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MODEL TO PRESS: DIGITAL DATAFLOW FOR THE DESIGN, RATIONALIZATION, AND MANUFACTURE OF FREE-FORM GLULAM BEAMS

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Abstract

While numerous built examples of free-form glulam structures demonstrate the complexities of creating glulam beams with out-of-plane curvature, the specifics of their modelling, rationalization, and realization have largely remained confined to specialist know-how and internal processes. We present a digital workflow that bridges unpredictable input design geometry and the reconstruction, rationalization, and preparation of free-form glulam beams for industrial production. This effort is part of an innovation project developing an automated press for serial production. It builds upon previous research into early-stage modelling and rationalization, extending it to real-world design contexts and industrial production constraints.

Introduction

While the complexity of timber structures has grown as their potential is discovered, the digital infrastructure required to translate free-form timber designs into robust, mass-produced industrial components remains sparse and fragmented. Techniques of rationalizing and modelling such geometrically complex structures are largely relegated to specialist experience and internal knowledge. The production of large-scale free-form glulam beams, for example, remains a labour-intensive and costly process, tailored to the specific delivery or project. The specifics of translating design geometry into feasible material specifications for such elements are often glossed over in favour of describing the wider design and production process (Stehling et al., 2017). As such, free-form glulam beams remain a largely craft-based product that resists automation and industrialization.

A number of wider efforts have spurred the tight intertwining of digital design and production in contemporary timber research and construction. New modes of relating timber properties and behaviours to architectural models or production environments (Svilans et al., 2019) have sought to imbue a sense of material agency in design and fabrication (Menges et al., 2016; Weinand, 2017). Considering this growing role of computation and automation within the timber manufacturing sector, we seek modelling and analysis methods for deriving production-ready data from coarse design models in an industrial production context, towards an industrialization of geometrically complex timber elements. A primary challenge in this process is the difference in fidelity between early-stage design models – often used for cost estimations and planning – and the necessary production data. Messy design geometry and poor interoperability necessitate interpretation and reconstruction of key manufacturing parameters and specifications. The use of coarse and ad-hoc models for early-stage design exchange often yields geometry that is unstructured and discretized. Further, free-form glulam beams present particular geometric and material constraints arising both from material properties as well as the nature of the pressing process. These must be respected, and the digital model must be validated against them to ensure that the production can be successful. Finally, considering the geometric constraints of bending timber lamellas, the discrepancy between the design geometry of the final beam and the geometry of the glulam blank must be recognized and integrated into the planning process.

We therefore develop a digital workflow for translating highly variable design inputs such as coarse and unstructured mesh objects into materially-responsive production data for pressing large-scale glulam beams under real-world constraints (Fig. 1). We draw from experience working with designers and architects on the delivery of complex timber buildings, and the observations made with respect to typical digital design models.

The presented work demonstrates a path towards the automation and industrialization of free-form glulam beam production from typical real-world design inputs.

Background and related work

Data exchange in free-form timber construction

The importance of robust digital workflows and good interoperability in AEC have been emphasized for a long time (Scheurer, 2012; Stehling et al., 2014), pointing at the wide variety of software used in the design, development, and production of a complex timber building and the lack of a "one size fits all" toolset. The prevalent use of Industry Foundation Classes (IFC) in AEC data exchange is beneficial for the general sharing of design information. However, in practice, the capabilities of the full specification are rarely utilized, especially when it comes to free-form surfaces. This means that the required input data is seldom authored in a

