

Identification of selected defects in beech timber by CT scanning

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Abstract

This study deals with the application of computed tomography (CT) for the design, application, and analysis of a methodology for identifying selected qualitative characteristics of unedged beech timber (*Fagus sylvatica* L.). In the context of growing interest in the use of hardwood in load-bearing structures, a methodology has been proposed that enables non-contact assessment of internal defects such as knots, cracks, and fibre deviation. CT scanning has demonstrated the ability to visualize local density variations that correlate with the occurrence of quality defects. Calibration using seven wood species of varying density confirmed a linear relationship between CT image intensity and wood density ($r = 0.998$). The results show that CT technology has potential not only for sorting roundwood but also for evaluating sawn timber after cutting, thereby contributing to the optimization of production and increasing the added value of wood products. Density-based defect identification provides new opportunities for automated grading using machine learning.

Key words: automated grading; beech timber; computed tomography (CT); timber quality; wood density

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1. Introduction

Climate change is altering the species composition of forests. European beech (*Fagus sylvatica* L.), widespread in western and central Europe, has traditionally been used mainly in furniture production, but its potential in load-bearing structures is increasingly being explored (Aicher et al. 2014; Ehrhart et al. 2016; Pramreiter & Grabner 2023).

Computed tomography (CT) allows us to visualize the internal structure of wood, including defects such as knots, cracks, and rot, as well as to determine local density and moisture content (Davis & Wells 1992). Since we cannot assign positive characteristics to wood, we must turn to negative ones, namely wood defects (Gejdoš et al. 2021). The price of sawn timber depends on defects visible on the surface, primarily knots, notches, and others (Stängle et al. 2015). When using CT scans to analyse the log and subsequently optimize the cutting plan, an increase in yield of up to 20% was achieved (Stängle et al. 2015; Rais et al. 2017). Most CT images are displayed as two-dimensional graphs of attenuation coefficients on a square grid. The elements of the square grid, pixels, have a size (grey level) that indicates the calculated aver-

age attenuation coefficient for the corresponding area in the cross-section of the object. If the density of the material is lower, the pixels appear as a darker shade of grey; if higher, the pixels appear as a lighter shade of grey. Changes in wood density depending on the structure of annual rings and the presence of qualitative features (knots, cracks, rot) are also visible (Davis & Wells 1992; Gejdoš et al. 2023). The attenuation of X-rays depends on the atomic composition of the investigated material and the energy of the X-rays. To allow comparison of images obtained by different scanners (e.g., operating at different X-ray energies), a normalized unit has been defined. Hounsfield units (HU) or indexes (H) or CT numbers are normalized to the X-ray attenuation of water as follows:

$$HU = 1,000(\mu_{\text{voxel}} - \mu_{H2O}) / \mu_{H2O} \quad [1]$$

Every manufacturer of commercial scanners provides a calibration procedure, generally using a standardized water-filled sample, which must be run periodically to ensure that $HU = 0$ in water and $HU = -1,000$ in air, regardless of the X-ray energy used (Davis & Wells 1992; Parr et al. 2004).

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However, the issue of CT quality in beech wood is still not fully resolved, as the standards for visual strength grading were adopted from coniferous woods, for which they were originally developed, and therefore do not fully correspond to deciduous wood (Plos et al. 2018). However, as Frühwald & Schickhofer (2005) point out, the correlation between strength and density is low (16%) in hardwood timber. On the other hand, local characteristics that reduce the strength quality of timber can be identified based on density. Therefore, it makes sense to use CT scanning to identify local density variations rather than to determine the average density of timber.

The aim of this research was to design, apply, and analyse a methodology for evaluating selected qualitative characteristics of unedged beech timber. The contribution of this research is the use of CT scanning for non-contact grading of wood in the production of wood products with higher added value.

