques could be incorporated seamlessly into the fabrication process. These pre-integrated joints eliminate the need for additional milling after bending, optimizing production efficiency.

This flexibility in joint creation opens up a multitude of possibilities for connecting elements to construct diverse and complex geometric structures. As illustrated on the following page, such beams can form intricate architectural frameworks, enabling numerous design possibilities while streamlining the overall fabrication process.

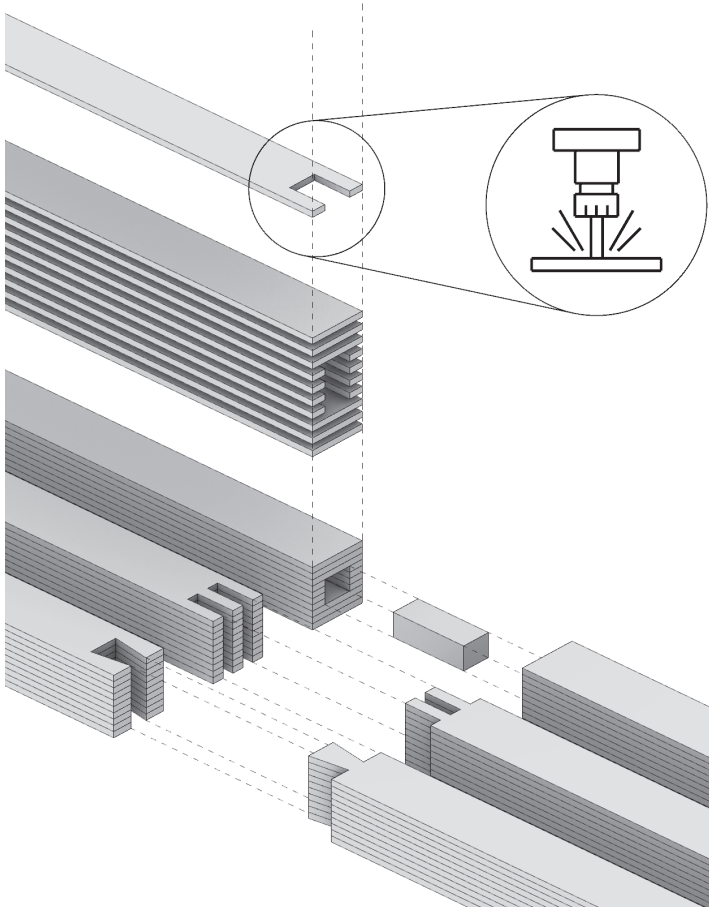

Figure 40
Illustration of possible joint types for timber beams, including mortise, finger joints, and dovetail connections.