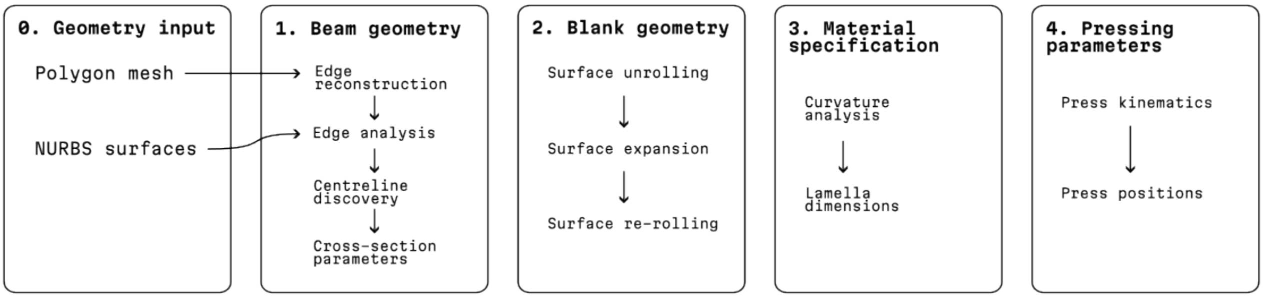

Figure 1 An outline of the digital workflow for automating the translation of coarse design data into production-ready information.

production-ready way. Specifically, the modelling of free-form beams is typically done through ad hoc or non-standardized ways and transferred as polygon meshes or overly detailed NURBS surfaces, creating hurdles for downstream processes. In the case of meshes, important features such as curvature and continuity must be inferred or interpolated. In the case of surfaces, fully detailed models can make it hard to extract precisely the necessary data for producing glulam beams since they might describe the final geometry of the fully detailed element rather than the glulam blank.

For evaluating material specifications and determining the correct press parameters, these geometric properties must be taken into account. Methods for reconstructing surfaces and edges that closely approximate the input design geometry are therefore required.

Single-curved glulam beams are relatively standardized in production, as both their geometry and production parameters are easier to derive. The planar curvature means that most considerations can be relegated to 2D analysis and rationalization. In this way, curvature calculations and lamella thicknesses are relatively straightforward.

For free-form glulam beams with out-of-plane curvature and torsion, previous work has developed modelling methods that result in appropriate material specifications and clean geometry for representing them (Svilans, 2021), however these rely on key data which is often absent in design models – such as a beam axis curve and related cross-sectional data and orientations. These must be introduced towards the beginning of the modelling process and are not always present in design models transferred from outside clients, partners, or collaborators. Additionally, these efforts do not include the translation of glulam blank geometry into specific press parameters for full-scale production.

Therefore, the transfer of information from design to the glulam press is shaky and unpredictable due to the large variance of inputs, necessitating techniques for stabilizing this translation into repeatable and automatable processes.

Industrial process and geometric constraints

Free-form glulam beams are typically fabricated using one of two methods:

- a two-step method where a single-curved blank is first fabricated out of individual *lamellas*, sliced into *layers* in the plane of its curvature, and then bent and laminated out of this plane; and
- a one-step process where approximately square lamellas are assembled in a grid and bent three-dimensionally at once.

We focus on the first method – the two-step lamination process – as it decouples the complex curvature into more manageable steps, albeit with some geometric caveats (Fig. 2).

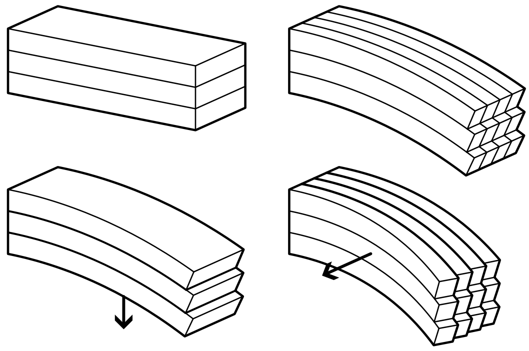

Figure 2 The two-step lamination process begins with straight lamellas (top left) which are bent into a single-curved blank (bottom left). This intermediate blank is resawn into layers (top right) and then bent and laminated in the out-of-plane direction (bottom right).

Double-curved glulam blanks present specific geometric constraints due to their production process. Given lamellas of equal length, as the blank is pressed into a curved shape, the lamellas will slide against one another, meaning that lamellas on the outside of the curvature will appear “drawn back” from the end of the beam and, conversely, lamellas on the interior of the curve will appear to be “pulled forward”. While for single-curved glulam blanks this is simple to account for and the cross-section of the blank stays rectangular, out-of-plane curvature causes this slippage to manifest in geometrically complex ways, causing the cross-section to also slip into a trapezoidal shape (Fig. 3). Calculating the final geometry of the double-curved glulam blank therefore requires more advanced methods of analysis and modelling to more accurately reflect the true shape of the glulam blank.