2. Material and methodology

Beech logs (Fig. 1) were cut down in September 2023, then they were stored in exterior landfill for about two months, after that they were labelled, scanned and numbered before being paired with corresponding CT images available in the LIBROARBOR database (Cloud database of CT Scans managed by National Forestry Centre). For the analysis of sawn timber in this article, we used sawn timber from the log number 8 (marked with a red

frame in Fig. 1). The analysed beech log was of quality class 3.B according to the STN 48 0056:2007, Qualitative classification of hardwood round timber, its length was 5,700 mm, the diameter of ends was 370 mm, and 400 mm, respectively.

In January 2024, live sawn timber with a thickness of 55 mm were made. The live sawn cut was selected because it is the most common method in research applying CT scanning of sawn timber (Chang & Gazo 2009; Stängle et al. 2015). However, several authors report its lower qualitative and quantitative extraction compared to other cutting schemes (Popadić et al. 2014; Vilkovský et al. 2023). The individual logs were reassembled from sawn boards. When assembling the logs from boards, spruce spacers measuring 2 × 3 cm were used, and each reassembled logs was fixed with a clamping strap to maintain shape stability of timber during drying (Fig. 2). The moisture content of the individual boards immediately after sawing ranged from 39 to 45%, and the moisture content was determined using a GMH 3851 (Greisinger) moisture meter for solid materials.

The prepared samples were air dried for 21 months in covered and dry areas, secured with clamping straps. The temperature in this area varied throughout the seasons. Before scanning, the moisture content of the individual boards was measured, reaching 16% in average. During log reassembling, the individual boards were marked (Fig. 3).

For the scanning process, the spruce spacers were replaced with aspen spacers due to their lower density and consequently easier CT image processing. The boards



Fig. 1. Frontal view of log No. 8 prepared for CT scanning and followed cutting.



Fig. 2. Beech logs after cutting.



Fig. 3. Labelling of sawn timber from a beech log prior to CT scanning.

were arranged to resemble the log shape and secured with plastic clip strapping (Fig. 4). The scanning procedure and methodology were previously described by Gejdoš

et al. (2023). Before image processing, the Hounsfield units were converted to an 8-bit intensity format (digital numbers) ranging from 0 to 255.



Fig. 4. Illustration of pre-scan log placement and post-log placement with marked boards.

The open-source software 3D Slicer 5.6.2 (Fedorov et al. 2012) was used for image processing. The first step was to adjust the rotation using the TRANSFORM function to ensure that as many boards as possible have a surface as close to the horizontal direction.

Next, a region of interest (ROI) with the required dimensions ($200 \times 2,000$ mm, defined by STN EN 975-1:2009, Sawn timber. Appearance grading of hardwoods. Part 1: Oak and beech and a height exceeding the thickness of the boards was inserted into the image (Fig. 5 and Fig. 6). The most favourable point was selected on each board (Fig. 6). Subsequently, the occurrence of selected defects (knots, cracks, fibre deviation) was identified in the region of interest on the upper and lower surfaces of each board according to the STN EN 975-1:2009 standard. We identified the presence of knots by segmentation based on differences in the density of the knots and the surrounding wood.

In order to verify the relationship between CT image intensity and density, it was necessary to calibrate the device. We used seven species of wood with different densities ranging from 300 to 800 kg m^{-3} that were conditioned to 12% of moisture content. Specifically, these were samples of paulownia, willow, aspen, pine, birch, beech, and ash wood. Samples with dimensions of $700 \times 16 \times 100$ mm (length, thickness, width) were

used. The first step was to create individual segment for each calibration sample and then determine the CT image intensity of the each segment using the Segment Statistics function.

3. Results

The correlation between the intensity of the CT image DN and wood density was linear (Fig. 7). A correlation of 99.8% was achieved using seven wood species with different densities (Wei et al. 2011). The relationship found between density (kg m^{-3}) and CT image intensity expressed as DN (Digital number), which indicates the numerical value of the intensity of the reflected or emitted signal in individual image pixels, is valid for the device we used. Assuming that the conditions remained unchanged, it was possible to use linear equation to subsequently determine the density of the unedged timber.

