

Predicting the mechanical properties of sawn timber: Basic non-destructive tools applicable to Norway spruce sawlogs

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Abstract

The sawmill industry traditionally relies on visual grading of roundwood, which primarily reflects commercial value rather than the mechanical performance of the resulting sawn timber. This study evaluates the potential of basic non-destructive methods for predicting the physical and mechanical properties of sawn timber based on sawlog characteristics. Sixty sawlogs of Norway spruce (*Picea abies* L. [H.] Karst.) were assessed using visual grading, manual evaluation of knot parameters, and vibro-acoustic measurements based on the frequency resonance method. The logs were sawn into 180 centre boards with nominal dimensions of 50 × 160 × 3,000 mm, which were tested for physical and mechanical properties in accordance with EN 408. The results show that visual quality grades of sawlogs are generally poor predictors of the sawn timber mechanical properties. In contrast, strong correlations between MOE_L at log level and MOR ($r=0.75$) or MOE_{glob} ($r=0.80$) were found. The study highlights the critical importance of using the actual wood density when applying the frequency resonance method. Also, only measurements in longitudinal direction should be performed. Knot-related parameters proved relevant, where the total number of knots showed the best results on the global level ($r=-0.68$ for MOR). The use of designed sliding windows further improved prediction accuracy. Overall, the findings demonstrate that basic non-destructive methods, especially acoustic measurements combined with selected knot parameters, can effectively support sawlog pre-sorting to produce strength-graded sawn timber. In follow-up research, these basic methods should be combined with the results of CT scanning.

Key words: sawn timber grading; roundwood grading; wood defects; acoustic methods; sawmill industry

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1. Introduction

The sawmill industry is the long-term largest consumer of industrial roundwood in the Czech Republic (Green Report 2025). Although technological modernization of sawmills is taking place in this important primary sector, little attention is paid to the development of quality grading of roundwood and sawn timber. At the beginning of the millennium, as in neighbouring countries, new criteria for measuring and grading of roundwood were implemented in the industry – in the Czech Republic, these are the Recommended Rules for Measuring and Grading of Roundwood in the Czech Republic 2008 (2007; hereinafter referred to as the “Recommended Rules”), which are the basic document at many sawmills. The qualitative assessment of sawlogs is based on the evaluation of wood defects, which are assigned to one of the quality classes

according to their type and extent. The assessment is performed by an operator, which can be supplemented by automatic evaluation of taper, sweep, and the presence of metals on large sawmills. Apart from the purposeful exclusion of completely unsuitable logs (presence of metals and logs of very poor quality), quality assessment is used only to determine the price of roundwood. Although this approach is simple and practical, it is also outdated and limiting in terms of the potential for producing strength graded products with high added value (Oja 2005).

Even with standing trees, it is possible to predict the future quality of products based on a simple visual assessment (Marenče et al. 2020). Simple visual assessments can be replaced or supplemented by more complex automated models, such as terrestrial laser scanning (Pehkonen et al. 2025). Conducted research shows that genetic traits, stand parameters, and site growth con-

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ditions can also be included in the assessment (Ji et al. 2021; Van der Merwe et al. 2024). Nevertheless, as far as the authors know, there are generally no visual-based methods available that can accurately predict the properties of final products from standing trees, mainly due to the difficulty of detecting internal defects (Marenče et al. 2020). Better predictions can already be achieved through visual evaluation of sawlogs. The basic method is assessment of defects by an operator (Edlund et al. 2006; Straže et al. 2020). In recent years, there has been a trend towards using photometry of log end faces, which can be used, for example, to predict the bow height of a log (Raatevaara et al. 2020) or to accurately determine the proportion of false hearth (Gejdoš et al. 2019). However, image analysis can also be used on the log surface, for example to measure the sweep and dimensions of knots (Nocetti et al. 2025). It is also possible to include additional parameters into the predictions to improve their accuracy, such as age (Gil-Moreno et al. 2024). Visual grades of logs correlate well with commercial grades of sawn timber (Marenče et al. 2020; Straže et al. 2020), but it is a very inaccurate method for predicting the yield of strength-graded sawn timber (Edlund et al. 2006). An important factor here is that some visually assessed defects of logs do not have a significant effect on the physical and mechanical properties of sawn timber (Denzler et al. 2015). Another significant disadvantage is the fact that this is a subjective assessment, where the human factor can have a significant impact on the results (Gejdoš & Gergel 2022; Nocetti et al. 2025).