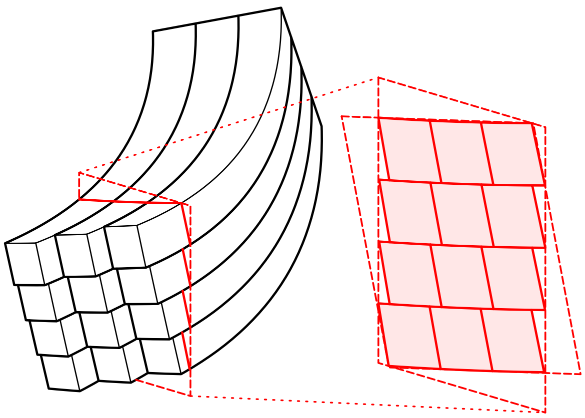

Figure 3 The out-of-plane bending causes the cross-section to become a trapezoid, depending on the degree of curvature.

Similarly, calculating the required lamella thickness for single-curved glulam blanks is straightforward: the lamella thickness is driven by the point of maximum curvature or the smallest radius of curvature in the plane of bending. The largest allowable thickness to avoid overstraining the lamella is defined by the ratio t/R, where t is the lamella thickness and R is the smallest radius of curvature. In Eurocode 5, this ratio must be less than 1/200 for softwoods. In double-curved glulam blanks, the curvature no longer lies in the plane of bending, therefore both the thickness and width of the lamella is affected. The assessment of curvature must therefore be broken down into components to arrive at the correct lamella thicknesses for both steps of the two-step process. To achieve this, the single-curved lamella thickness constraint must be reformulated to work with out-of-plane curvature.

Other challenges are similar for double-curved glulam blanks as for single-curved ones: as curvatures increase and lamella thicknesses get smaller, the spacing of the press pads must decrease to accommodate the sharper changes in geometry. Practically, this becomes an issue when the pressing infrastructure starts to get in its own way and inhibit the ideal distribution of lamination pressure.

Related research in this area has sought to avoid the difficulties of the double-curved lamination process in intriguing ways, such as through novel methods for sawing curved lamellas, thus reducing the bending required to achieve a particular 3d form

(Chai et al., 2021; Zhang et al., 2023). However, these prototypical approaches are not suitable for current industrial contexts that are based on the use of standardized lumber and straight timber lamellas.

Methodology

The project takes places in the factory of ZAZA Timber Production Ltd., a Latvian producer of large-scale timber building components (Fig. 4). An existing single-curved Ledinek press is used as a starting point to implement the two-step lamination process for double-curved glulam blanks. A separate modified press is used to perform the second pressing step, with the objective to eventually automate both presses and digitize their operation.

Figure 4 The industrial production environment at ZAZA Timber Production Ltd.

The developed workflow is structured into three distinct phases:

- the conversion and reconstruction of design inputs,
- the analysis-driven validation of glulam blank geometry and decision support for material specifications,
- and the extraction of press parameters for production.

The aim is to robustly connect variable design inputs with a large-scale free-form glulam press towards an eventual automation of the preparation and pressing of free-form beams. The digital workflow makes extensive use of the IfcOpenShell (IfcOpenShell, 2025) and RhinoCommon (Baer, 2019) programming APIs.

Geometry reconstruction and rationalization

Early-stage geometry is often ad-hoc, non-standardized, and not appropriate for fabrication, due to uncertainty regarding the final outcome of the design process.

As such, design inputs for the planning and production preparation of glulam beams are usually coarse or otherwise unsuitable, requiring extensive remodelling before manufacturing. Free-form geometry is typically described either as NURBS surface patches or approximated mesh objects. While continuous surface data is ideal for transferring geometric features, limitations of popular exchange formats often hinder their usage, even when supposedly supported by the format. For example, the IFC specification – being related to the STEP format – fully supports structured geometric surface data, however this is rarely fully implemented in the interfaces with different software environments (Fig. 5).

To better understand the nature and variety of input geometry, small batches or individual beams were selected from recent projects. The majority of these were either coarsely modelled meshes with varying resolution – such as an increased density of polygons around details – or full-detailed surface models. Both types of input model benefited from the same approach to estimating the "blank of best fit": the difference chiefly being that the surface models didn't require reconstructing continuous splines from discretized mesh edges.

