Geometrical analysis of naturally grown timber for the design of load-bearing structures

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Abstract

Combining tradition and innovation, timber plays essential roles in building structures for architecture and engineering. Tree branching geometries and timber in natural state often serve as sources of inspiration. However, the mechanical properties of naturally grown timber, inherently inconsistent and geometrically varied, remain insufficiently studied, particularly for construction and simulations. This knowledge gap perpetuates the prevalent use of straight, uniformly harvested timber, while neglecting curved and bifurcated elements with smaller cross-sections.

This research investigates the potential of naturally grown timber in structural design. The central idea emphasizes that a thorough understanding of the natural characteristics and growth patterns of trees can improve how we use timber. This methodology is developed to facilitate the design of structures that align with natural growth principles. Utilizing non-invasive, such as Computerized Tomography (CT), precise geometrical and material properties of wood can be obtained. This work combines these data sources to visualize cross-sectional geometries and material properties. The methodology integrates an analytical approach based on Generalized Scaled Boundary Isogeometric Analysis, enhancing the accuracy and efficiency of simulations. This approach fosters sustainable resource practices, and promotes the use of major tree parts, transforming discarded material into valuable resources. This paper concludes with a practical application through a construction demonstration.

Keywords— Naturally grown wood, load-bearing structures, growth analysis, non-invasive scanning techniques, isogeometric analysis

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Impact Statement

This research enhances the use of naturally grown timber in architecture and engineering, promoting sustainable construction practices. By uncovering the potential of irregularly shaped wood elements, the study introduces a shift towards "organically grown" structures. Using advanced non-invasive scanning and computational models optimizes timber use and transforms overlooked materials into valuable resources. This breakthrough contributes to the evolution of innovative and environmentally conscious building practices, aligning timber utilization with its inherent properties and promoting a return to the natural materials cycle, see Fig. 1.

Figure 1: Bridge over a stream in the forest with on-site collected elements. Location: 50.683, 6.157.

1 Introduction

The concept of growth emphasizes organic development, where materials adapt to and respond to external stimuli.

Bio-based materials can expand across various micro scales, influenced by the biological conditions of substance transport. This growth can often seem disorganized; however, recent advancements indicate promising rapid development. Applying these materials at meso and macro scales poses a challenge in construction. Nonetheless, when combined and bound with other biomaterials, such as wood, they present potential opportunities (Saez et al. 2022).

In the context of load-bearing structures, grown trees and timber exhibit notable capacities due to their strength and lightness. This is studied and demonstrated since the construction of the earliest primitive huts. However, the tree growth spans several generations. Growth guidance forms a significant branch within timber construction and finds applications here. Techniques for tree control, based on static study and load analysis, have been studied and implemented in (Wessolly and Erb 2014). This can be applied to the cultivation of mechanical elements, for their incorporation into grown wooden structures, or the cultivation of complete structures. Baubotanik –or living plant constructions–, a term initiated by Ludwig 2012, serves as an example of this. It demonstrates how various experiments with tree growth patterns can be applied to architectural scale over the years Bukauskas et al. 2019. If these properties are able to

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be measured and simulated, a broader and more efficient use of naturally grown wood elements can be achieved.

1.1 Motivation

Wood has been extensively processed into boards, beams, slats, and veneers, primarily using tree trunks and leaving branches and forks underutilized due to their small cross-sections and curves. The round wood collected, after processing, is approximately 50% preserved (Ramage et al. 2017). This practice results in significant waste, as only about 30% to 40% of the felled tree is used as building material –especially for deciduous trees– see Fig. 2. The production of wood-based materials involves the extensive use of adhesives, often mixed with synthetic materials that may not be biodegradable. This process requires significant energy input due to the intensive level of processing involved. With the rising trend of using wood as a versatile and transformable material in architecture, there is a pressing need to enhance utilization efficiency in the timber industry to meet the increasing demand. This involves better utilization of the finite wood supply, including branches and other curved elements, in their original, round shape with minimal processing.

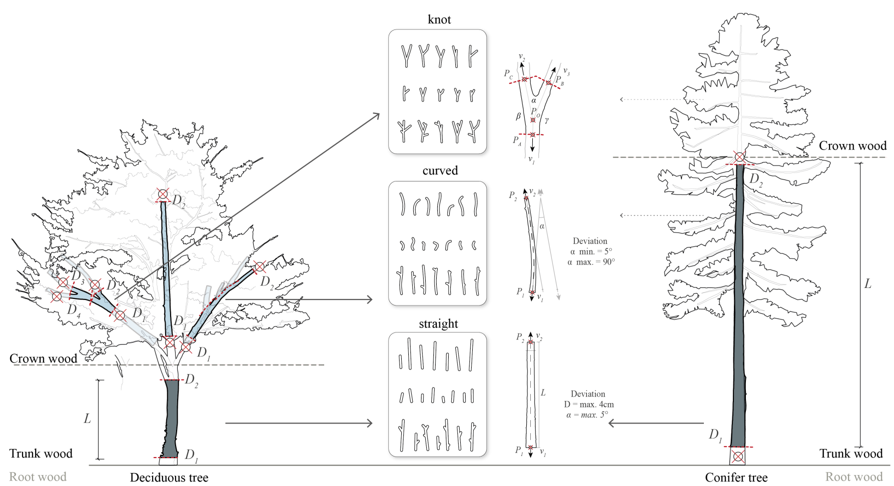

Figure 2: Segmentation of trees and their use for building materials: Straight segments, additionally curved elements and bifurcated elements (knots) (Wages 2022).

Each tree develops unique material characteristics due to its immediate environment. These traits are results of natural optimization and economizing of the material due to static and dynamic loads (C. Mattheck 1990) (Claus Mattheck 1998). Innovative methodologies, including non-invasive scanning techniques, are currently being employed for the detailed investigation of individual material properties of naturally grown wood. These techniques, such as Computed Tomography (CT) scanning, provide an in-depth analysis of the timber's internal properties, including the detection of knots and the determination of fiber orientation (Huber et al. 2022), thereby contributing significantly

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to our understanding of the material's inherent characteristics. This data can help in the development of a better understanding of its material properties and in creating more efficient load-bearing structures. This interdisciplinary approach has the potential to unlock new possibilities in sustainable construction, leading to a more efficient use of resources.