Acoustic methods have been used in Europe since the 1970s, primarily for strength grading of sawn timber (Bucur 2023). The frequency resonance method (FRM) is considered the most suitable, where similar accuracy is achieved for sawn timber in the longitudinal direction and in bending (Uzcategui et al. 2023). Since measuring the natural frequency in the longitudinal direction is technically simpler, the majority of the grading machines are based on this principle (Varis 2019). However, researchers are also working with new approaches, such as transversal ultrasound (Kovryga et al. 2020). In the case of standing trees, the time of flight method is mainly used, but such prediction of the mechanical properties of sawn timber is inaccurate (Simic et al. 2019). This is due to the short distance at which the measurement is taken (Rais et al. 2014) and local defects in the wood, which do not have a significant impact on a global scale (Fischer et al. 2015). A significant reduction in accuracy also occurs with large-diameter trees (Krajnc et al. 2019). Better results are achieved on the log level, where the FRM is primarily used (Llana et al. 2020; Nocetti et al. 2025). Knowledge of the moisture content (MC) and real density of the log is essential for this method (Ruy et al. 2018; Llana et al. 2020; Rais et al. 2020). According to research, the natural frequency of the log in the longitudinal direction is a suitable parameter to pre-sort logs for the production of strength-graded sawn timber (Edlund et al.

2006; Rais et al. 2014). On the contrary, according to current research, acoustic methods are not a suitable tool for distinguishing between visual quality classes of logs (Straže et al. 2023; Nocetti et al. 2025).

One of the most recent technologies in the wood industry is X-ray scanning (Ridley-Ellis et al. 2016). For decades, it has been used for roundwood, primarily in Scandinavia, in the form of discrete X-ray scanning (Raatevaara et al. 2020; Pehkonen et al. 2025). The most modern variant is computed tomography (CT) scanning with a rotating X-ray source (Gergel et al. 2022). These scanners enable the accurate determination of characteristics such as knot size, heartwood proportion, and density (Gergel et al. 2019; Longo et al. 2019). Furthermore, digitizing data using CT scanners allows evaluating a large number of parameters over a longer time period. For example, Ravoajanahary et al. (2025) evaluated the type, size, and number of knots, the proportion of sapwood, moisture content, and density in 726,000 spruce and pine sawlogs. In addition to qualitative evaluation, scanning can also be used for log positioning (Fredriksson 2014). Current research has shown that it is possible to build models for predicting the mechanical properties of sawn timber based on X-ray scanning of logs. Such models can be constructed both for individual final boards (Johansson et al. 2015) and generally for the entire log (Fredriksson 2024). However, these models have not achieved industrial accuracy yet.

This study evaluates the potential of basic non-destructive methods to predict the mechanical properties of sawn timber based on properties of sawlogs. The primary objective is to quantify the relationships between (i) the mechanical properties of sawn timber and (ii) selected log-level parameters, specifically vibro-acoustic characteristics and visual properties. The secondary objective is to identify the most suitable knot-related parameters at the log level that can reliably predict sawn timber strength and can subsequently be implemented in CT scan data processing.

To address these objectives, the study tests the following hypotheses:

- **H1:** There is a statistically significant relationship between the mechanical properties of sawn timber (MOR and MOE) and the vibro-acoustic properties of logs (MOED_L and MOED_B).
- **H2:** Visual grading of sawlogs currently described by industrial standards is not a reliable predictor of the mechanical properties of sawn timber.
- **H3:** Selected knot-related parameters measured at the log level significantly contribute to the prediction of sawn timber strength and they are suitable inputs for the development of CT-based strength prediction models.
- **H4:** Wood properties of the material differ at each stage of production (sawlog – green sawn timber – dry sawn timber – dry sawn timber with a final length).

Follow-up research will integrate these basic non-destructive methods with advanced CT scanning in order to develop comprehensive and robust prediction models.

2. Material and methods

2.1. Material

Sixty Norway spruce (*Picea abies* L. [H.] Karst.) sawlogs were processed. All samples came from the South Moravian Region in the Czech Republic, specifically from the University Forest Enterprise Masaryk Forest in Křtiny. Material was selected from standard supplies at the Olomučany sawmill in May 2025. Logs of the same length (3 m) and similar mid-diameter (approx. 30 cm) were selected. During the selection process, an effort was also made to obtain a set of logs with a diverse range of wood defects. Basic descriptive statistics on the dimensions of the logs are summarized in Table 1.