The aspen spacer was proved ineffective in CT image processing. The difference in density between aspen and beech was not sufficient for filtering the aspen spacers (Fig. 8). In extreme, the aspen spacers had a similar CT image intensity as beech sapwood.

We evaluate the transformation positively; image rotation has facilitated processing, but it still cannot completely solve the problem of cup and twist. The two ends of a board may not be parallel (twist) and the curvature radius of the transverse curve may not match with horizontal axes (Fig. 9). A thicker ROI (Fig. 5) covers the space curvature imperfection of a board.

Within the ROI, it was not difficult to identify the knot (Fig. 10). Defects can be identified in sawn timber, but also during the preparation of the cut, where we can influence the position of the knot in the board (Beaulieu & Dutilleul 2019; Gejdoš et al. 2023).

When working with dried timber, cracks are easily identified (Fig. 11) and are usually found near the sapwood (Bhandarkar et al. 2005; Wei et al. 2011; Gejdoš et al. 2023). When working with logs, it would be necessary to process a larger number of cuts in order to obtain the data needed to create a predictive model that would make it possible to predict how drying cracks will form in wood.

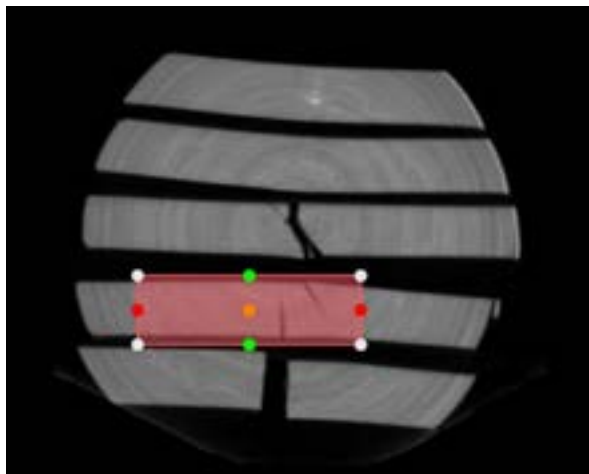


Fig. 5. Cross-sectional view of the selected area of interest.

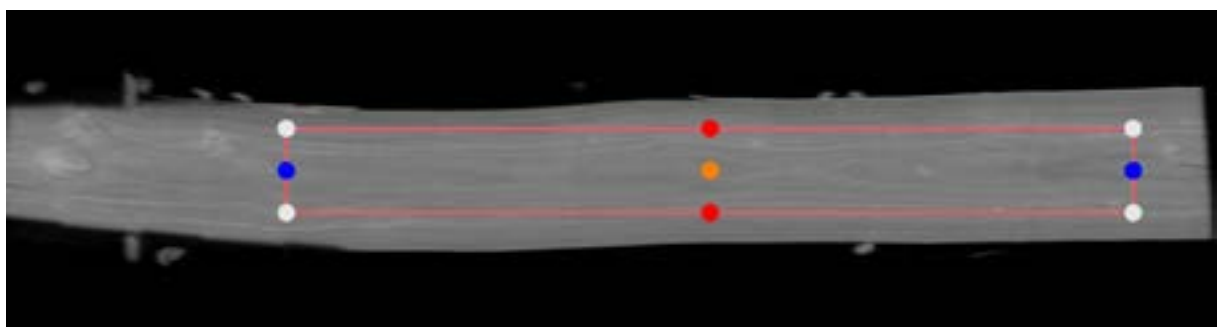


Fig. 6. Longitudinal section view of the selected area of interest.

