Non-Destructive Assessment of Reclaimed Timber Elements Using CT Scanning: Methods and Computational Modelling Framework

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This paper evaluates non-destructive assesment of reclaimed timber using computed tomography (CT) scanning and modelling to determine structural integrity and predict the stiffness and strength of timber. By providing a methodology for analysing timber with uncertain histories, it contributes to the wider knowledge base on high value timber reuse.

Although not directly produced within the **Drastic** project, the research is highly relevant to **Drastic's Nordic Demonstrator**, which focuses on reclaiming timber for innovative structural and load-bearing applications in temporary commerical buildings. The paper's methods support the Demonstrator's aim to reuse timber across multiple lifecycle stages by helping identify damage, predict performance, and reduce uncertainty in the process of reclaiming timber.

The connection to Drastic is reinforced by the involvement of project partner **Omtre**, who contribute both to this research and co-lead the Nordic Demonstrator. Their role helps align scientific advances in reclaimed timber assessment with the demonstrator's practical objectives, furthering Drastic's broader efforts to advance circular, multi-cycle timber use.

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1 Introduction

1.1 Reclaimed Timber

Circularity emphasizes the importance of maximizing service time for wood products through cascading use, directing them towards various destinations [1]. This approach ensures that these products contribute the highest value to society for as long as possible, primarily due to their capacity for carbon storage [2]. For wood, it is

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the objective to maintain its use at the highest utility level and structural integrity before it transitions in multiple use cycles to lower-grade applications and incineration. This circular concept is challenged [3, 4]. Key issues for timber reuse are concerns around the treatment, usage, and storage, and especially the quality of reclaimed wood. While virgin wood comes with certification and other data, this lacks for used timber. Here, data might have never been determined, or have been regarded as unnecessary and deleted, or lost during a building's life. This complicates its reintegration into the building industry [5]. Robust and automated methods for efficient non-destructive estimation of mechanical properties and quality assurance become crucial to bridge these gaps, ensuring reclaimed timber's reapplication in the construction, including means to ensure the longevity of data and its maximized use in material passports, templates, or catalogues of secondary material suppliers.

1.2 Goal and Objectives

This study is based on an ongoing investigation with the goal of developing a non-destructive modelling pipeline for the prediction of mechanical properties of reclaimed timber based on X-ray CT scanning and numerical modelling. The objectives of this paper are to (i) provide a background of the challenges that the current practice of quality assessment of timber is confronted with regarding reclaimed material and (ii) propose and describe a data-driven modelling pipeline for the prediction of stiffness and strength of individual reclaimed timber elements based on CT scans.

2 Background

2.1 Challenges of Traditional Grading Regarding Reclaimed Timber

Timber used in the structural capacity in European buildings must adhere to the harmonized standard EN14081 and supporting standards. It sorts rectangular cross-section timber into categories based on the three grade-determining properties (GDPs) strength (MoR), stiffness (MoE), and density. These categories do not state anything about the actual properties of the individual piece of timber but solely operate on a statistical level. In particular, the lower fifth percentile of the underlying distribution defines the strength and density of a class, whereas the mean is used for stiffness. Similar approaches are used for all materials with inherent uncertainty induced, e.g. by heterogeneity as in wood (see EN 1990). Building codes consider these uncertainties and make, e.g. engineers apply structural calculations (punitive) safety factors on the mechanical properties of materials. This results—at least from a structural engineering and economic perspective—in an overengineering of timber buildings and increased consumption of resources.

2.2 Non-Destructive Assessment of Virgin Timber

The challenge of the resources' heterogeneity and uniqueness of every piece is addressed in the non-destructive assessment of each piece in the grading process. The current European system for grading allows visual and machine grading. In both cases, some measurements are used to establish a correlation to the three GDPs, which in turn must be elicited during destructive testing on a sufficiently large sample from the specific growth area [6]. Visual grading is executed by humans, who assess a range of features that affect strength, stiffness, and density, including knots, slope of grain, ring width, and reaction wood. Machine Grading assesses in contrast only one or a few properties of the timber. The measurement results of e.g. resonance or density establish indicating properties (IPs) that are then used to predict the GDPs and thus the grade. IPs typically serve as more robust indicators of quality compared to those assessable through visual grading. Machine strength grading expedites the process significantly and reduces susceptibility to human errors.