Table 1. Basic dimensions of sawlogs.

	Mean (cm)	Minimum (cm)	Maximum (cm)	CV (%)
Total length	300.9	299.8	302.3	0.15
Mid-diameter	29.3	26.8	33.0	5.36

Note: CV is Coefficient of Variation.

2.2. Measurement of the logs – basic description

After selection of the material, 1. samples were taken to determine moisture content, 2. logs were weighed, 3. acoustic properties were measured, 4. visual parameters were measured manually, 5. CT scanning was performed, and 6. the logs were sawed (Fig. 1). All these phases took place in May and June 2025.

Manual measurements

Samples were taken from the large diameter side of all logs to determine moisture content. After sampling, logs were weighed using a BAXTRAN STE 500 kg scale (Giropès SL, Girona, Spain) with an accuracy of 0.1 kg. The actual density was calculated based on the volume and weight data. A detailed description of sampling, measurement, and calculation of moisture content and density is provided in Berezjuk (2025). Logs were numbered and photographed on both sides.

The mid diameter, top diameter, and large diameter were measured using a calibrated tree caliper with an accuracy of 0.1 cm. The resulting diameter value is the arithmetic mean of measurements taken on two perpendicular directions. The length was measured using a calibrated tape measure with an accuracy of 0.1 cm. Descriptive statistics of dimensions are summarized in Table 1.



Fig. 1. Low-quality sawlog III.D (a); Sample for the determination of the moisture content (b); High-quality sawlog III.A (c); Measuring area at the Sawmill Olomučany (d); Cant sawing with a resulting 3 centre boards 50 × 160 × 3,000 mm (e).

Quality was determined using the Recommended Rules (2007). These rules distinguish four quality classes for sawlogs: A, B, C, and D, with class assignment based on an assessment of the presence and extent of defects. The dominant wood defects were recorded (Marenče et al. 2020). Examples of qualities are shown in Fig. 1. Main sawing axis were determined and marked based on visual assessment and industrial practice.

To assess the impact of knots on the physical and mechanical properties of sawn timber, manual measurements of knots on the log surface were performed. The measurements were taken using an INOX PN 25 1125 steel ruler (Kmitex, Prague, Czech Republic) with an accuracy of 0.18 mm. All measurements were performed by the same skilled operator to ensure consistency of results. The dimensions of each knot were measured in two mutually perpendicular axes. The resulting dimension is the arithmetic mean of both measurements, with values rounded to 1 mm. Only knots larger than 10 mm were recorded. For each knot, the distance from the large diameter end face was also measured, rounded to 0.5 cm.

Several parameters were designed and calculated (Fig. 2). The total number of knots (K_n), the average size of knots (K_D), the knot with the largest size (K_{Dmax}), and the sum of the sizes of all knots were calculated (K_{nD}). Furthermore, a function was designed to quantify the number of knots in a log within a 30 cm sliding window starting at a specified position. For each log, three windows with the highest number of knots (KW_n) and the sum of the sizes of all knots (KW_{nD}) were determined. The number of knots and sum of knots diameters for the worst window (KW_{n1} and KW_{nD1}), the two worst windows (KW_{n2} and KW_{nD2}), and the three worst windows (KW_{n3} and KW_{nD3}) have been evaluated.

Acoustic measurements

The FRM was used to measure vibrations in the longitudinal direction and in bending. A KS813B accelerom-

eter (MMF, Radebeul, Germany) was fixed to the larger diameter end face (bottom of log) when measuring the frequency in the longitudinal direction and to the sawing axis in the middle of the total length when measuring the frequency in bending. In both cases, the impulses were excited by three hammer hits—for longitudinal frequency by hitting the top diameter end face, and for bending frequency by hitting the opposite side of the sawing axis (Fig. 3). Data were recorded using a DEWETRON-41-T-DSA (DEWETRON Inc., Grambach, Austria) with a sampling rate of 10 kHz. After completing the field measurements, the data were processed using Fast Fourier Transform with MATLAB R2025a (The MathWorks Inc., Natick, USA) software. The dynamic modulus of elasticity in the longitudinal direction was calculated using:

$$MOED_{L1} = 4 \cdot f_{L1}^2 \cdot l_1^2 \cdot \rho_1 \quad [1]$$

where $MOED_{L1}$ is dynamic modulus of elasticity of the log in the longitudinal direction; f_{L1} is fundamental eigenfrequency in the longitudinal direction; l_1 is total length of the log; ρ_1 is real wood density of the log. The dynamic modulus of elasticity in bending was calculated using:

$$MOED_{B1} = \left(\frac{2 \cdot f_{B1}}{2.5 \cdot \pi} \right)^2 \cdot \left(\frac{m_1 \cdot l_1^3}{I} \right) \quad [2]$$

where $MOED_{B1}$ is dynamic modulus of elasticity in bending; f_{B1} is fundamental bending eigenfrequency; m_1 is total mass of the log; I is the moment of inertia of the cross section.

X-ray scanning and log sawing

After completing acoustic and manual measurements, the samples were transported to the National Forest Centre Zvolen research center. Here, the samples were scanned using an industrial CT.LOG X-ray computed tomography scanner (MICROTEC, Bressanone, Italy).

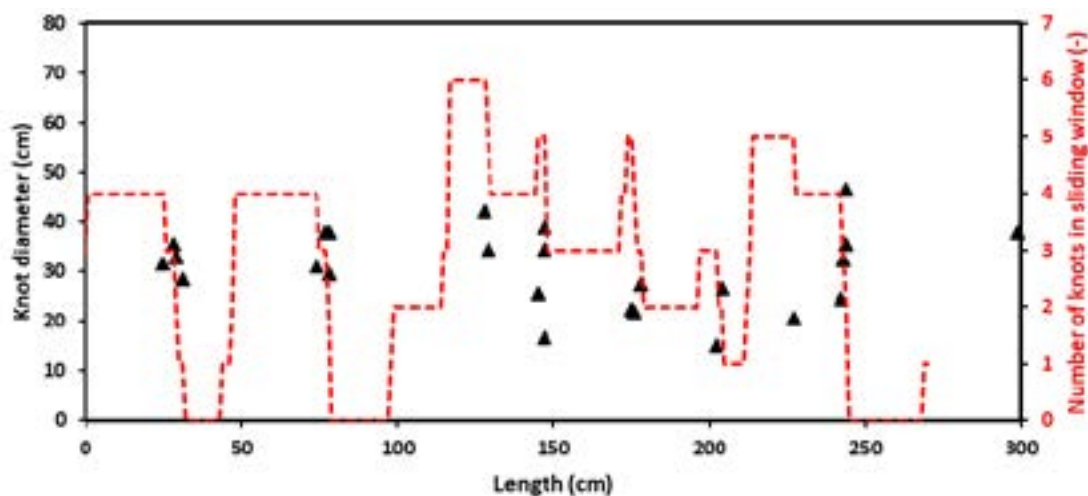


Fig. 2. Knot distribution and dimensions (Log No. 42): $K_n = 25$; $K_D = 30.7$ mm; $K_{Dmax} = 46.5$ mm; $K_{nD} = 768.0$ mm; $KW_{n1} = 6$; $KW_{nD1} = 192.0$ mm; $KW_{n2} = 11$; $KW_{nD2} = 351.5$ mm; $KW_{n3} = 16$; $KW_{nD3} = 488.0$ mm).

The resolution of this scanner in the transverse direction is 1×1 mm, with images in the longitudinal direction taken at 1 cm intervals. The results were used to reconstruct the volume of the logs, with a more detailed description of the methodology provided in Berezjuk (2025). In follow-up research, the CT images are processed to expand the models for predicting the mechanical properties of sawn timber.

After scanning was completed, sawlogs were transported back to the Olomučany Sawmill, where they were processed using cant sawing. Three pieces of centre boards with dimensions of $50 \times 160 \times 3,000$ mm were produced from each log (Fig. 1). These boards were marked according to their position within the log as L (left), C (central), and R (right). In this way, a total of 180 boards with a nominal volume of 4.32 m^3 were produced. The resulting side boards were not used further in the research.

2.3. Measurement of the sawn timber – basic description

The sawn timber was measured in several steps (Fig. 3):

1. Green sawn timber with a full length of 3 m;
2. Dry sawn timber with a full length of 3 m;
3. Dry sawn timber with a final length of 1.5 m.

Acoustic properties, dimensions, and weight were measured at each stage. Drying was performed in kiln drying chamber at the Olomučany Sawmill to a target moisture content of $w = 12\%$.