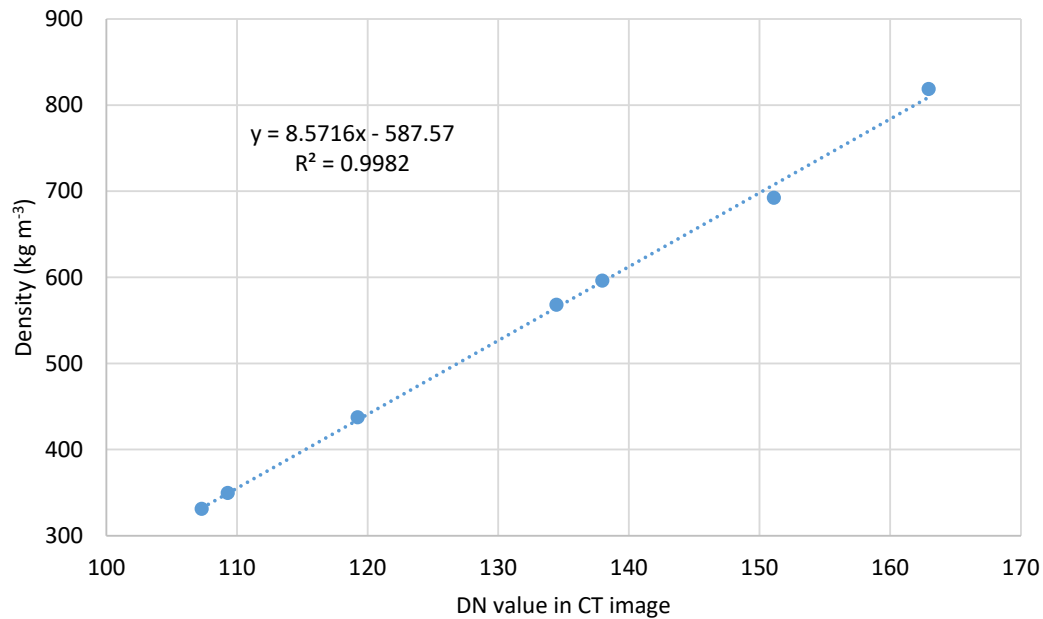


Fig. 7. Graph showing the relationship between average segment density and average density of calibration samples.

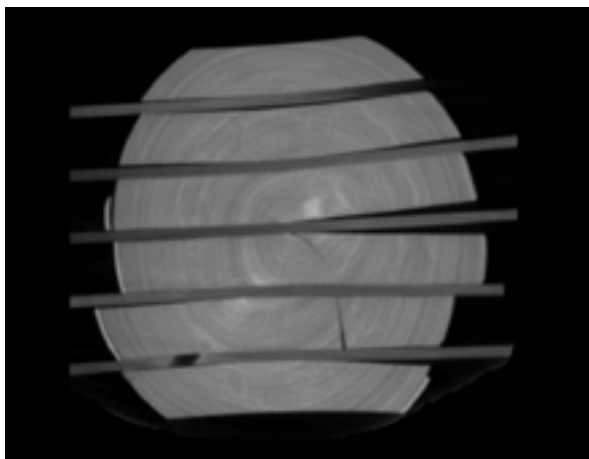


Fig. 8. View of the cross section at the point with aspen spacers.

Fibre deviation is the most difficult defect to identify using CT scans. With beech, measuring fibre deviation is generally problematic, and visual methods are unreliable. The only reliable way to measure fibre deviation of beech is to measure the angle of the fracture gap after a destructive test (Aicher et al. 2001; Frühwald & Schickhofer 2005, Westermayr et al. 2018). However, with a live sawn cut, we can assume that the fibre deviations will approximately correspond to the natural convergence of the roundwood. Another factor may be the spiral grain in the trunk around the pith, which varies in the radial direction and which CT technology is currently able to deal with at ultra-high resolution only (Hu et al. 2022).

The analysis was carried out on 11 boards produced from two sections of a single log. Table 1 shows that the occurrence of cracks was increased in the central

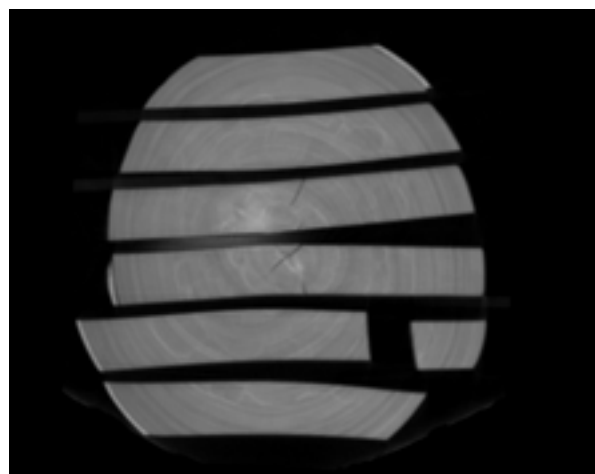


Fig. 9. Cross section before and after rotation.