To automatically reconstruct a suitable glulam beam model from variable input geometry, an edge-based heuristic method is developed for both mesh-based representations as well as NURBS surface models (Fig. 6). For mesh-based representations, the main additional step is the finding and reconstruction of longitudinal edges of the beam (Fig. 7). The subsequent steps are generally the same for both types of representations.
Reconstructing edges from a mesh model is done as follows:

- mesh edges are found based on their sharpness or angle between corresponding faces
- successive chains of edges within a certain continuity threshold are found
- splines are built through these chains to best approximate them in a curvature-continuous way

Subsequent steps are similar for both mesh and NURBS representations:

- the collection of splines or NURBS edges is evaluated to find the subset that is the most parallel over the longest length, suggesting a common "flow" or axis of movement
- a median curve is generated from this subset, spanning the longitudinal extents of the curve subset
- at regular intervals, a perpendicular plane is constructed on this median curve
- the intersection between the sample plane and the rest of the edge curves is found and the resultant points are used to generate a 2D convex polygon within the sample plane
- a bounding rectangle is fitted to the convex polygon, testing alignment with each edge to find the smallest enclosing boundary
- the resultant rectangle is taken as a cross-section candidate and compared to preceding and succeeding candidates, until the best candidate – i.e., the one that minimizes twist between preceding and succeeding sections – is found
- this step is iteratively refined until some defined threshold is reached
- the axis curve is fitted to the centre points of all resulting cross-sections

The process yields the equivalent of a solid sweep of a rectangle along the axis curve, with a constant cross-section. In similar terms, the resulting geometry creates an enclosing "beam coordinate system" around the input geometry, with one axis being the curved and elongated centreline of the beam. This also ensures that the faces of the resultant beam model are developable.

The resultant *glulam beam model* is an idealized rectangular sweep that must be further processed in order to arrive at the free-form glulam blank model – a more precise geometric representation of the form of the material after pressing, due to the aforementioned geometric constraints and deviations that occur during pressing.

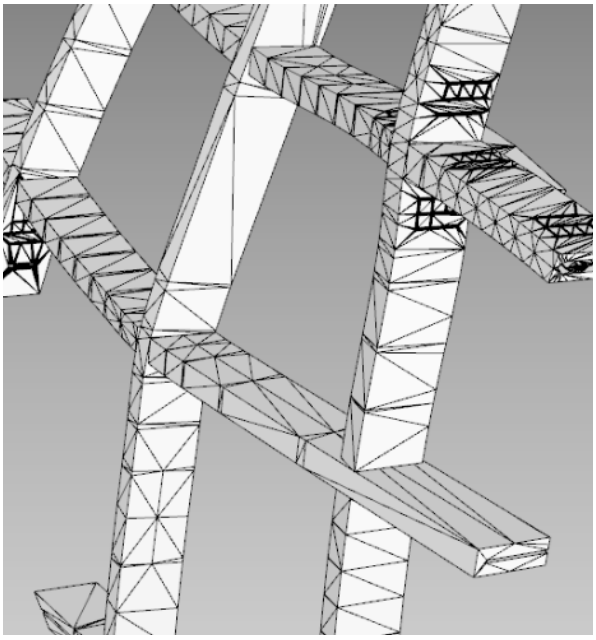

Figure 5 Example of a coarse mesh from an IFC model used for estimation and planning.

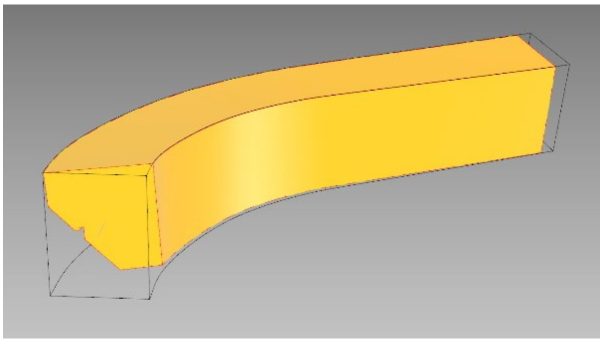

Figure 6 Example of a fitted beam model (black outline) over a detailed NURBS input model.