The underlying principle of both approaches is the correlation between detected features and grades. This correlation is established in large test series and is upheld through repeated testing of samples. The correlation is specific to a species and a growth area, which limits the use of the data to a specific region and even individual sawmills or other manufacturers have their own set of IPs.

2.3 Towards Non-Destructive Assessment of Reclaimed Timber

The transition of these assessment practices to reclaimed timber introduces significant challenges due to the inherent diversity and unpredictability of reclaimed materials [7]. Unlike virgin timber, reclaimed wood comes in a wide range of dimensions and conditions and contains potential contaminants such as metals in the form of nails or dust and surface modifications (e.g. brushed surfaces, impregnation, and coating). This variability, resulting from, e.g. mechanical wear, environmental exposure, and alterations from previous uses, demands flexible and robust systems for quality assurance.

The current rules for non-destructive timber assessment have been developed for a narrow set of variations in the input material with respect to, e.g. geometry and moisture content, while factors, which affect the quality of reclaimed timber, such as loading history or cracks would today in most cases disqualify the timber from use in a building context [8]. A further challenge is the classification systems focus on specific species and their place of growth to determine IPs, such as density. While this approach fits well with sawmills with a regional intake of wood, it becomes challenging when an urban area with heterogeneous buildings becomes the site for timber sourcing.

Related research and standardization efforts are going on for many years, motivated by emerging circular timber practices, or preceding this in building conservation and restoration, where the quality of old timber needs in structures needs to be assessed. Recently standards have been proposed to deal with the terminology and general rules for reclaimed timber and how contamination and treatments of reclaimed timber shall be evaluated [9]. The first standard for the visual grading of reclaimed timber shall undergo a hearing in the summer of 2024. Some existing standards, such as the Italian UNI11119, provide already means for the assessment of old timber using a combination of on-site inspections and non-destructive techniques [8], while other research shows how measurement of samples in accordance with US standards might provide means to assess the necessary mechanical properties for construction [7]. While the latter approach is cost intensive and project specific, reports about the former show that neither visual nor non-destructive testing methods, such as ultrasound or stress wave methods or local methods such as pilodyn or resistograph measurements show a sufficient correlation with mechanical properties determined in mechanical tests [8]. Bergsagel and Heisel list a series of criteria that should be considered, when characterizing reused timber: (i) the different dimensions of traditional timber elements with respect to actual sawmill products, (ii) technological characteristics, such as wane, must not exclude timber from being assessed, but simply influence the effective resistant cross-sectional area, (iii) the importance of knots on the mechanical properties and the need to take the actual size, shape, and direction of the internal knots into account and not solely their ‘superficial incidence’, (iv) the need to have a homogenous moisture distribution in the timber elements, and (v) the frequent use of hardwood in existing structures and the need for its improved characterization.

A transfer of the current quality assessment for timber, based on grading with its limitations regarding region and species, into a circular economy faces inhibitive challenges. It is, therefore, necessary to develop alternative assessment methods, adapted to dissimilar pieces of timber with unknown origins and with a large variety of defects and additional unknowns.

2.4 CT Scanning for Reclaimed Timber

X-ray computed tomography (CT) has originally been developed for clinical applications, but today it is also an industrially available technology which can provide information about the internal density distribution of a scanned object non-destructively. CT scanning of wood at the millimetre scale is used in the sawmill industry for optimizing the positioning of the cut [10], but research has shown that CT images at this resolution (growth ring scale) can also be used for investigations of wood physical [11–13] and wood mechanical properties, in particular, if the local variations of fibre orientations can be estimated from the image gradient. The field-based nature of the gathered data enables the creation of models based on computational mechanics, e.g. finite element (FE) models, which have been used to successfully predict the stiffness, strength, and initial crack location in individual pieces of dry virgin sawn timber [14].