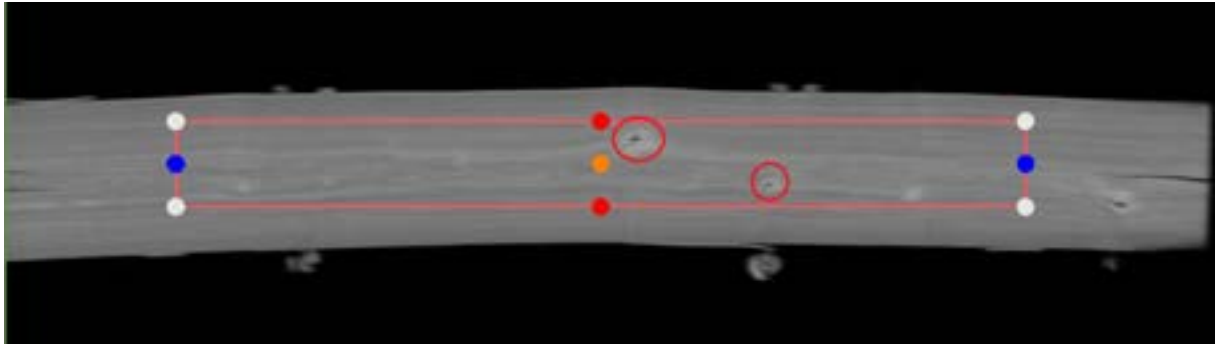


Fig. 10. Identified knots on the longitudinal section.

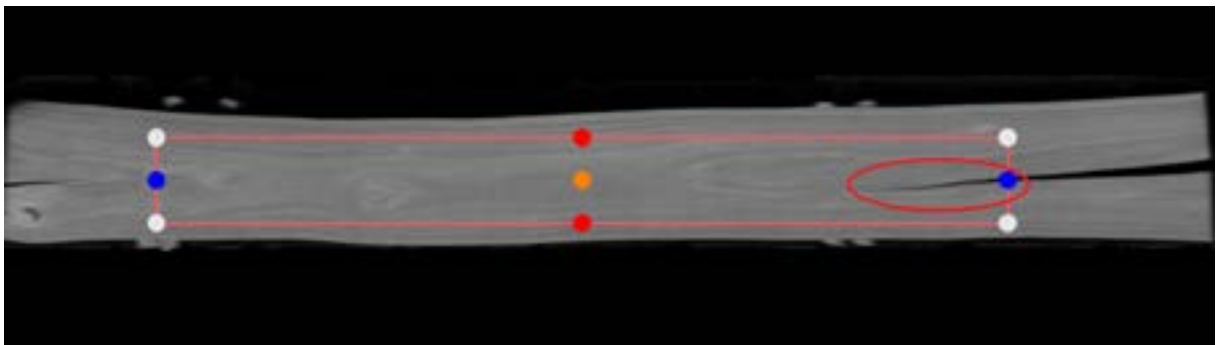


Fig. 11. Identified cracks on longitudinal section.

Table 1. Table showing the occurrence of defects in individual boards.