After drying, the boards were shortened to 1.5 m. The cutting position was selected so that the section containing the most significant defects was located at or near the centre of the board. This worst section was determined in accordance with ČSN 73 2824 as a 15 cm segment exhibiting the highest concentration of defects and the maximum knot area ratio (KAR) criterion (Rais et al. 2017).

Acoustic measurements and static tests

A smaller KS94B10 accelerometer (MMF, Radebeul, Germany) was used to capture the frequencies of sawn timber. The measurement and data processing methodology corresponded to the procedures used for round timber (see section 2.2., chapter Acoustic measurements).

Static tests were performed on sawn timber with a final length of 1.5 meters in accordance with EN 408. The measurements were performed on a LabTest 6.500H hydraulic testing machine (Labortech, Opava, Czech Republic). Boards were placed in the testing machine so that the worst section was in the middle between the supports. The load was applied until the element failed, with the displacement being measured in accordance with EN 408 (for both local and global modulus of elasticity). After completion of the static tests, samples were taken to determine the density and moisture content of the wood, with the moisture content being determined using gravimetric analysis in accordance with EN 13183-1. The research aims to evaluate the log as a single unit. Three centre boards were obtained from each log. Measurements were performed at the board level, and the resulting values were subsequently aggregated to the log level by calculating the arithmetic mean for each property fol-

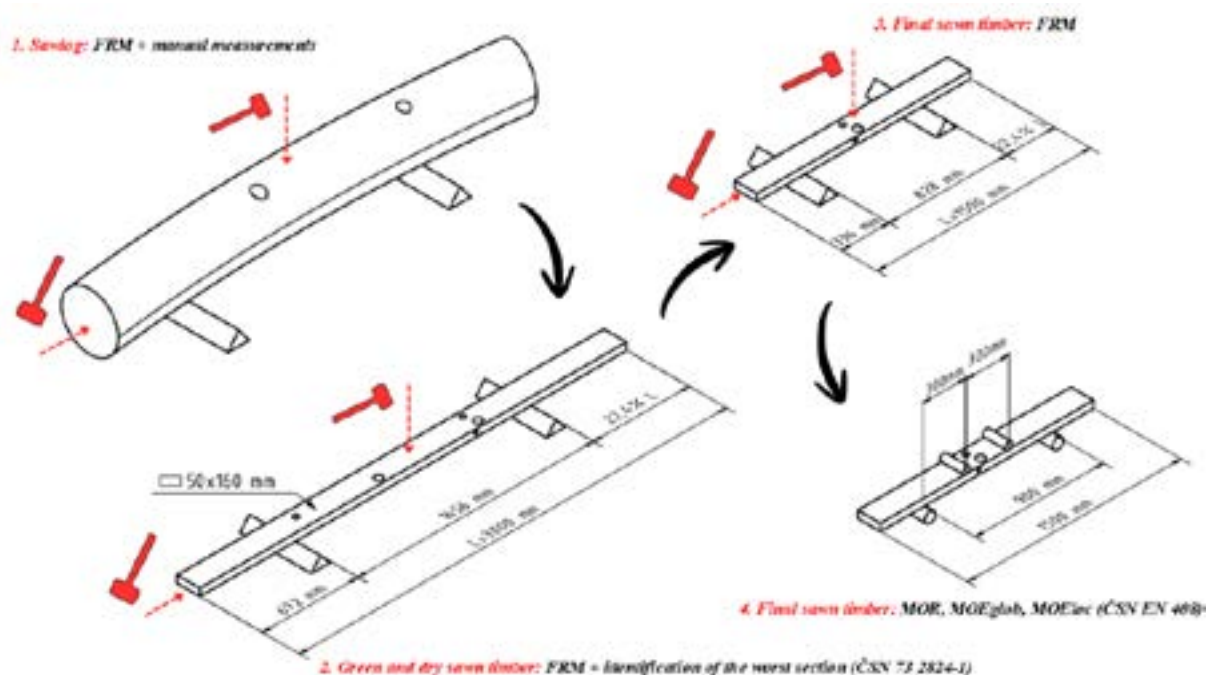


Fig. 3. Steps of non-destructive and destructive testing.

lowing Fredriksson (2024). An overview of the nomenclature for tested parameters is provided in Table 2. The Spearman correlation coefficient is used as the primary measure of correlation throughout entire work.