1.2 Background

Wood analysis and its application in construction, specifically in Architecture, Engineering, and Construction (AEC), have been partially explored. On the one hand, a preliminary stage of this work presented methods of abstraction and simplification of tree growth for its simulation (Moreno Gata, Musto, and Martin Trautz 2020). On the other hand, innovative digital technologies, including photogrammetry and laser scanning, have merged natural and digital geometries, streamlining the design and manufacturing process in constructions involving raw timber. The examples of Self and Vercruysse 2017 and *WholeTrees - Technology* 2023 show the still exploratory but potential in large scale constructions. Simultaneously, the study of tree growth has led to the production of geometrically unique, constructive elements, (Amtsberg, Huang, Moreno Gata, et al. 2021), (Larsen and Aagaard 2020), (Buelow et al. 2018). Recent studies performed on raw timber (Desai 2020) and on "green oak" wood of smaller diameter (Hofmann et al. 2023), using material characterization and loading tests, are initial attempts to ascertain the load-bearing capacity within technical structures.

2 Methodology

2.1 Data Collection with Non-Invasive and Image-Based Methods for geometry and material analysis

The first aim of this work is to systematically document and comprehend the intrinsic properties of naturally grown timber, with the ultimate goal of creating a model applicable to the evaluation and design of future structural elements.

The acquisition of tree geometry employs advanced methods such as photogrammetry and 3D scanning, as showcased in Fig. 3. In subsequent stages, non-invasive data sampling techniques, specifically X-ray Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), have been extensively employed to analyze plant growth, particularly concerning reaction wood and root structures (Brereton et al. 2015)(Pflugfelder et al. 2015). These non-invasive modalities, grounded in different physical principles, present unique potentials and challenges. In this context, CT, with its capability to analyze density variations within wood specimens, is utilized.

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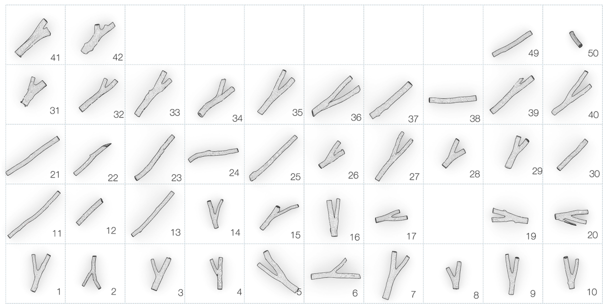

Figure 3: Data-set of naturally grown elements based on 3D laser scanning and photogrammetry.

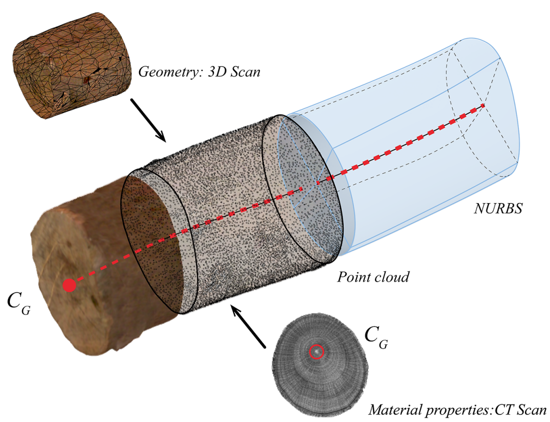

Figure 4: Development of a combined geometric and material model analysis environment based on surface images and tomographic computer scan. Center line (in red) along the volume and generation of a NURBS model.

CT methods, along with various information types and calibration methodologies, facilitate the detailed acquisition of density variations. Observing density gradients along plant growth in three dimensions reveals variations from the center to the bark. Post-processing of this information, coupled with CT generation, enables further slicing to investigate specific areas, seamlessly integrating into future workflows, particularly those focused on material modeling.

The integration of this information, in tandem with standard superficial 3D laser scanning methods, is feasible, as illustrated in Fig. 4. The geometric acquisition is further integrated into a Non-Uniform Rational B-Spline (NURBS) superficial Geometrical Model. This model, augmented by CT images, provides crucial growth parameters, including rings, thereby unveiling both geometric and material properties.

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2.2 Development and Construction of a Geometric Model

2.2.1 Generic model

The geometric construction of the model, based on previous documentation or scans, results in a general geometrical model. This process yields a discrete surface approximation of the specimens analyzed previously.

The pathway unfolds as follows: it starts with the importation of an image-based model, re-positioned according to (Moreno Gata, Seiter, et al. 2023). The mesh volume is subdivided into transverse sections parallel to the relocation plane α_i, defined by the vertical vector h and the normal vector a_i. This generates a section s_i, determining a geometric center point A_i, later generalized as uppercase C_g. This process constructs a geometric center line c_g, composed of the individual geometric centers.

Subsequently, this information is hierarchically organized for NURBS construction. Given the cross-sections s_i, they are divided into a maximum of 4 points S_i. These points segment the sections, later used to construct a degree-3 transition surface. These 2D surfaces, termed patches, along with the geometric center line, are exported for subsequent mechanical simulations, see Fig. 5

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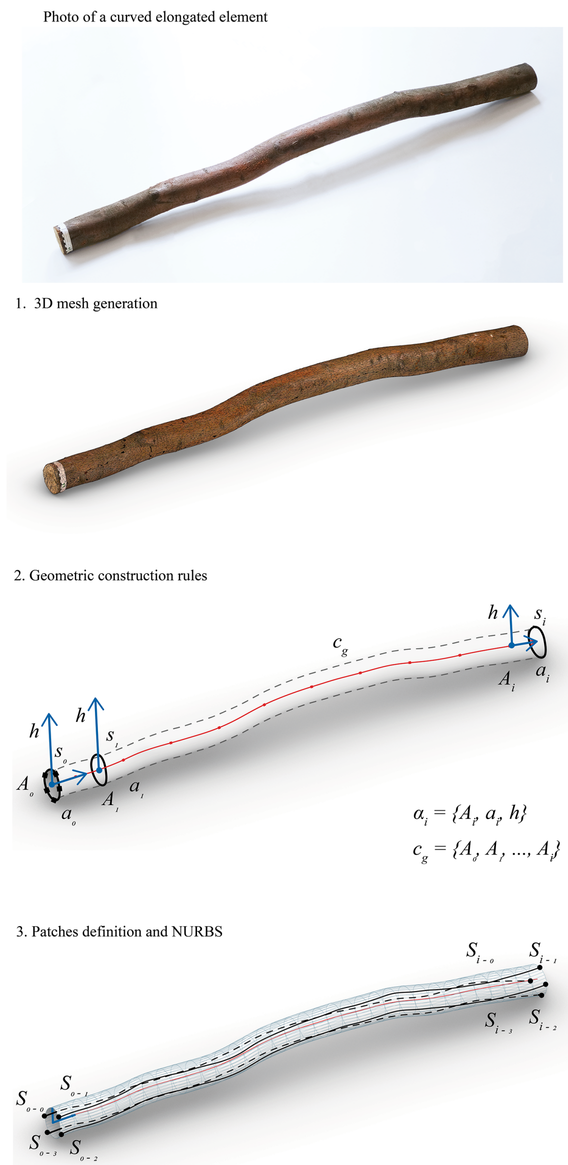

Figure 5: Pathway for the geometric construction of a generic elongated curved element.