Log	Part	Board	Knots	Cracks	Fibre deviation	CT image intensity	Density (kg m ⁻³)
8	TL	1	✓	✓	×	151	704
8	TL	2	×	×	×	154	721
8	TL	3	✓	✓	×	154	728
8	TL	4	×	×	×	154	726
8	TL	5	×	×	✓	150	695
8	BL	1	×	×	✓	154	734
8	BL	2	×	✓	×	154	730
8	BL	3	✓	✓	×	153	724
8	BL	4	✓	×	×	154	728
8	BL	5	×	×	×	153	721
8	BL	6	×	×	×	150	700

Legend: ✓ – the selected error was found in the board, × – the selected error was not found in the board TL, Top log, thinner part of the trunk, BL – Butt log, thicker part of the log, Board number – number of the board in the reassembled log from sawn boards, see Fig. 4.

zone, which we attribute to the presence of wood rays. The occurrence of knots and cracks was identified on 4 boards, representing 36%. Fibre deviation was identified visually on 2 boards, representing 18%. For this reason, we would classify both cuts as quality class F-S3 according to the STN EN 975-1:2009. The density of individual boards in an air-dry state ranged from 695 to 734 kg m⁻³, with an average density of 719 kg m⁻³. Our density values are between those reported in the literature, where Lagaña & Babiak (2012) report a density of 680 kg m⁻³ for beech, and Gryc et al. (2008) report values ranging from 736 to 768 kg m⁻³. The average density of the knots was 936 kg m⁻³, and therefore was possible to distinguish knots based on their different density (Fig. 10). This finding is important for the further devel-

opment of machine learning approaches to feature identification. However, the method also revealed several limitations: some selected objects were not actual knots or knot cones, and reaction wood or bark had similar densities. This deficiency can be solved by considering geometric differences between these features. Reaction wood or bark has a high length-to-width ratio and can be eliminated by smoothing and removing protrusions. Hollow knots can be filled using a hole-filling process. Then the difference in density between the grown wood and the cone around a knot is so different that it will allow automatic identification of its presence based on machine learning. Geometric modelling of knots is necessary for accurate determination of their diameter (Fig. 12).