Once a feasible glulam beam model is acquired, it is decomposed into two phases that correspond to the two pressing steps and their respective constraints. To derive these two phases, the decomposition is done in reverse order of the production process.

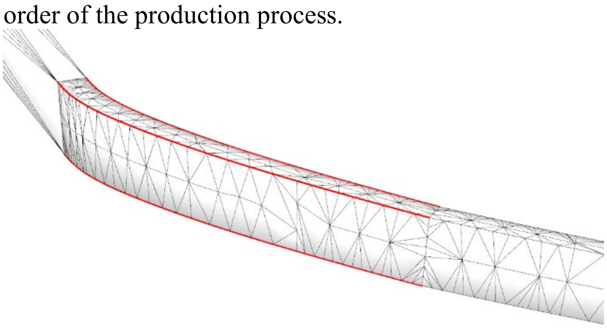

Figure 7 Reconstructed beam edges from a coarse mesh from an IFC model.

Firstly, the pair of beam faces that is least curved is taken as the second pressing step. This is due to the thickness limitations in the resawing of the first pressed form. A median surface between the two faces of the pair is extracted and serves as the neutral axis of the form. Both faces are geodesically unrolled with respect to this median surface. Overlaying the unrolled faces shows how – due to the double curvature of the beam – achieving a rectangular cross-section is only possible if each layer of the second pressing is different (Fig. 8).

However, since each layer is the result of the same single-curved blank being resawn into layers, each layer is identical and therefore must be expanded so that it envelops both of the unrolled beam faces. This expansion is done by sampling both unrolled faces in relation to the centreline curve of the unrolled median surface to find the farthest point on either side, and offsetting it at the corresponding distance.

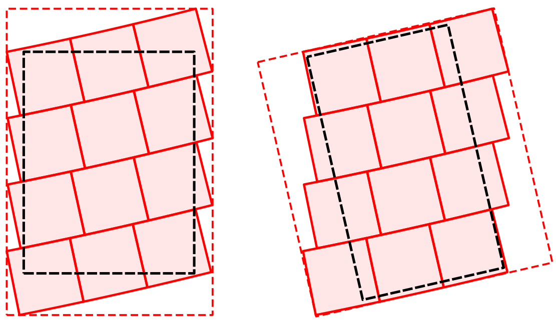

Figure 8 The skewed cross-section means that a rectangular cross-section (black) cannot fit neatly inside of the blank.

The resultant enlarged unrolled shape becomes the required form of the first pressing – in effect, the plan of the single-curved glulam that is to be resawn into layers for the second step (Fig. 9).

The resultant shape is then re-rolled onto the median surface of the glulam beam model, using the relative positions of the original faces. The edges of the resulting faces are connected, forming a closed solid. Depending on the degree of curvature from both pressings, the cross-section of the final glulam blank model becomes trapezoidal (Fig. 10).

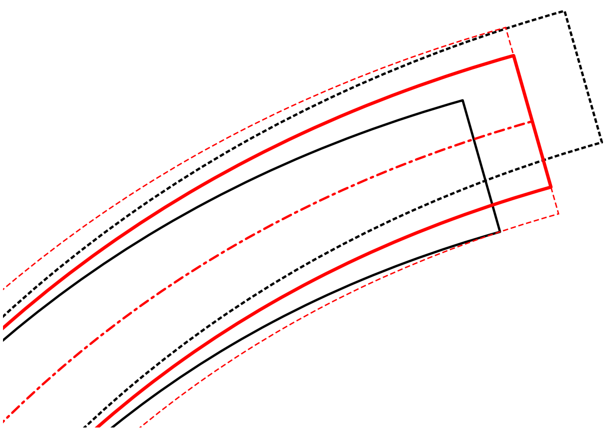

Figure 9 The difference in shape between the top (solid black), middle (solid red), and bottom (dashed black) surfaces when unrolled. A single, widened surface (red dashed) is needed so that the entire beam is encompassed by the re-rolled blank geometry.

Thus, the geometric and process constraints from the two-step pressing result in a particular geometric form that encompasses the original glulam beam model and a more accurate representation of the glulam blank model.