2.2.2 Generic model for bifurcations

The digital processing of bifurcated elements, or forks, is determined by an integration in three axes of the generic model. The oriented model, in 3D mesh format, interprets a bifurcation with 3 central lines, a, b, and c, which are discretized in their length, yielding vectors a_0, b_0, and c_0 at their initial segment starting from the bifurcation.

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This process allows the generation of sections s_{A-0}, s_{B-0}, and s_{C-0}, whose centroids (A_0, B_0, C_0) define the plane π. This plane π have a normal vector h_π. The sum of possible combinations of vectors a_0, b_0, and c_0, along with the vector h, and the central geometric point C_{g-0}, gives us the cutting planes α, β, γ. These planes intersect the volume of the 3D mesh.

The subsequent step of defining patches and constructing NURBS is determined, similar to the generic model, by the division of cross-sections s_i, in this case coinciding with the edges defined by the cutting planes. For a proper curvature transition, a subdivision geometry element (Sub-D) is employed. This is followed by exporting for subsequent mechanical simulation.

This geometric process is integrated and programmed within Rhinoceros (McNeel et al. 2023) environment to facilitate its automation.

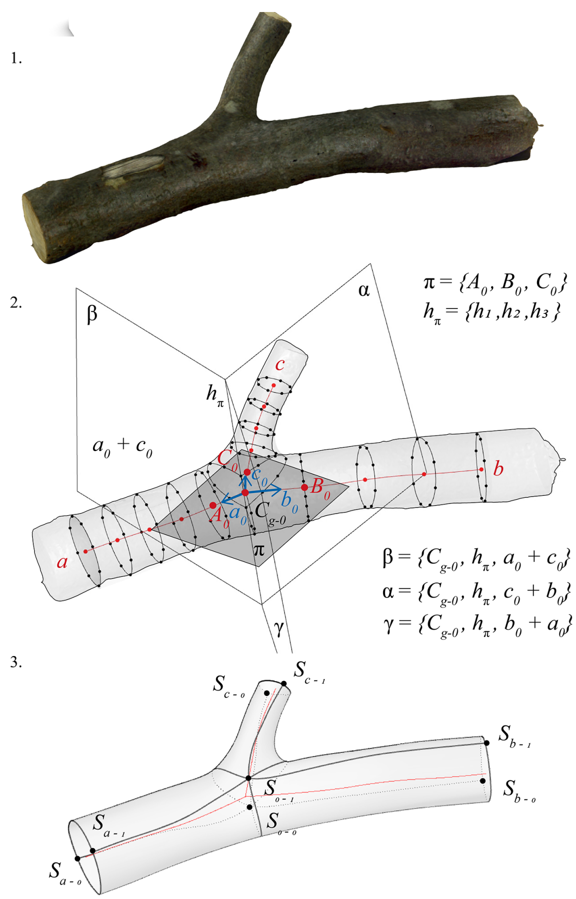

Figure 6: Geometric construction of a tree bifurcation based on sub division modeling.

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2.3 Growth-induced material properties

The distribution of biomass material within a tree exhibits a polar pattern influenced by its natural growth. Understanding and accurately representing this distribution is crucial for creating comprehensive mechanical models, especially for raw timber elements. The described methodology involves calibrating 3D-scanned components by aligning system axes with volume distribution obtained from CT scans. This calibration ensures an authentic representation, capturing complete spatial dimensions and effective spatial axes. This results in an enriched model with superficial two-dimensional representation and internal information. It allows for preliminary studies on the implications of asymmetry in curved and bifurcated grown elements. To comprehensively analyze trees, it would be necessary to supplement the work with information from sources, such as MRI or data with varying water content.

2.3.1 Polar definition of the cross-section

A significant challenge in this context is accurately determining the center line, also known as the growth central axis, often mistakenly assumed to be the geometric central axis. This center line is formed by the union of growth centers C_G, currently only obtainable through visual information or CT data. The center C_G represents the tree's initial growth center, located at the central point of the annual rings. In a straight element with a circular cross-section, the geometric centroids C_g and growth centers C_G tend to coincide. However, this deviation becomes more pronounced in irregular elements, such as oval-shaped cross-sections primarily generated by reaction wood or in a bifurcation. This is supplemented with a the Center of Mass, –C_M–. This is the sum of all masses within the section. In a rectilinear element, it tends to be the same as C_G and C_g. To determine its location in an irregular element, it is necessary to conduct a density variation study. This center allows observing the displacement of biomass throughout growth. This is applied to analyze eccentricities and displacement of the centers along the tree length, see Fig. 7.

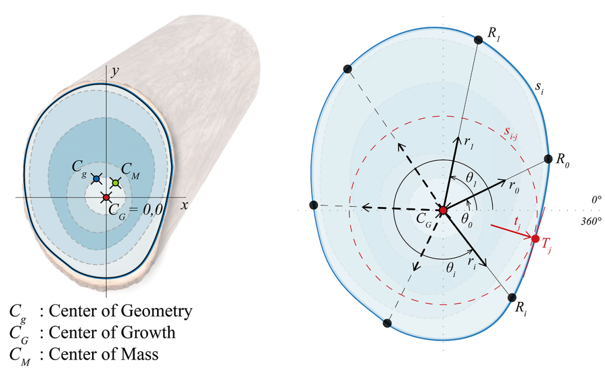

Figure 7: Definition of the three centers of the cross-section: Geometric center –centroid–, Growth center, and Center of mass. Polar ray (r) positioning for cross-section analysis.

Wood cross-sections are commonly considered with a polar coordinate system. The center C_G, serving as the center of the polar system, acts as the starting point for

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drawing rays r_i extending to the previously defined geometric perimeter s_i. Rays are determined at an angle θ_i. The intersection of r_i with s_i gives us the points R_i. These rays are utilized for a density variation analysis later in Fig. 9.

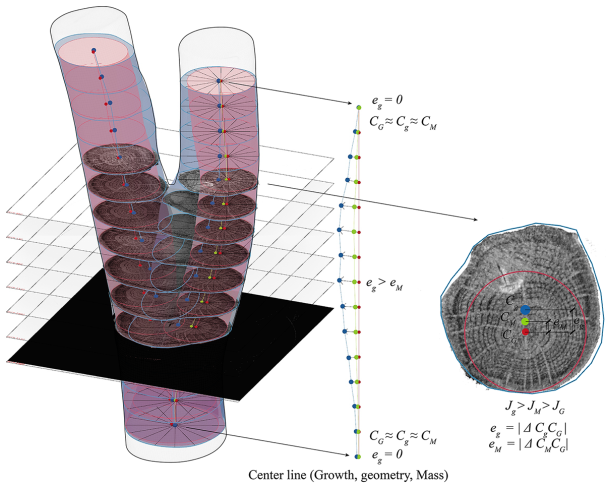

Figure 8: Visualization of the bifurcation of a small specimen of oak. In red: reference tangent circular geometry with C_G, if the tree grow straight. In blue: grown geometry with eccentric displacement of C_g. The production of tension wood can be seen in blue. C_M calculated after applying the derived polynomial density.