3. Results

The resulting physical and mechanical properties are summarized in Table 3. The logs had variable moisture content, but this moisture content was above the fiber saturation point. The average moisture content of the final sawn timber after drying was 12.6%, with a minimum moisture content of 11.3% and a maximum moisture content of 16.0%. Only 3 of the 180 boards had a moisture content ranging from 14.0% to 16.0%. The dynamic modulus of elasticity in the longitudinal direction ($MOED_L$) was similar in all phases, but in bending ($MOED_B$) there was a gradual slight increase in values until the final length phase, when a decrease was observed compared to the previous phase.

3.1 Visual classes

Based on visual assessment, 75% of the logs were graded B or C. Only two logs were assessed as the lowest grade D; due to this very limited number of samples, the group was insufficiently represented and therefore could not be included in the statistical tests. Of the total 47 logs graded B, C, or D, knots were the dominant defect in 33 cases. In addition to knots, two logs had other equally significant defects (one insect damage and one reaction wood). In 12 logs, knots were not the dominant defect (nine reaction wood, two insect damage and one check). The resulting physical and mechanical properties are shown in Table 4.

There are no significant differences in the physical and mechanical properties between the individual quality grades of sawlogs for most properties (Fig. 4). According to the results of the T-tests performed, there is a statistically significant difference only for MOE_{loc} ($p = 0.03$) and $MOED_{B1}$ ($p = 0.04$) between grades A and C, and for ρ_5 ($p = 0.04$) between grades B and C. Class D cannot be included in the tests due to the low number of samples.

Table 2. Nomenclature.

Phase	Sawlog	Green timber	Dry timber	Final timber	Static tests
Moisture content	w_1	—	—	—	w_5
Wood density	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5
Dynamic MOE – longitudinal	$MOED_{L1}$	$MOED_{L2}$	$MOED_{L3}$	$MOED_{L4}$	—
Dynamic MOE – bending	$MOED_{B1}$	$MOED_{B2}$	$MOED_{B3}$	$MOED_{B4}$	—
Modulus of rupture	—	—	—	—	MOR
Global MOE	—	—	—	—	MOE_{glob}
Local MOE	—	—	—	—	MOE_{loc}

Table 3. Details of the basic results (CoV is stated in the columns).

Phase	w (%)	ρ ($kg\ m^{-3}$)	$MOED_L$ (MPa)	$MOED_B$ (MPa)	MOR (MPa)	MOE_{glob} (MPa)	MOE_{loc} (MPa)
Sawlog	60.6 (0.30)	687.9 (0.12)	11,611 (0.15)	7,664 (0.15)	—	—	—
Green timber	—	503.4 (0.09)	10,285 (0.17)	8,355 (0.18)	—	—	—
Dry timber	—	444.7 (0.09)	11,663 (0.15)	9,405 (0.16)	—	—	—
Final timber	—	446.4 (0.09)	11,492 (0.16)	8,909 (0.16)	—	—	—
Static tests	12.6 (0.03)	419.9 (0.09)	—	—	42.6 (0.23)	9,511 (0.17)	7,962 (0.24)

Table 4. Physical and mechanical properties for individual quality grades (CoV are stated in the parentheses).

Grade	Number (–)	$MOED_{L1}$ (MPa)	$MOED_{B1}$ (MPa)	MOR (MPa)	MOE_{glob} (MPa)	MOE_{loc} (MPa)	ρ_5 ($kg\ m^{-3}$)
A	13	12,338 (0.12)	8,253 (0.14)	46.9 (0.20)	9,909 (0.17)	8,649 (0.18)	409.3 (0.10)
B	25	11,631 (0.12)	7,645 (0.13)	41.2 (0.18)	9,350 (0.16)	7,879 (0.22)	409.8 (0.08)
C	20	11,113 (0.17)	7,351 (0.17)	41.4 (0.25)	9,337 (0.16)	7,367 (0.21)	432.4 (0.08)
D	2	11,610 (0.42)	7,203 (0.32)	44.4 (0.55)	10,670 (0.35)	10,474 (0.59)	490.6 (0.10)