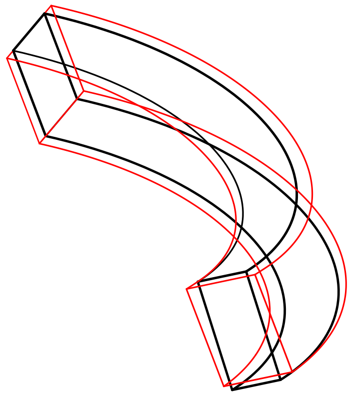

Figure 10 The difference between the beam geometry (black outline) and blank geometry (red outline).

Material parameters and production mechanics

Having arrived at the glulam blank geometry, the next step in the workflow is the selection of material specifications according to performance requirements and material limitations. The relationship between curvature in free-form beams and the lamella dimensions is developed from the typical method used for single-curved beams into a more broadly-applicable simulation-informed validation method. Mechanical tests done in a parallel effort transfer material properties from simpler glulam specimens into generalised design values.

For single-curved glulam beams, lamella thicknesses are related to the maximum curvature the beam, typically expressed as a simple linear ratio between the radius of curvature and the thickness of the lamella. While this provides a straightforward way of arriving at material specifications for planar glulam beams, double-curved – or free-form – beams require additional considerations.

Initially, in the two-step lamination process, curvature was also considered in two parts, leading to a lamella thickness specification for the first pressing and a different one for the second pressing out of plane. While this allows the curvature estimates to be done in a decoupled way, using only the planar curvature at each step, it does not capture the full strain induced on the lamella by the combination of both together, along with torsion.

To overcome this, the curvature limits from single-curved glulam specification are translated into strain coefficients which can then be used as limit values in more complex and three-dimensional scenarios. Bending strain in a beam can be defined by $\varepsilon = \kappa y$ where ϵ is the longitudinal strain, κ is the curvature of the beam (also defined as 1/R, where R is the radius of curvature), and y is the distance from the neutral axis. Since individual lamellas themselves behave like long and slender beams, we assume a Euler-Bernoulli model where bending strain dominates and shear caused by bending is negligible.

Considering the Eurocode ratio of 1:200 between the lamella thickness and the smallest allowable radius of curvature for softwoods (t/R, where t is the lamella thickness and R is the radius of curvature), the maximum induced bending strain for a curved lamella can be 0.0025. Transferring this principle to free-form glulam blanks therefore can be done through a projection of the curvature vector onto the cross-section and its decomposition into width and height values for the lamella dimensions, which is subsequently validated through simulation using the finite element method (FEM). The smallest 3d radius of curvature is found at the innermost lamella edge of the blank. The vector of curvature is decomposed into height and width components relative to the blank cross-section, giving the amount of bending in each direction. The thickness is then found using the established t/R ratio. To introduce a simulation-based validation step in our workflow, finite element analysis is used to simulate the bending of the critical lamella into its final shape in the glulam blank. The maximum longitudinal strain is compared to the strain limit to verify an appropriate dimensioning of the lamella. While this step is still at a preliminary stage in the project, further work will improve both the robustness of the FE model as well as compare the simulation with results of physical testing. This has implications for scenarios where the second pressing step induces substantial torsion on the layers, where shearing across the plane of the layer becomes a significant source of strain. The mechanical testing of lamellas and curved glulam prototypes is an on-going adjacent stream in the project. This parallel effort seeks to also experimentally arrive at generalizable strain limits for different lamella species such as spruce and pine to help with selecting the most appropriate material type and quality for a particular glulam blank.

As a decision-making tool, the lamella material and dimensioning are used to assess the feasibility of a producing a particular glulam blank, as the calculated optimal parameters must nevertheless be compared against process constraints along the glulam production chain. For example, board thickness at the material intake can dictate available lamella sizes, based on whether or not they can be resawn into thinner boards or the degree to which they should be planed. Similarly, the minimum resawing and planing thickness after the first pressing step constrains the possible curvature in the second pressing step, as the size of the first blank is much greater than the individual lamella, necessitating larger resawing and planing equipment. Finally, the spacing of the pressing heads on the glulam blank is strongly related to the thickness of the lamella – thinner lamellas require a closer and more consistent press spacing – however the geometry of the press and its kinematics dictates the possible head layout for a given glulam blank geometry. The ability to confidently identify these constraints and how an incoming glulam beam model stacks up against them is therefore a valuable tool for the assessing and planning of a project.