2.3.2 Growth-induced mass displacements

The mass displacement can be observed in the model, see Fig. 8. For visualization, a tubular volume with variable radius $|\mathbf{t_j}|$ is traced along the central growth line as a reference. This tube is determined at each cross-section, taking the smallest modulus of all $|\mathbf{r_i}|$. This defines a circle s_{i-j}, with a tangent T_j at s_i. Using this method, it is possible to visualize an approximation of the volume generated by the tree as reaction wood. In the example in Fig. 8—based on a reference oak specimen— it can be recognized how the added volume in growth corresponds to tension wood. Furthermore, one central line of a bifurcation element has been extracted. With the C_G of each section in a straight line, one can observe the quantitative difference in geometric eccentricities, which increase along with the tension in the wood.

The last part of this section outlines the application of the polar method for analyzing density variations within the volume. These techniques are instrumental in detecting higher density zones, such as heartwood. The relevant eccentricities are then defined. The eccentricity e_g of the central axis, is calculated as the distance between C_g and C_G. After calculating the C_M, with the help of the density distribution (in Fig. 9) the e_M can be found. This is relevant for a mechanical understanding of the tree, as it has implications on the moment of inertia of each section s_i. In Figure 8 the cross-section on the right illustrates the variation in moment of inertia due to geometrical J_g, in comparison to a moment of inertia reference due to growth J_G. For

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instance, in a straight-grown tree with a perimenter s_{i-j} –delineated in red–, its J_G would be much lower than the actual J_g. This consideration requires complementing with a calculation of the mass moment of inertia J_M.

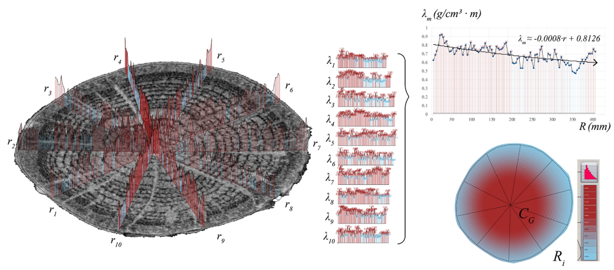

Figure 9: Material density variation λ along the radius R. λ_i corresponding to every r_i, and λ_m represents the resulting density in the cross-section. Using a polynomial, a formula can be derived, which can then be reapplied to the cross-section from C_G to R_i.

2.3.3 Exploration of material stiffness

The polar structure has been used to determine the moments of inertia and densities, as discussed above. In addition, there are more properties that vary along the radius, starting from C_G, such as strength and stiffness. Studies have shown that there is a relationship between density variation and strength. Matsuo-Ueda et al. 2022 shows that in Japanese cedar –softwood–, its modulus is higher in the center and decreases in the radial direction, see. Fig. 10, right; on the contrary, in deciduous trees –hardwood– their modulus is lower in the center and increases in the radial direction, which can be contrasted with the density variation study of the previous section. The integration of material properties and the E modulus, based on material tests, can be employed for further analytical methods and simulations. In Figure 10, a general formulation of area distribution proposes how to numerically analyze the variation of stiffness and the inertia moment J along the radius. Where A_i is the area of every accumulation of growth rings, J_i the moment of inertia, and E_i the Young modulus.

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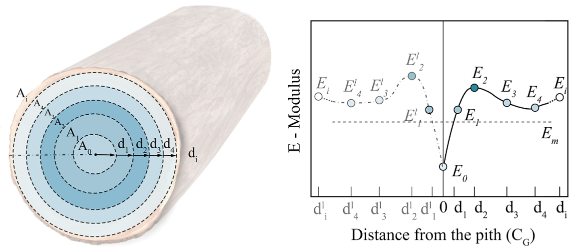

Figure 10: Symmetrized variation of the E-modulus over the cross-section according to Matsuo-Ueda et al. 2022, in a softwood.

$$\mathrm{A}_0 \;\ldots\; \mathrm{A}_i$$
$$J_0 \;\ldots\; J_i$$

$$\begin{aligned}
\mathrm{A}_{\mathrm{tot}} &= \mathrm{A}_0 \frac{E_0}{E_{\mathrm{tot}}} + \mathrm{A}_1 \frac{E_1}{E_{\mathrm{tot}}} + \ldots + \mathrm{A}_i \frac{E_i}{E_{\mathrm{tot}}} &&= \sum_{n=0}^{n=i} \mathrm{A}_i \frac{E_i}{E_{\mathrm{tot}}} \\
J_{\mathrm{tot}} &= J_0 \frac{E_0}{E_{\mathrm{tot}}} + J_1 \frac{E_1}{E_{\mathrm{tot}}} + \ldots + J_i \frac{E_i}{E_{\mathrm{tot}}} &&= \sum_{n=0}^{n=i} J_i \frac{E_i}{E_{\mathrm{tot}}}
\end{aligned} \tag{1}$$

3 Isogeometric Analysis

Geometries in engineering design applications are typically modeled in CAD software by non-uniform rational B-splines (NURBS). As Hughes, Cottrell, and Bazilevs 2005 initially demonstrated, these geometry-describing functions can be used in the isogeometric analysis to solve engineering problems. In contrast to classical simulation approaches, such as finite element analysis, the computational effort of meshing the geometry can be neglected. Many efficient and numerically stable algorithms exist for processing NURBS in NURBS objects. Besides its usefulness in accurately describing conical cross-sections such as ellipsoids, circles, spheres or cylinders, the significant advantage towards the finite element analysis (FEA) is the higher continuity over element borders and the efficient mesh refinement possibilities. As stated in the previous chapter, through modern 3D-scanning techniques, an accurate description of arbitrary geometries is possible. Here, a two-dimensional NURBS surface patch in a three-dimensional space is created. Coming from 2D image data, a solid volume description can be generated by scaling the NURBS surface in a scaling center point. This method is called scaled boundary isogeometric analysis (SBIGA) Chen, Simeon, and Klinkel 2016, Chasapi et al. 2022. For the application in modeling long slender geometries, such as wooden branches or trees, this technique has drawbacks since numerical condition problems due to obtuse-angled polyhedral patches can occur. To avoid this, a novel generalized scaled boundary isogeometric analysis (GSBIGA) approach is introduced. This new method employs a scaling center line instead of a scaling center point (Spahn et al. n.d.). Figure 11 shows the basic principles.