CT-based modelling presents an opportunity for an accurate and detailed assessment of the mechanical properties of individual reclaimed timber elements, especially since their moisture content is typically below fibre saturation, which yields a higher contrast between the various biological features in the CT images.

CT scanning at the required scale for modelling can be performed at high feed speeds like a sawmill's processing speed, i.e. approximately 1–2 m/s. However, CT-based numerical modelling, like in [16], may depend on the model complexity and the specific hardware and software implementation, currently not be able to keep up with this pace. If individual pieces of timber can be tracked throughout a processing facility, then in-line high-speed evaluations may not be necessary. Instead, once a piece of timber has been scanned, it could be stored until its mechanical properties have been estimated and its optimal use has been determined. CT-based numerical modelling at a high level of detail may also be a precursor for more simplified data-driven modelling, e.g. based on laser scanning or discrete X-ray scanning, which both require less investment in equipment.

3 Materials and Non-Destructive Data Acquisition

The reclaimed timber for this study was supplied by the Norwegian company Omtre AS. From their storage in Hønefoss, Omtre contributed timber samples, including 56 planks with cross-sectional dimensions 49×98 mm^2 and five round barn logs, all varying in length. The materials represent two exemplary histories of reclaimed elements: one for premium barn elements and one for reclaimed construction wood.

The barn timber originated from an old barn in Brøttum, Ringsaker (Fig. 1). Constructed in 1870, the barn was a timber-framed structure with exterior cladding.

Fig. 1 Demounting the barn in 2022, provided by Omtre

This style of barn, known as an ‘enhetslåve’ or ‘one-unit barn’, became prevalent in Norway around 1850 and consolidated multiple farm functions (storage for hay, equipment, and animal shelter). The log house portion provided weather and cold protection for the animals, utilizing pine for its rot-resistant heartwood.

The original positioning of the barn logs in the building could not be reconstructed, since this information was lost during Omtre’s reclaiming of the logs [17]. Nevertheless, based on knowledge concerning cultural heritage preservation, Omtre estimates that the barn logs used in this study very likely served as the supporting foundation and beams under the first floor.

The reclaimed construction timber originated from a building site of student apartments at Kringsjå (Norway) and had been temporarily used in the construction process and was subsequently regarded as waste. Due to Omtre’s collaboration with contractors, this wood was collected in containers at the site and saved from incineration. Any remaining metal fasteners were removed from all timber elements prior to storage in Hønefoss, where shelter from precipitation was provided, but neither heating nor air conditioning. The timber remained in storage for approximately 2 years.

The timber was *CT scanned* without additional treatment or cleaning at the Division of Wood Science and Engineering of Luleå University of Technology (LTU) in Skellefteå, in January 2024. For the construction timber, all samples were positioned standing upright in the scanner, maintaining consistent orientation regarding the pith and the ends corresponding to the top and bottom of the tree (see Fig. 2). A consistent identification (ID) numbering system was applied and a specific positioning sequence was followed in the image plane to identify the individual beams in the scans.

The timber was scanned employing a helical scanning trajectory in an industrial CT scanner (Microtec MiTO) adapted for research, at a tube voltage of 180 kV and current of 5.55 mA. The images were reconstructed to an equally spaced voxel grid of $0.5 \times 0.5 \times 0.5$ mm^3, and the density in kg/m^3 was calculated from the CT number.

Fig. 2 56 planks and 5 barn timber logs (left), sample setup during CT scanning (middle) and a section of the scan (right)

4 Computational Modelling Framework

The workflow of the developed framework is illustrated in Fig. 3. On a conceptual level, it consists of three steps: (1) image analysis and feature detection, (2) geometry extraction and volumetric discretization, and (3) data-driven material modelling. Prior to analysis, the 3D CT images were cropped to represent only single timber elements including a small frame of 30 voxels containing the surrounding air. All image processing was performed using the free and open-source libraries SimpleITK, DIPlib, and OpenCV in Python.