Production integration and prototyping

The final step in the workflow before production is the generation of positioning data for each of the pressing steps. In an automated workflow, this also includes the position of each linkage in the kinematic chain of the press and the motion planning of the entire assembly.

For the two-step lamination process, the pressing positions need to be generated for the first, single-curved step and then subsequently for the second, out-of-plane bending step. Future work will additionally investigate the feasibility of using the single-step process of bending a free-form glulam directly using smaller, more squarish lamellas.

For the first step, the intermediate or "unrolled" form of the glulam blank model is used. The resultant shape which encloses the unrolled top and bottom faces of the glulam beam model is effectively the 2d representation of the result of the first pressing. This is oriented so that it lies along the longitudinal axis of the single-curved press. For each press track, its linear axis is intersected with the inner – that is, the one closes to the resting position of the press – edge of this shape. The tangent vector of the inner edge at that intersection point yields the angle of the pressing head as well as its position along its track. This therefore gives the full press parameter description for the first step – the single-curved blank.

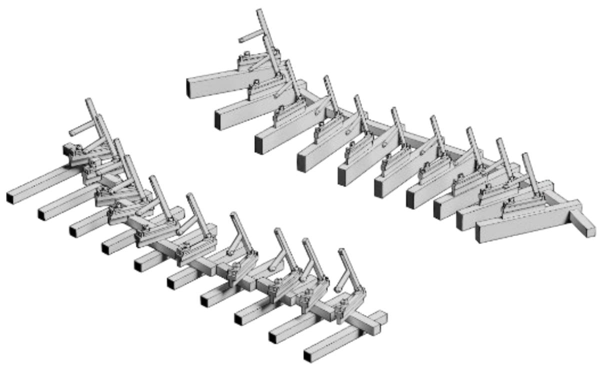

Figure 11 Visualization of the free-form press prototype, showing the modular and articulated pressing heads.

For the second step, a more complex route is required due to the additional degrees of freedom necessary to achieve the out-of-plane curvature. The design of the second press consists of a modified single-curved glulam press which introduces additional press heads that give additional axes of movement and rotation (Fig. 11). For this, a digital kinematic model is constructed consisting of the individual linkages in the press, their axes of rotation or displacement, and relative offsets. The simplicity of the linkage arrangement means that a direct numerical method can be used to solve the inverse kinematic problem instead of an iterative solver, greatly simplifying the computational complexity. For every target press position, the required linkage positions are determined by their offsets and relative rotations. The accuracy of the result is therefore dependent only on the quality of manufacture of the press linkages and the measurement of their true offsets and relative positions. The kinematic solution is output as a structured dataset consisting of joint rotations and distance values for each press head. These are used to position the press into the required pose for pressing the target form.

The workflow is tested at a reduced scale using the full industrial infrastructure to evaluate the validity of the material specifications and the accuracy of the press data by producing 15 beam prototypes out of spruce lamellas (Fig. 12). Following the methodology, they are first formed as single-curved blanks in a Ledinek press, resawn and planed, and then pressed into the final 3d form with the second modified press. Lamellas thicknesses of 15mm are used for the first step – the minimum thickness driven by the resawing limitations for individual lamellas in the current production line – and 50mm for the second step – limited by the resawing and planing capacity in the current production.

Figure 12 Free-form glulam blank prototypes produced using the digital workflow.

Discussion and future work

The developed workflow demonstrates how inconsistent and coarse design geometry can be translated into a useful glulam blank model so that it can be evaluated against material and process constraints and further used to drive the generation of production data. This effort shows how a typically laborious and craft-based process can be augmented and streamlined through computational methods towards eventually becoming an automated and industrialized process for the construction of curvilinear timber structures. Key data for generating the glulam blank model is extracted or reconstructed from rough design models. Material limits from established standards are integrated into the specification and planning steps, with these being eventually supplemented with experimental data. Production data for the pressing of the glulam blank is derived from the model through geometric and kinematic analysis.