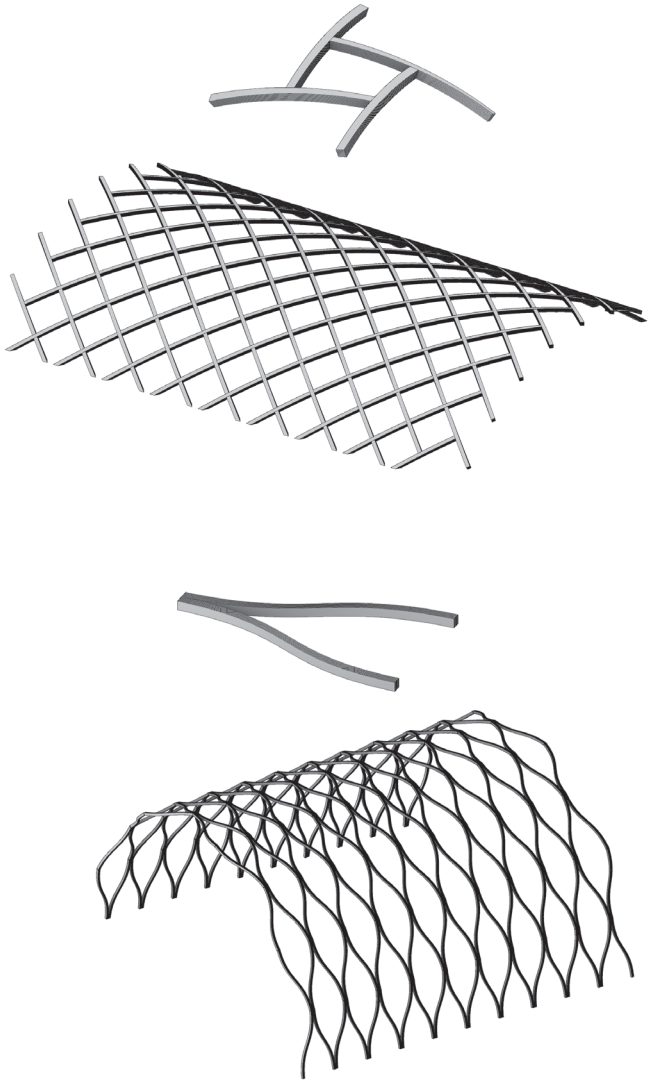

Figure 41
Examples of potential structures using curved timber elements

Figure 42
Examples of potential structures using curved timber elements

Challenges and Limitations

Dimension Limitations

The dimensions of the final product are inherently restricted by the physical capabilities of the robotic system and its components. The maximum length of the Glulam beam is determined by the size of the robot and the length of its rails, limiting the scale of production to the workspace constraints. Additionally, the cross-sectional dimension of the beam is influenced by the torque capacity of the robotic arm. A higher torque is essential for manipulating larger and heavier sections of timber, but even with advanced robotics, this capacity has its limits.
The weight of the timber element also imposes restrictions. Certain steps in the production process require manual handling, meaning the beams cannot be excessively heavy to ensure safe and practical manipulation by humans. This weight constraint further influences the allowable dimensions of the final product.
Another significant factor is the strength of the end-effectors. These tools must securely hold the timber in place and endure the internal stresses generated by the bending process until the adhesive fully cures. If the end-effectors are unable to maintain sufficient grip or stability, the timber may shift during production, compromising the precision and structural integrity of the final product. These dimensional constraints collectively pose challenges for scaling up production or achieving designs that require exceptionally large or intricate geometries.
Another challenge lies in the fixed dimensions of the end effectors, which limit the curved beams to a square cross-section of 150 mm. Only the number and thickness of the lamellae can vary, but their selection is primarily determined by the radius of curvature required for the beam.

Workflow Limitations

While the proposed workflow introduces efficiencies by eliminating the need for formwork, it is not without its challenges. Certain aspects of the process still rely heavily on manual intervention, which limits the degree of automation achievable with the current setup. These limitations impact various stages of production, from the preparation of lamellae to the handling of end effectors, and collectively influence the overall efficiency of the workflow.

One limitation of the workflow lies in the glue application and stacking process. While the absence of formwork streamlines certain aspects of production, this workflow still requires at least two workers to manually handle the lamellae. The lamellae must be cut to precise dimensions, glued, and stacked together before being transferred to the robots. These tasks cannot be automated within the current setup, as they involve manual adjustments to ensure proper alignment and preparation. Although existing tools like glue curtains or conveyor systems can assist, these steps remain a bottleneck in the overall production process.

Another challenge involves the reliance on screws for attaching and detaching the end effectors. For each beam produced, 24 screw operations are required—4 for attaching each end effector to the robot, and 4 more on each side for detaching the bent beam after production. Additionally, 8 screws are used to tighten the scaffolding clamps that lock the beam in place during curing. While electric tools can expedite this process, the need for manual intervention adds time and complexity to the workflow. This repeated screwing and unscrewing, though straightforward, can become a limiting factor when scaling up production.

Finally, although the workflow eliminates the need for traditional formwork, it still requires multiple pairs of end effectors to maintain continuous production. Once a beam has been bent and is curing, the end effectors holding it cannot be reused until the adhesive has fully dried, which may take up to six hours depending on the curing time. To produce additional beams during this period, extra pairs of end effectors are required, increasing the equipment costs and logistical complexity of the workflow. This dependency on multiple sets of end effectors presents another limitation.