For *step (1)*, the CT image data of each beam can be regarded as a volumetric density field, $J\ (x, y, z)$, on an equally spaced rectangular grid. First, wood needs to be separated from the background (e.g. air), which can be achieved by thresholding on J and subsequent image closing operations to remove internal holes. The segmentation results in a Boolean mask which allows a fast estimation of the element boundary and its rough shape. The total volume of the object can be derived simply by summing up the voxels contained within the mask and accounting for the voxel scale. For segmenting other regions of interest with distinctly different densities, like knots, growth rings, high-density inclusions, or contaminants, e.g. nails, thresholding may be also suitable. Some features may require a more subtle analysis of the density field and its spatial rate of change, i.e. its gradient and higher-order derivatives. These include the separation of early- and latewood, the location of the pith [18], and the estimation of the fibre tensor (longitudinal, radial, and tangential material orientations) using the gradient structure tensor [15]. For the preliminary trials of our study, only the volume mask and outer shape of the timber were extracted, and the fibre tensor was calculated.

The density field and the extracted biological regions and features—the volume mask, the knots and contaminant regions, the early- and latewood regions, and the fibre tensor—were collected in a data structure referred to as the *Body of Properties* (BoP). The BoP serves as an expandable record of relevant properties in the underlying continuum that can be 'harvested' for subsequent modelling and simulation steps. Most properties are stored as volumetric samples at various resolutions, depending on the property. For example, density is available at the full scanning resolution, while material orientation might be available at a coarser resolution

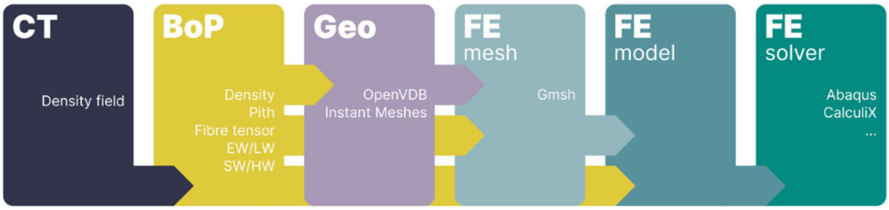

Fig. 3 Schematic overview of the prototyped framework

depending on the radius of the kernel that is used to analyze the volume gradient. Features such as knots are stored as volume regions, but they could also be represented by a lightweight parametrized shape or a computer-aided design (CAD) surface.

In *step (2)*, for usage in further analysis, simulation, and CAD environments, the volumetric data is converted to a boundary representation such as a non-uniform rational B-spline surface (NURBS) or a discrete triangle or quad mesh. The most straightforward method is to extract the isosurface of the density field at the masking threshold described above, which results in a robust and watertight mesh. For this study, the open VDB library and toolset were used to extract the surface mesh. In applications, where a surface mesh at the full scanning resolution is undesirable or too unwieldy, the volume grid may be down-sampled to a coarser resolution prior to meshing. Here, the remeshing software Instant Meshes was used to decimate the surface mesh and generate a higher-quality mesh topology to facilitate further usage. The remeshed surfaces contained only quad elements that follow the topology of the original timber element (Fig. 4). The quads were subsequently converted to NURBS patches, creating a solid NURBS model for use in traditional CAD environments, which provides high flexibility for downstream applications and modelling.

For volumetric finite element (FE) meshing of the identified geometry of the scanned object, the free and open-source meshing software Gmsh was used in Python. Its interface is particularly convenient regarding finding the locations of Gauss quadrature integration points for each element, which is required for the subsequent material modelling (Fig. 5a).