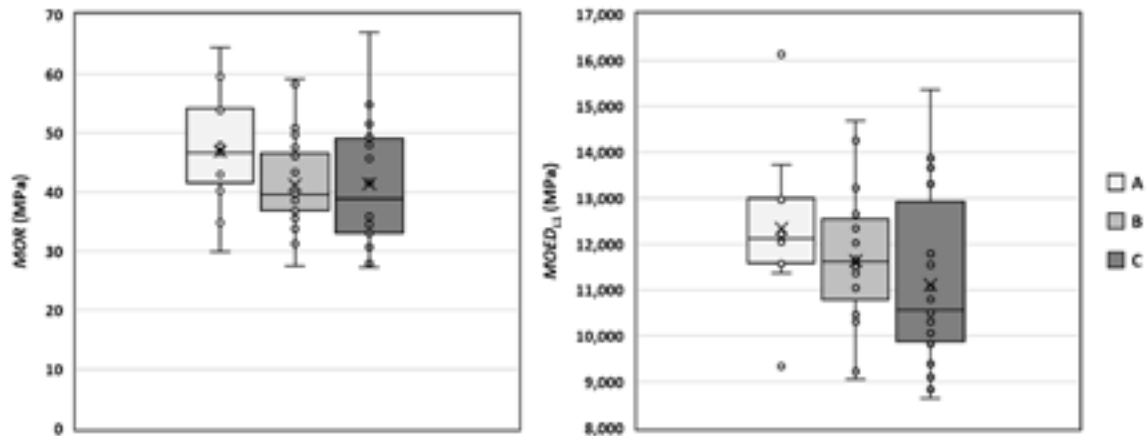


Fig. 4. MOR for quality grades A/B/C (a); Dynamical modulus of elasticity in longitudinal direction of sawlogs for quality grades A/B/C (b).

3.2. Knot parameters

Among the basic parameters, the total number of knots (K_n) correlated highly with mechanical properties. Surprisingly poor correlation was found between maximum knot size (K_{Dmax}) and MOR ($r = -0.49$), even though the size of the largest knot is one of the main criteria for assessing log quality grades. The sum of the sizes of all knots (K_{nD}) provided an average correlation with mechanical properties. The worst sections correlated well with both mechanical and acoustic properties. The correlation with MOR increased slightly when considering the 2 or 3 worst windows, while no clear trend was apparent for the MOE_{glob} and MOE_{loc} . Again, the total number of knots in a given window correlates best with MOR (in the case of the 3 worst windows, $r = -0.73$). An interesting trend is observed in the relationship between acoustic properties and knot parameters. The results show that there is a relatively good correlation between the sum of the sizes of knots in the worst windows and the $MOED_{L1}$ (for all variants of the worst windows, $r = -0.71$). On the contrary, no significant relationship was found between the parameters for knots and the final density of sawn timber (Table 5).

The Spearman correlation coefficient between MOR and K_n is $r = -0.68$ (Fig. 5). There are several extreme examples, such as log number 33 (Fig. 5a) and log number 48 (Fig. 5c). In the case of log number 33, only two knots were measured on the surface, but the boards had a very low average strength of MOR = 34.8 MPa. In contrast, 18 knots were detected in log number 48, but the boards had an above-average strength MOR = 59.2 MPa. Deviations from linear relationship were also found in several other logs, and explanations must be searched primarily at the level of individual boards and corresponding worst board sections (Fig. 5b, Fig. 5d).

3.3. Acoustic properties

The FRM showed strong correlation for most of the physical and mechanical properties examined (Table 6). $MOED_L$ had very similar correlation coefficients with MOR and MOE_{glob} ($r = 0.85 - 0.88$ and $r = 0.96 - 0.98$, respectively) for both green and dry sawn timber. The deviation from ideal linearity was observed for sawlogs ($r = 0.75$ and $r = 0.80$, respectively). For $MOED_B$, lower

Table 5. Correlation coefficients for different knot parameters and wood properties.

	MOR	MOE_{glob}	MOE_{loc}	ρ_5	$MOED_{L1}$	$MOED_{B1}$
K_n	-0.68	-0.63	-0.56	-0.21	-0.67	-0.58
K_{Dmax}	-0.49	-0.37	-0.41	0.12	-0.57	-0.56
K_{nD}	-0.60	-0.51	-0.48	-0.02	-0.67	-0.62
KW_{n1}	-0.70	-0.71	-0.61	-0.34	-0.64	-0.51
KW_{nD1}	-0.66	-0.59	-0.57	-0.08	-0.71	-0.63
KW_{n2}	-0.72	-0.70	-0.61	-0.31	-0.67	-0.54
KW_{nD2}	-0.67	-0.59	-0.55	-0.08	-0.71	-0.63
KW_{n3}	-0.73	-0.69	-0.59	-0.30	-0.67	-0.55
KW_{nD3}	-0.68	-0.59	-0.54	-0.09	-0.71	-0.63