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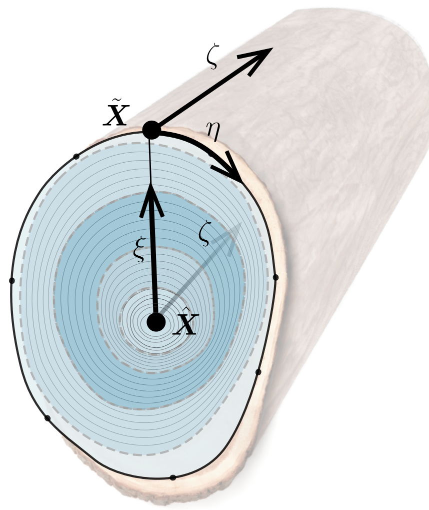

Figure 11: General SBIGA approach depicted, spanned by parametric coordinates ξ, η and ζ. Functions as polar scaling approach in cross-sectional area for ξ and η at a given ζ.

For this purpose, the parameters η, ζ and ξ are introduced. The boundary surface is spanned by η in tangential and ζ in the longitudinal direction; the spatial scaling direction is described by ξ. All three parameter are defined on the interval from $0 \leq \eta,\, \zeta,\, \xi \leq 1$. The modeled slender geometry of the domain Ω_0 has a defined longitudinal direction, coinciding with the primary growth direction of wood and its center line. This modeling technique shares the characteristics of wood as the polar definition in the cross-sectional area. This relation is advantageous for modeling the polar dependency of material properties as already suggested in Fig. 7. The position vector $\hat{\boldsymbol{X}}(\zeta)$ contains the Cartesian coordinates of an arbitrary point on the center line $(\hat{X}_1,\, \hat{X}_2,\, \hat{X}_3)$, also known as the center of growth C_G. A point on the boundary surface $(\tilde{X}_1,\, \tilde{X}_2,\, \tilde{X}_3)$ is described by the position vector $\tilde{\boldsymbol{X}}$, while the position vector $\boldsymbol{X}$ describes an arbitrary point $(X_1,\, X_2,\, X_3)$ in the interior of the domain. For an arbitrary point on the boundary $\partial\Omega_0$ the following relation exists

$$\tilde{\boldsymbol{X}}(\eta, \zeta) = \mathrm{N}_i(\eta)\mathrm{N}_j(\zeta)\boldsymbol{X}_s = \mathbf{N}_b(\eta,\, \zeta)\boldsymbol{X}_s \quad \text{on } \partial\Omega_0. \tag{2}$$

Here, $\boldsymbol{X}_s$ contains all control point coordinates of the boundary surface and $\mathbf{N}_b(\eta,\, \zeta)$ the corresponding NURBS basis functions.

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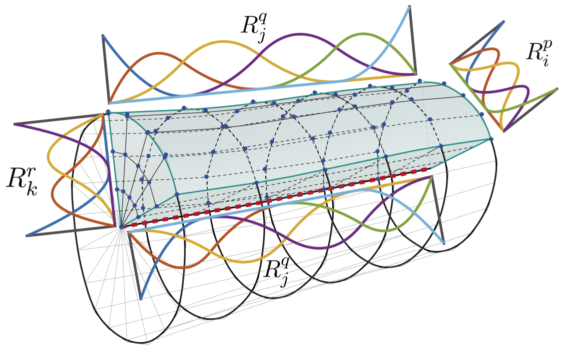

Figure 12: Geometry patch and its NURBS functions. Boundary surface spanned by R_j^q and R_i^p, volume spanned additionally in scaling direction by R_k^r. NURBS functions in longitudinal direction of the center line identical to surface functions R_j^q.

Any point on the center line can be expressed by

$$\hat{\boldsymbol{X}}(\zeta) = \mathrm{N}_j(\zeta)\boldsymbol{X}_0 \ , \tag{3}$$

with the location vector $\boldsymbol{X}_0$ containing the coordinates of all control points of the center line. An arbitrary point in the interior domain of the geometry Ω_0 can be expressed by

$$\begin{aligned} \boldsymbol{X}(\xi,\eta,\zeta) &= \xi\Big(\tilde{\boldsymbol{X}}(\eta,\zeta) - \hat{\boldsymbol{X}}(\zeta)\Big) + \hat{\boldsymbol{X}}(\zeta) \\ &= \xi\,\mathbf{N}_b(\eta,\zeta)\boldsymbol{X}_s + (1-\xi)\mathrm{N}_j(\zeta)\boldsymbol{X}_0 \qquad \text{in } \Omega_0 \ . \end{aligned} \tag{4}$$

In contrast to the SBIGA, for the novel GSBIGA, the center line needs to be described with the same NURBS basis functions as the boundary patches in the longitudinal direction. This is depicted in Figure 12, with R_i^p and R_j^q being the NURBS boundary functions and R_k^r being the NURBS functions in scaling direction. In longitudinal direction, share the boundary and the center line the same NURBS basis functions R_j^q. The general concept of the scaled boundary method remains unchanged. The 3D scanned geometric model, including the NURBS description of the body, is directly used to analyze the structure. Since isogeometric analysis is used, mesh refinement is straightforward by applying the aforementioned refinement methods. The center line should represent the initial annual ring (pith). The shape of a tree's pith, or growth center 7 is individual as its shape and strongly depends on wood type and constraints such as light, soil, or altitude. The shape of the center line and position can be arbitrarily chosen to match these obligations. Thus, the shape of the boundary surface and the shape of the center line are generally independent. The only prerequisites are the center line position in the geometries interior domain and using similar basis functions to the longitudinal boundary patches.

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3.1 Exploratory analysis on grown elements

3.1.1 Elongated elements

When simulating naturally grown unprocessed structural elements, exact mapping of the structure is essential since small deflections or imperfections can significantly impact stresses and deformations if not considered correctly. Figure 13 shows a wooden branch under longitudinal compression. The deformed geometry is plotted over the non-deformed structure in the bottom part. The displacement field is plotted over the deformed body.

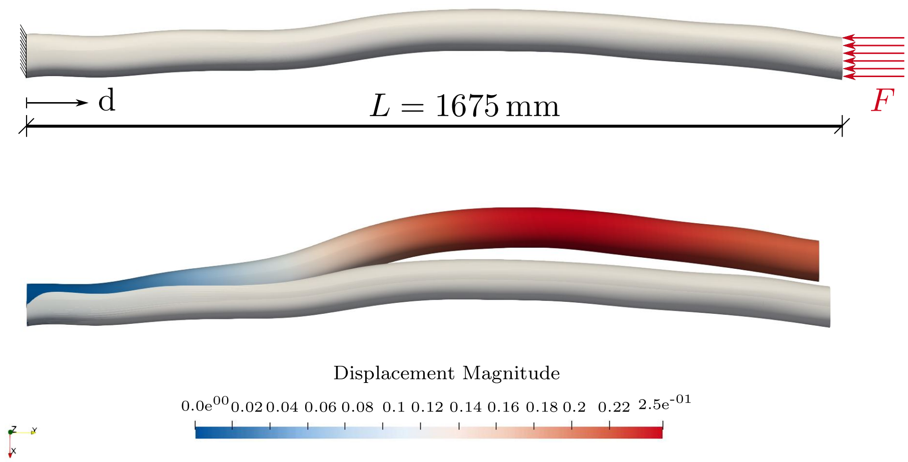

Figure 13: Longitudinally loaded compression test of unprocessed slender wooden branch. Deformation figure is given in the bottom view.