For *step (3)*, the FE mesh is incorporated into an FE model, where loads and boundary conditions were applied according to the desired analysis, and a material model was employed which was informed about the underlying properties from the BoP at each integration point. The model was written to an input file (.inp) which is interpretable by the commercial FE solver Abaqus and open-source solvers like CalculiX. The material model was implemented by user subroutines for either Abaqus or CalculiX, in which the local material orientations and the density were imported at each integration point (Fig. 5b). Since any information from the BoP

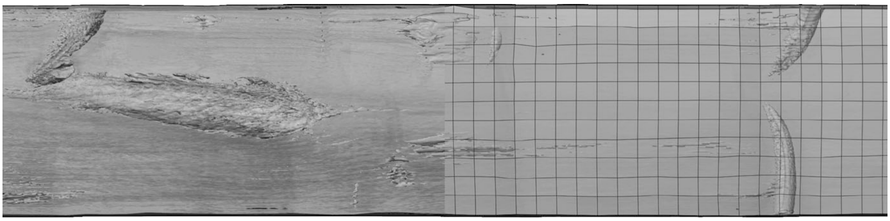

Fig. 4 The isosurface of the timber element boundary (left) is remeshed into a coarser quad-only surface mesh, suitable for further conversion into NURBS surfaces (right). The isosurfaces of knots are included for reference. The information about these is finally stored in the BoP

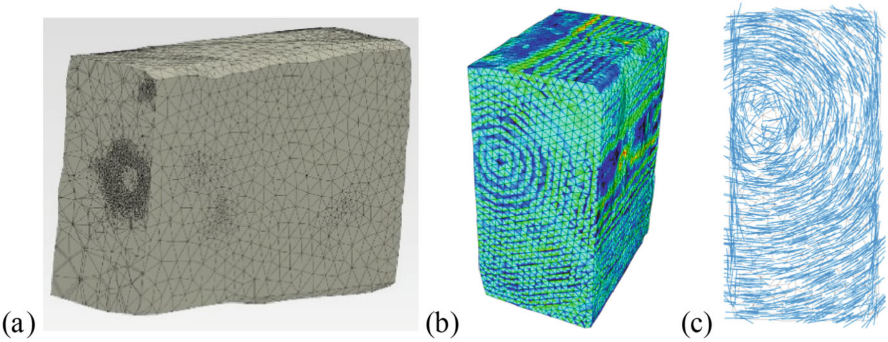

Fig. 5 Adaptive 3D meshing of a portion of the timber element using Gmsh, with a smaller element size around high-density regions, such as knots (**a**), 'harvested' density field in a FE model (**b**), and corresponding tangential material orientations (**c**)

could be accessed by the material model, arbitrarily refined approaches could be implemented, e.g. scaling the stiffness tensor by factors related to density and proximity to knots [16] or varying a hygromechanical material behaviour depending on features in the BoP [12].

For CalculiX, a custom user material was created as a stand-alone shared library which is called by the solver. Currently, it replicates the behaviour of a standard orthotropic material model; however, it can be adapted to incorporate the range of properties from the BoP, as well as different methods of loading and querying them. Typical procedures for loading external data into the solver in user material involve writing per-integration point data to one or many files and then opening these files during the model initialization. In this study, the user material accesses a block of shared memory that is populated by another process, allowing it to query the BoP directly without writing and reading files. While the primary advantage is to access speed, it also means that this procedure could be expanded to query the BoP dynamically or include other behaviours defined during runtime. The vision is to arrive at a model ecosystem where the BoP—or several BsoP—can inform and mediate between design, material analysis, and simulation models in a flexible and extensible way.

A linear elastic orthotropic material law was applied using a stiffness tensor with constant textbook values for spruce, while the material orientations were varied according to the BoP (Fig. 5c). To evaluate the mechanical properties of the modelled timber, pure bending was simulated on partial lengthwise sections along the beam and on the full beam. The mid-point deflection during bending was recorded and the local bending stiffness (MoE) was calculated from it using the approach in [16]. In addition, a frequency analysis with free boundary conditions was conducted to extract eigenfrequencies and eigenmodes.