While the accuracy and implementation of the actual physical press infrastructure is outside of the scope of this paper, validation of the physical prototypes is nevertheless seen as a critical path forward in tuning and verifying the digital workflow. To this end, the prototypes have been 3d scanned and compared to their digital beam models to begin preliminary quality assessment of the pressing process (Fig. 13). As a feedback method, this is expected to identify areas of improvement and potentially additional geometric factors to test incoming models against. The result of this validation will primarily affect the generation of press parameters by determining how they must be compensated to better achieve the target form.

Preliminary analyses of the scans show mean deviations of point distance to model geometry between 0.32 and 3.84 mm with standard deviations between 3.42 and 8.14 mm. The mean deviation between beams is 1.29 mm with a standard deviation of 0.92 mm. A greater deviation was observed in the direction of the second pressing. Considering that there were fewer, yet thicker and therefore stiffer, layers in this direction, it is likely that this was caused by greater springback in the material after pressing. The analysis could be improved with more refined registration methods and by observing deviations separately for each step, instead of only for the final result. In 9 of the prototypes, over 90% of scan points were within 10 mm of the beam model, while in 4 prototypes, over 70% of the points were within 5 mm.

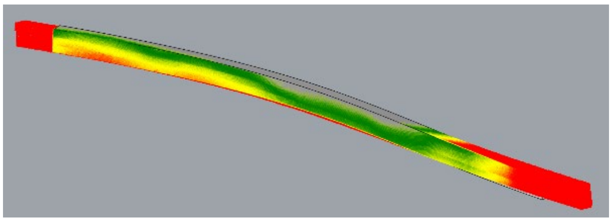

Figure 13 A preliminary comparison between the beam model and scan of a physical prototype, showing areas that lie within a 10mm tolerance (green and yellow) and areas that exceed this tolerance (red), especially at the longer ends.

Future work will also seek to include more nuanced material properties and strain limits based on the results of parallel material testing on both straight lamellas as well as free-form laminated prototypes, to arrive at a reliable material model that is tuned to the particular species and geometry type.

Alongside these plans for the digital workflow from model to press data, we plan for further automation of the press infrastructure itself and therefore using the results of the digital workflow directly in the actuation of motors to drive the press positions. The ability of the second press to achieve three-dimensional forms also shows potential in being used for the one-step lamination process with more squarish lamellas, bypassing the need for two pressing steps. The design and manufacture of free-form glulam elements using either method can therefore be achieved in a seamless manner, avoiding the need for laborious planning and manual work.

Regarding the wider positioning of this effort within the digital design chain, the sussing out of these material specifications and production parameters can serve as feedback mechanisms for evaluating designs at early stages. By relating geometric properties to specific barriers in production, challenging beams could be identified and revised or else directed towards alternative fabrication methods. For example, pressing constraints – distances between the pressing heads, track sizes, and so on – imply that particular forms might exceed the capacity of a particular setup. This suggests a diversity of press configurations – some finer, some larger and heavier – to deal with a variety of input geometries as opposed to a "one size presses all" solution.

Along the same line of thinking, the issue of tolerances touched upon before also raises the idea of adaptive or performance-driven pressing, where tolerances are tightened around geometrically or structurally critical areas of the beam while relaxed elsewhere. This would enable a more efficient allocation of effort and energy, with implications not only for production time and cost but for material use and sustainability metrics.

Conclusion

We envision a fully automated and industrialized process for fabricating free-form glulam beams from coarse input data in typical architectural workflows.

The described work is positioned as a contribution to digital construction and industrialised timber fabrication, focusing on the design-to-production information workflow required to realise free-form glulam structures under real-world industrial constraints. The work demonstrates how computational modelling, automated rationalisation, and analysis-informed validation can be integrated into a robust, end-to-end digital pipeline that translates imperfect design input into production-ready manufacturing data. It foregrounds automation, data robustness, and scalability, addressing a key challenge in industrialized timber construction: the reliable manufacture of complex architectural intent in free-form structures. In doing so, it demonstrates how materially-aware computation in construction processes can lead to increased industrial efficiency, a greater flexibility and feasibility of manufacturing outcome, and new potentials in achievable architectural expression.

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