The stress plots from Figure 14 in the x and z directions show that the perpendicular stresses can not be neglected since they vary with the factor 10^1 - 10^2. This should underline how important an accurate representation of the actual geometry is. Even minor imperfections of an approximately straight wooden branch result in significant deflection radial to the center line.

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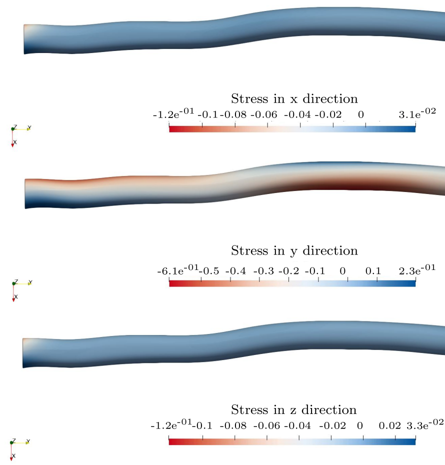

Figure 14: Stress distributions in x,y, and z directions for stresses separated.

Throughout the polar description of the parametric model, different densities, stiffness, and shear stiffness of naturally grown wood can be described in the future based on the cross-sectional radius. Using multiple Young's moduli over the cross-sectional area results in more accurate simulations. A preliminary simulation is conducted in 15 with a distribution of Young's modulus smaller in the center. This is a consideration taken as a reference from the density variation of a softwood or deciduous tree (Matsuo-Ueda et al. 2022), which is less resistant at the core. The simulation results show less deformation compared to a reference simulation of a uniform averaged E-modulus E_m.

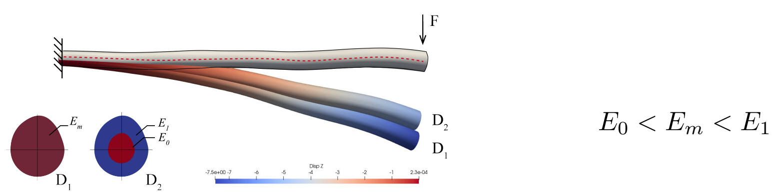

Figure 15: Comparison of a branch under bending for calculation with a constant mean modulus of elasticity distribution, with calculation with different E-modulus ranges.

3.1.2 Bifurcated elements

Multiple patches and center lines in the longitudinal direction are necessary when modeling bifurcated structural elements. Figure 16 shows the structural analysis of a wooden bifurcation model. The structure is loaded in the xy-plane towards the axes and clamped at the support. An isotropic linear elastic material model was used for the simulation. The advantages of the polar geometric description will be used for material modeling in future works.

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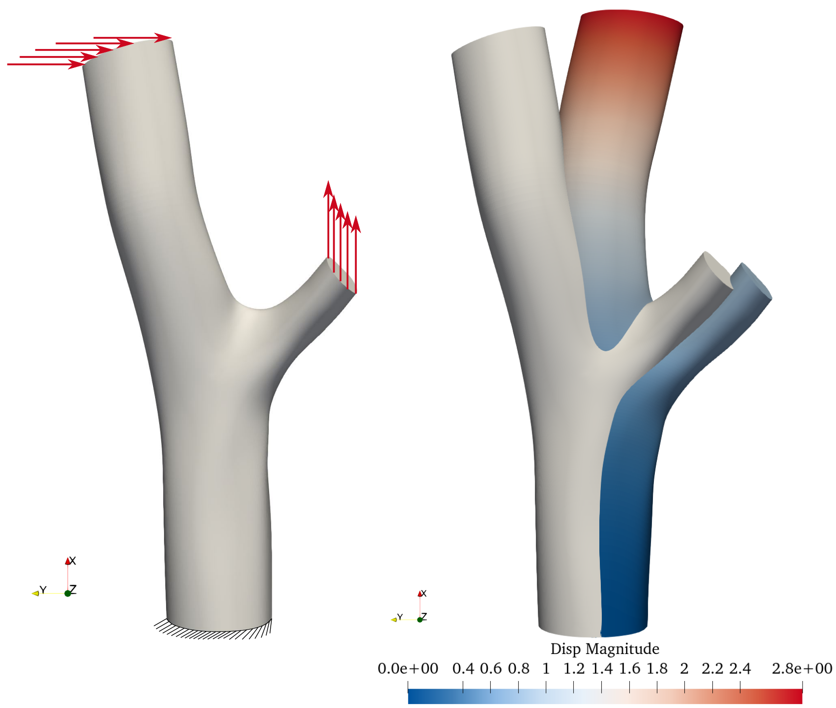

Figure 16: Combined bending and tension test, while bending is induced by force in the y direction, the tensional force applies in the x direction. A structural model with boundary and loading is given on the left. The deformation figure of loaded and clamped bifurcation in the bending test is on the right. The displacement field is plotted over the deformed structure.

4 Construction Elements

The analysis of the naturally grown elements enables the estimation of load capacities based on their geometry. These raw elements can be utilized individually or globally in load-bearing structures as a living tree structure. In this study, our emphasis is on individual elements, leading to a diverse array of construction methods that explore various structural typologies. As outlined in the introduction, the considered geometries encompass straight, curved, and bifurcated elements, with bifurcations being particularly intriguing due to their mechanical capabilities, as depicted in Fig. 17. It is essential to note that structural connections must be positioned at the ends of the center line.

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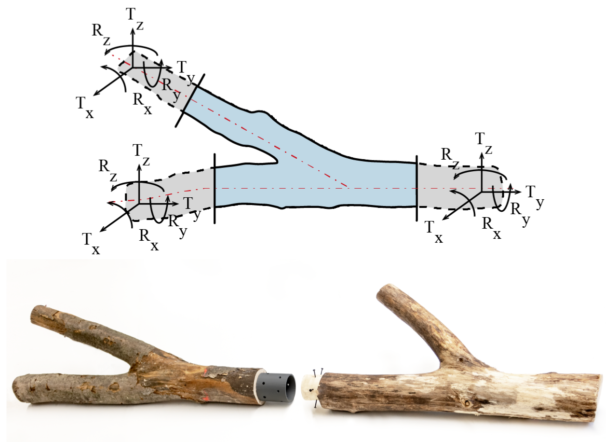

Figure 17: Above: Mechanical capacity of raw wood elements. Below: Development of joints that allow the transmission of loads, displaced from the topological node —Off-knot connection.—

Conventional timber bar structures, typically configured as trusses, demand intricate connection nodes, often made using slotted steel plates. These critical connections are strategically positioned at structural nodes. Using the capabilities of naturally grown timber —specially the bifurcations,— Martin Trautz et al. 2024 introduces an innovative approach by developing ”off-knot” structural nodes that function as rigid nodes.