5 Preliminary Trials and Discussion

Our investigations are part of an ongoing study, and therefore the results mainly serve demonstrative purposes. Results of the analysis of a single beam from the construction timber are presented. From the CT image analysis, an average density of 536 kg/m^3, a total weight of 5.694 kg, and a length of 2.194 m were elicited. Figures 6 and 7 show the 'harvested' density field in the FE model of the beam and, respectively, for a partial section with corresponding absolute transverse stress (perpendicular to the fibre) during pure bending. All displacements are scaled, and the plotted values are qualitative for comparison (red indicates higher, and blue indicates lower values). Figure 6 additionally shows the first longitudinal mode in the frequency analysis, at a longitudinal eigenfrequency of 440 Hz. The bending stiffness was evaluated for consecutive 250 mm long sections along the beam (Fig. 8) and in the resulting profile, the bending stiffness dropped as expected in regions with large knots.

The simulation-based bending deflections, eigenfrequencies, and stiffness profile may be used to assess the stiffness of the individual pieces of reclaimed timber and serve as predictors for bending strength. The stress field during bending may be used

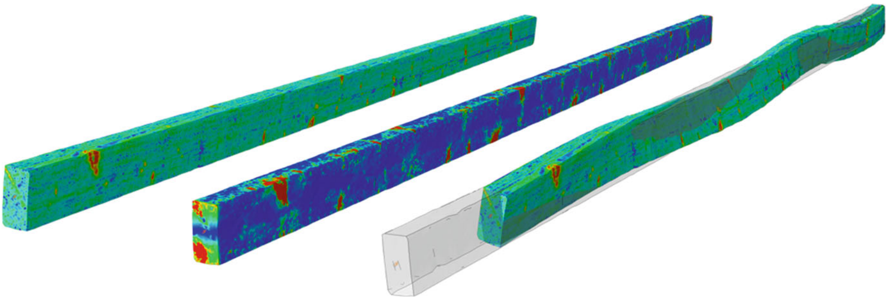

Fig. 6 Full beam FE model showing the density field (left), the absolute transverse stress field under pure bending (middle), and the first predominantly longitudinal vibration mode (right)

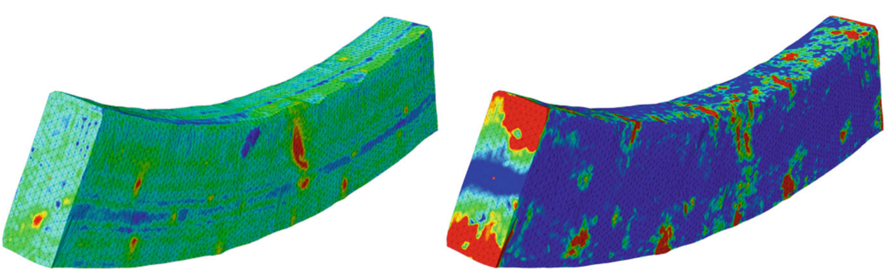

Fig. 7 FE model for a partial section of the beam, density field (left) and corresponding absolute transverse stress field (right)

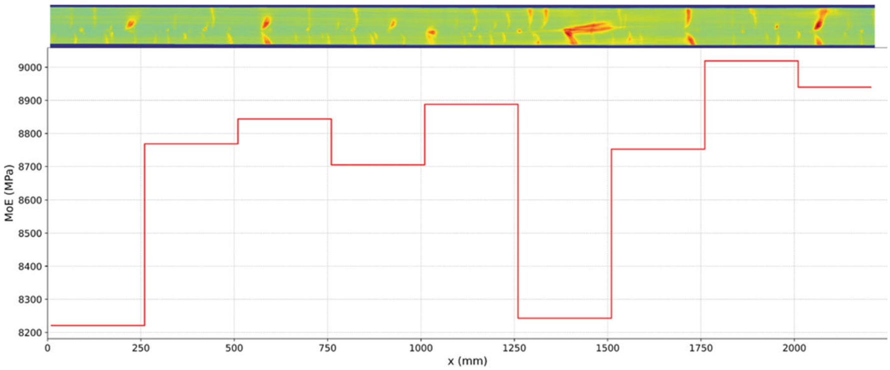

Fig. 8 Bending stiffness profiles for the evaluated sections of the studied beam. The average density along the thickness direction is plotted on top, and red colours indicate higher and blue lower values