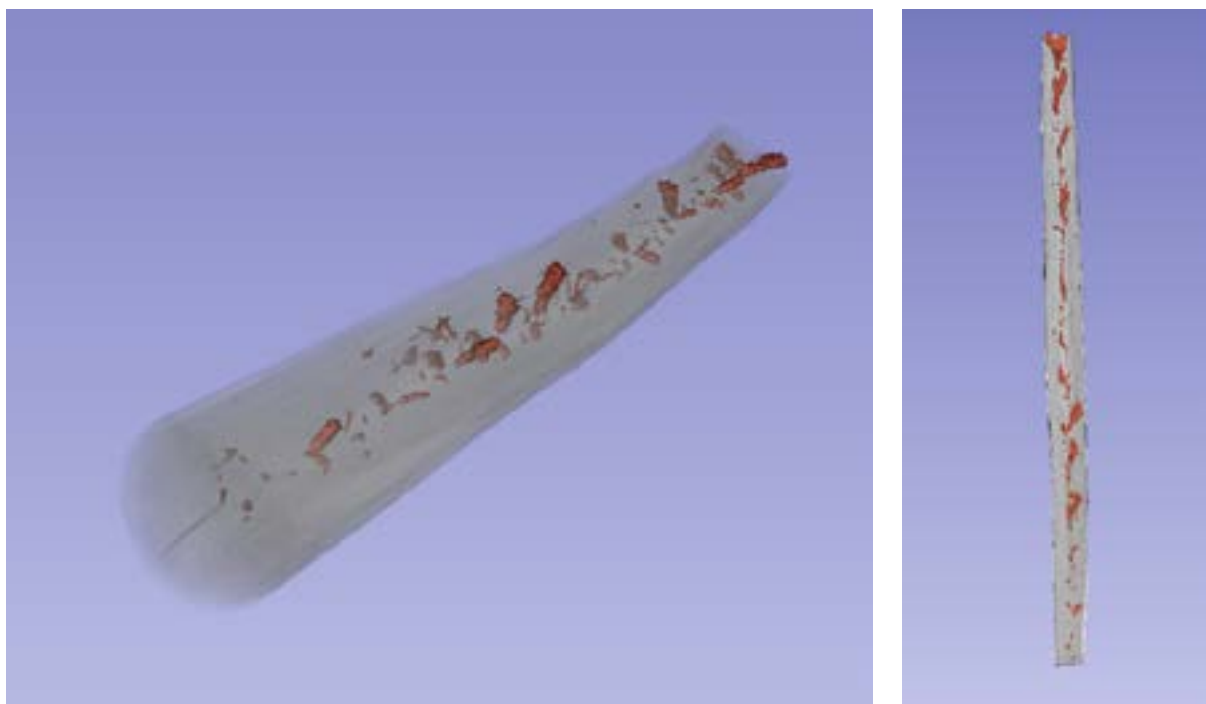


Fig. 12. Distribution of knots in the log – processed by segmentation in 3D Slicer.

4. Discussion

The results of the study confirmed the high accuracy of computed tomography (CT) in identifying qualitative defects in beech timber, especially knots and cracks. The linear correlation between CT image intensity (DN) and wood density ($r=0.998$) is consistent with previous studies (Freyburger et al. 2009; Wang et al. 2019), confirming the reliability of this method for non-contact wood assessment.

Identification of knots based on density differences was successful, with the density of knot clusters (936 kg m^{-3}) significantly exceeding the density of the surrounding wood. This difference allows segmentation of defects using machine learning algorithms, as reported by Liu et al. (2021), who applied convolutional neural networks (CNN) to classify defects in wood with high accuracy. The occurrence of cracks near the pith corresponds to findings on stress zones during drying (Yin & Liu 2021), confirming the assumption that the central areas of the trunk are more susceptible to drying cracks.

Fibre deviation has proven to be the most difficult parameter to identify by CT. Visual methods are not reliable for beech (Frühwald & Schickhofer 2005), so it's necessary to look for alternative approaches. Zabler et al. (2020) point to the potential of phase contrast tomography in detecting fibre orientation, but its application in industrial conditions is still limited.

The contribution of moisture to the intensity of the CT image is significant. De Ligne et al. (2022) report that

a 10% moisture content difference can cause a deviation in DN of up to 15 units, which can affect the accuracy of defect identification. Therefore, it is necessary to calibrate the scanner at different humidity levels, especially if the technology is to be applied in real production conditions.

A comparison of CT scanning with other technologies, such as ultrasound or laser profiling, shows its higher accuracy in detecting internal defects (Asa et al. 2024). Despite higher implementation costs, CT has the potential to significantly increase the yield and quality of sawn timber, especially in the production of higher value-added products.

In terms of methodology, replacing spruce spacers with aspen spacers proved to be insufficiently effective. In some cases, aspen spacers had a similar CT image intensity to beech wood, which made them difficult to filter. For future applications, it is recommended to use spacers made of materials with significantly lower density, such as extruded polystyrene.

The findings show that CT technology has the potential not only for sorting roundwood but also for evaluating sawn timber after cutting. Combined with machine learning algorithms, it can contribute to automated strength grading and production optimization. In further research, it will be appropriate to increase the set of calibration samples, to verify the effect of moisture on DN, and to explore the possibilities of geometric modelling of defects for machine learning purposes.

5. Conclusion

Within the framework of the study, a comprehensive methodology was developed and implemented to assess selected qualitative attributes of unedged beech timber through computed tomography (CT). Each methodological stage was examined individually, and its influence on the overall outcome was systematically evaluated. The results confirmed that the use of CT scanning allows for reliable evaluation of the qualitative characteristics of beech timber, both prior to and following the cutting process.

The analysis further revealed a statistically significant linear relationship between CT image intensity and wood density. These findings underscore the potential for broader implementation of CT technology in the assessment of sawn timber, offering prospects for optimizing wood processing workflows and facilitating the production of higher value-added products.

Recent study points to the future research focusing on extending CT-based quality assessment from logs to construction timber, thereby broadening the technology's applicability. Additional efforts will include expanding the calibration dataset and examining the influence of moisture content on CT image intensity.

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