4.1 Bar type structures. Key Study: Growing Bridge

The methodologies employed in Moreno Gata, Seiter, et al. 2023 illustrate various truss configurations featuring rigid nodes. The bending moments at the corners within these frameworks exhibit characteristics typical of Vierendeel and frame systems. In these trusses, the elements needed to connect nodes can be supplemented with either straight or curved bars. The positioning of these elements is determined by the scheme illustrated in Fig. 18.

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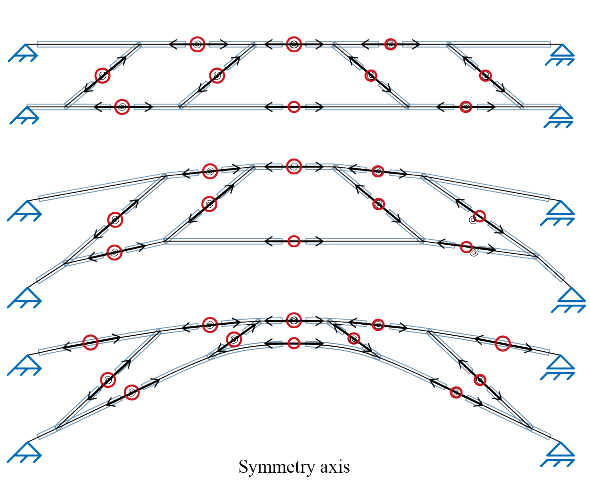

Figure 18: Diagram of a framework with rigid nodes, where the joint positions are adapted to suitable locations based on the material stock. This framework is later applied with bifurcations and curved elements in three dimensions.

As a demonstration of the analyzed concepts, the design and construction of a load-bearing structure composed of two mirrored frameworks have been proposed. This structure's topology is applicable in different scenarios, such as a roof truss. However, its application was chosen for constructing a self-supporting bridge, serving as a connection between various disciplines that have been part of this project, see Fig. 1. Methods of optimization, based on the reuse of elements and circular design principles (Amtsberg, Huang, Marshall, et al. 2021) (Huang et al. 2021), aided in the design of this construction by implementing a data-set –collected elements from local forest in Aachen– shown in Fig. 3.

The scanned elements, totaling 43, were individually analyzed. The outcome of static considerations, cross-section assessments, material properties of each species, and the optimal positioning of connection points resulted in a structure composed of 26 elements. Five hardwood species were utilized: Oak, Beech, Hornbeam, Birch, and Maple (see Fig. 20).

The assembled structure spans 4.6m with a total length of 6.7m, as illustrated in Fig. 20. The structure narrows at its central point, providing a usable clearance of 0.75m, opening outward and varying in height. The conceptualized bridge is named "Growing Bridge" because this topology can be additively expanded towards the ends. In other words, additional elements can be added, increasing the span, if necessary to cover a larger space. Elements to be added must fulfill criteria such as an increased cross-section.

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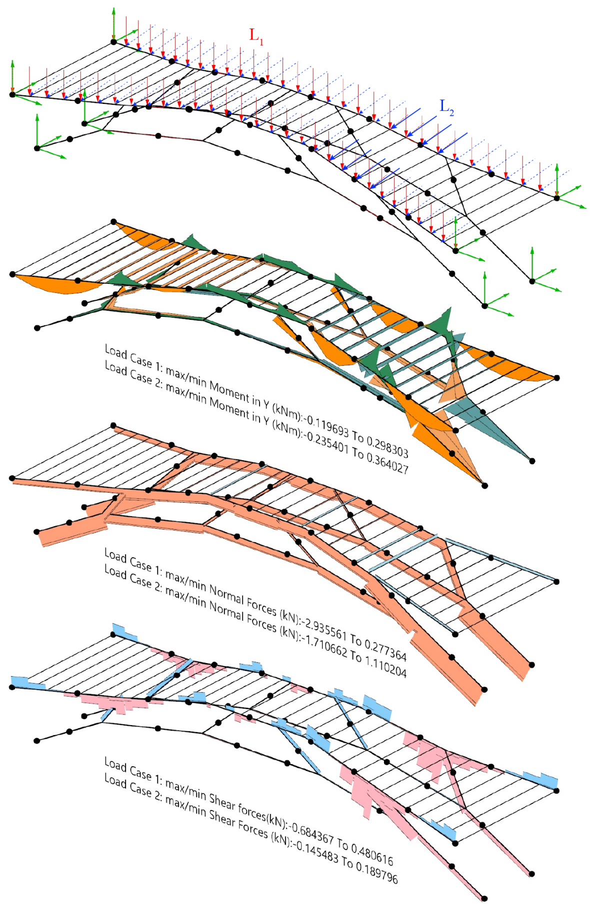

Figure 19: Static analysis: Load cases L_1 and L_2, and joints. Graph of moments, normal forces, and shear forces.

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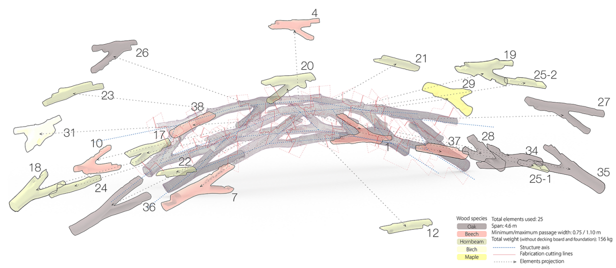

Figure 20: Structure composition. Numbered elements with color-coded species identification and construction joints.

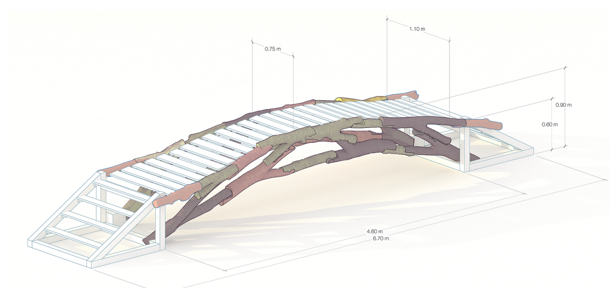

Figure 21: Assembled structure.