to evaluate the susceptibility to failure under increasing load, e.g. by employing maximum stress or a Tsai-Wu anisotropic failure criterion.

The preliminary trials of our presented pipeline demonstrate the soundness of its working principle and that the simulation results already reside in a reasonable range. The used models have not yet been fine-tuned, e.g. by error checking the fibre reconstruction, in specific at boundaries, or by letting the stiffness tensor vary depending on the underlying biological tissue (knot, latewood, earlywood, etc.), which are both expected to increase the resulting bending stiffness. In addition, the models need to be adjusted for the climatic conditions monitored during storage before scanning and the resulting approximate moisture content (MC).

Once the development of the pipeline has reached a state that enables a more automated treatment of irregularities in the input geometries (diverse shapes of timber, cut or broken ends) and thus the analysis of a larger number of beams, extensive validations will be conducted. For this purpose, we are currently collecting mechanical data on all the scanned timber, i.e. longitudinal eigenfrequency by dynamic excitation, local and global bending stiffness and strength by non-destructive and destructive four-point bending, and measurements of the MC during testing. This data and the corresponding models will yield a base for validation of our framework and enable a comparison to alternative methods, like stress grading based on mechanical tests and even visual grading (using, e.g. surface visualizations from the CT images).

Sources, propagation, and impact of uncertainties need to be assessed to evaluate the framework's robustness. To achieve this, we will conduct sensitivity studies on input factors to establish uncertainty ranges for the predictions, instead of single point values. We will include factors from the data acquisition stage (e.g. scanning speed, CT artefacts, and effects of timber surface quality), the image analysis and model creation stage (e.g. image resolution, geometric assumptions, and discretization strategies), the modelling stage (e.g. material parameters and their dependency on the underlying tissue, fibre reconstruction, model boundary conditions, and load application), and the evaluation stage (e.g. stiffness evaluation and failure criterion).

We expect our framework's accuracy to be limited to the amount of information extractable from the density field of a piece of timber. In practice, also the available computational resources will limit the achievable fidelity.

6 Conclusion and Future Steps

We highlight the limitations of current timber assessment methods with reclaimed timber and the need for the development of a non-destructive assessment method that is independent of regional data and species. This paper presents a first step into the necessary groundwork by demonstrating a framework to assess the mechanical properties of individual reclaimed timber elements by models based on the extraction of properties from CT scans. The preliminary results demonstrate the modelling pipeline and outline the evaluation of mechanical properties. This reduces some uncertainty concerning the reuse of the reclaimed timber and its reuse as structural. Further research is required for validation and demonstration of the robustness of our method, specifically regarding the large variability of reclaimed timber.

The modelling framework is based on free and open-source software to promote interchangeability, extensibility, and longevity. Its design is modular, minimizing dependency on specific formats and maximizing its flexibility. It allows for varying resolutions and degrees of approximation and may in principle also be adapted to different modes of data describing the BoP, e.g. laser and X-ray scanning. Finally, this study is part of a larger research effort to compare different non-destructive methods which can be deployed to classify and sort for different destinations. Herein, the assessment and validation of reclaimed timber is a crucial component.

To this effect, we position our work within this collective effort to show how these advancements in a digital timber practice can lead to an increased utilization of reclaimed timber and a more sophisticated usage of this new resource—an integrative 'hyper-grading' of timber that spans the digital value chain between resource, analysis, design, and re-utilization.

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