Bending Limitations

The bending process for creating curved Glulam elements faces several inherent limitations. The radius of curvature is primarily constrained by the thickness of the lamellae, as is the case in conventional production methods. Thicker lamellae require larger radii, limiting the potential for tighter curves. This constraint restricts the range of achievable geometries, particularly when intricate designs call for sharper bends.
Since the process uses planks rather than sticks, the achievable double curvature is limited to a combination of single curvature and torsion. While this produces a beam with a double-curved geometry, it does not allow for the creation of all possible double-curved shapes. The bending method is inherently limited by the material's anisotropic properties, meaning only certain geometries are feasible without compromising structural integrity.
Additionally, the bending process relies on applying pressure at the extremities of the beam to shape it. This approach means the final curve is not fully controlled but instead depends on the natural elasticity and behavior of the wood under stress.

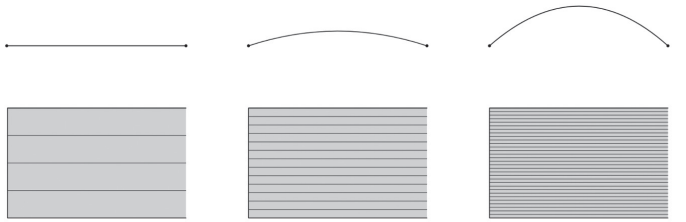

Figure 43
The lamella thickness depends on the maximum curvature of the centerline curve. (Svilans, 2021)

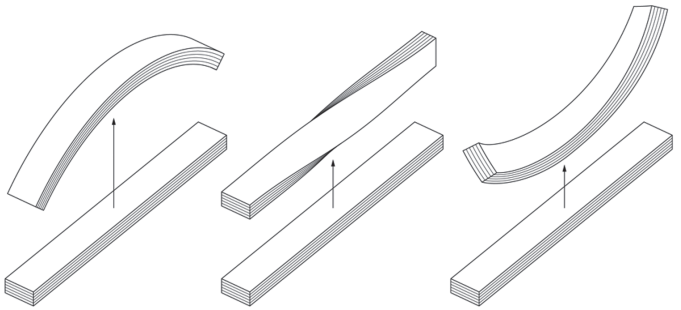

Figure 44
left: single-curved beam
center: twisted beam
right: Combination of bending and twisting

Discussion & Outlook

This research introduces a robotic workflow for fabricating curved Glulam elements, addressing existing limitations in traditional production methods. The proposed system enhances design flexibility, reduces material waste, and minimizes reliance on post-processing, while eliminating the need for traditional formwork, thereby simplifying the production process. However, further exploration is necessary to fully understand the potential and limitations of this approach.

The robotic system allows for the creation of single and double-curved elements with a high degree of precision, offering architects new opportunities to explore complex geometries. Additionally, the assembly of these discrete bent elements requires further consideration. How curved beams connect and interact in a structure is heavily influenced by the type and alignment of their curvature. For instance, the compatibility of curves with differing radii or bending behaviors could impact structural integrity and aesthetic outcomes. Future studies could investigate the interplay of these elements in modular systems, providing a clearer framework for their architectural application.

The ability to integrate pre-milled joints into the beams before bending represents a notable improvement enabling efficient assembly of complex structures. However, challenges such as ensuring precise alignment of these joints during bending and curing must be addressed.

The bending process, while innovative, is constrained by the properties of timber. The thickness of lamellae and the type of bending forces applied limit the achievable radii of curvature. These constraints restrict the design possibilities for tighter curves or double-curved geometries.

From an architectural perspective, the proposed workflow shows considerable potential. By streamlining pro-

duction and assembly, it enables the creation of intricate frameworks, pavilions, or large-span structures with reduced resource requirements. To further enhance its architectural relevance, future work could focus on integrating these elements into real-world projects, demonstrating their performance in various environmental and structural conditions.

This research lays the foundation for a transformative approach to curved timber fabrication. While challenges remain, particularly in bending limitations and assembly workflows, addressing these issues through continued exploration could unlock the full potential of this system. The resulting advancements have the potential to redefine how curved timber elements are designed, produced, and utilized in sustainable architecture.

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