4.1.1 Development of structural joints

The development of structural joints was primarily based on a combination of shape, interlocking, and the use of fully threaded screws, allowing for assembly and disassembly without the use of adhesive materials.

For the joint development, an automated system for positioning cut planes at each joint was implemented (see Fig. 22). These joint planes were parametrically developed and aligned along the center line, facilitating the transmission of loads through the natural wood geometry. Despite static calculations treating the joints as rotational springs, receiving only axial forces, screws were strategically placed to ensure proper load transmission and prevent asymmetric horizontal forces from causing dislocations at the joints.

The structure was fabricated and assembled during the Summer Semester of 2023 as part of a research assignment course in the Master of Architecture program at RWTH-Aachen University (Structures and Structural Design 2023).

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Figure 22: Structural connection: Photo of a construction element from an oak specimen, depicting the position of the contact faces of the joint, considering the central line of the tree's growth.

Figure 23: Final state. The construction is currently located in the inner courtyard of the Faculty of Architecture (Schinkelstr. 1, 52064, Aachen, Germany) for testing and public use.

4.2 Sandwich panels

The bar type structures are therefore the most used method in literature, and an example was presented here. However, alternative concepts can be explored, such as sandwich structures, where raw wood is positioned in the core of a wood panel. The project "reGrowth", as outlined in Moreno Gata, Amtsberg, et al. 2023, illustrates a practical application of these principles. By aligning the growth direction of timber elements with stress trajectories, it achieves a naturally grown timber panel that is oriented in harmony with the distribution of forces, ensuring optimal stress alignment.

5 Future Works

5.1 Automatizing process

Work in progress to extend the findings presented here. In particular, geometry and simulation developments are currently being automated to provide an open source package.

Besides that, the automated interpretation of timber can be enhanced through the application of neural networks, proving their applicability in growth ring recognition (Abdeljaber, Habite, and Olsson 2023). This research encompasses a testing phase that leverages the neural network *Detectron2* 2023 to identify crucial points or zones within wood trunks indicative of tree growth from CT Scans, see Fig. 24. It utilizes Cartesian information, derived from perimeter and the pith —the Central Point—, to ascertain

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the growth path of the tree —Center Line—. This data proves instrumental in training the neural network and is subsequently implemented in new CT scans. The primary objective lies in the recognition of shifts in the tree's center of gravity due to static loads.

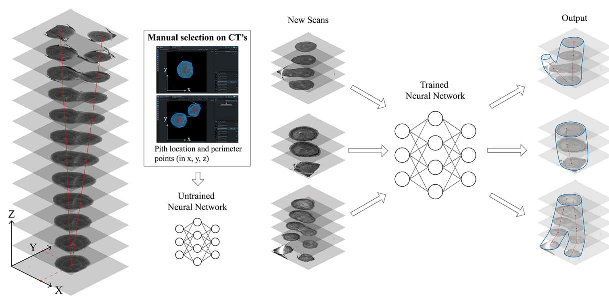

Figure 24: Automation of geometric development based on CTs through neural networks.

5.2 Experiments in plant growth

This research also extends into the study of growing trees and plant guidance. For the past three years, an ongoing data collection on plant growth has been conducted as part of a current research project Moreno Gata, Grizmann, and M. Trautz 2021. Regular documentation of several Paulownia specimens is been compiled, including measurements of the base perimeter and diameter, to analyze trunk curvature. The collected data seeks to demonstrate that the static response of the young tree contributes to an elliptical shaping of its trunk, see Fig 25.

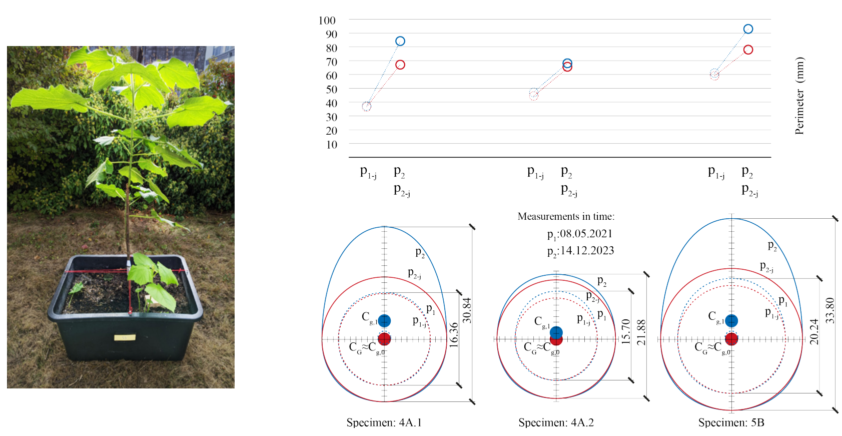

Figure 25: Continuous growth measurements on 3-year-old Paulownia trees. Deviated perimeter p_2, from p_1 tending to an egg-like shape and displacement of the center of mass. In red, the tangent circle reference p_{1-j} and p_{2-j}.

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6 Conclusions

The handling of trees and their raw wood in construction technology expands the possibilities for timber utilization, including previously overlooked wood such as undergrowth logs and various curved logs. Homogenized, highly processed timber is not imperative for all structural applications. Naturally grown timber can be integrated with traditionally processed semi-finished wood products like boards, beams, or panels and can also be incorporated into conventional timber construction methods.

With naturally grown timber components, wood species that were previously unused due to difficulties in processing, such as curved, bifurcated, or twisted growth, can now find application. These considerations add value to a natural material that is underutilized. Moreover, alongside the strength values of the cross-sections of naturally polar-structured wood, mechanical verification becomes feasible, expanding its potential applications, including in load-bearing structures.

Ongoing research and geometric developments create conditions for a significantly broader use of wood in construction and load-bearing structures than before. A non-invasive documentation procedure, 3D scanning, and the automation of geometrical and analytical procedures significantly simplify the application process, enabling the calculation of raw wood and trees in their real form. This advancement facilitates a more aligned utilization of timber with its natural properties, allowing it to seamlessly return to the natural materials cycle without restrictions at the end of its use.

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8 Author contribution statement

The authors contributed to this work in the following ways:

- Author A: Conceptualization, Methodology, Writing - Original Draft.
- Author B: Data Analysis, Simulation, Visualization.
- Author C: Supervision, Project Administration, Funding Acquisition.
- Author D: Supervision, Project Administration, Funding Acquisition.

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10 Conflicts of interest statement

The authors declare no conflict of interest. The founders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

11 Ethics statement

This research project does not involve human subjects, animal experimentation, or any other activities requiring ethical approval. As such, an ethics statement is not applicable to this study.

12 Data Availability Statement

Data-sets are currently available upon request, future works will include the establishment of a dedicated repository to facilitate automated processes and plugins, interested parties can contact the corresponding author for further details.

13 Connections References

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