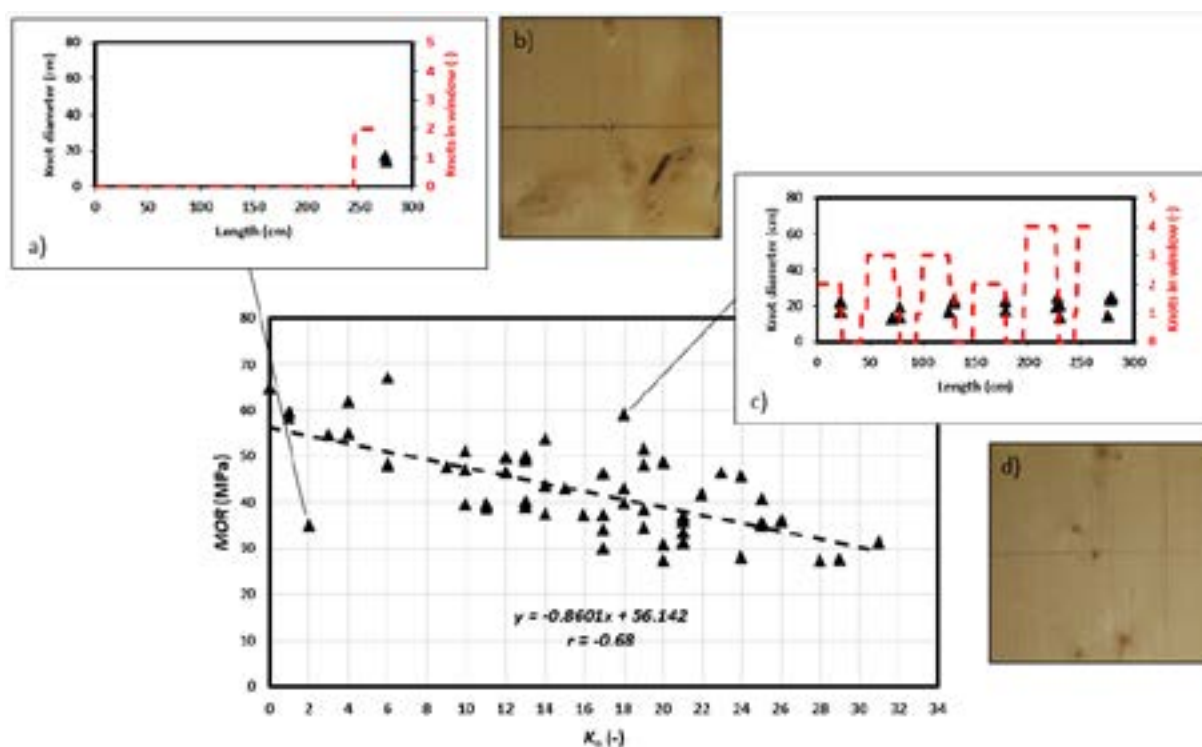


Fig. 5. Relationship between total number of knots (K_n) and MOR: Log number 33; $K_n = 2$; MOR = 34.8 MPa (a); Worst section of the board 33C (b); Log number 48; $K_n = 18$; MOR = 59.2 MPa (c); Worst section of the board 48P (d).

Spearman correlation coefficients were recorded at the log level ($r = 0.55$ for MOR, $r = 0.60$ for MOE_{glob}). The correlations with the final density of sawn timber were low for both $MOED_{L1}$ and $MOED_{B1}$ ($r = 0.52$ and $r = 0.38$, respectively).

Table 6. Correlation coefficients for different acoustic parameters.

	MOR	MOE_{glob}	MOE_{loc}	ρ_s
$MOED_{L1}$	0.75	0.80	0.62	0.52
$MOED_{L2}$	0.88	0.97	0.72	0.73
$MOED_{L3}$	0.85	0.96	0.72	0.74
$MOED_{L4}$	0.87	0.97	0.71	0.72
$MOED_{B1}$	0.55	0.60	0.46	0.38
$MOED_{B2}$	0.87	0.96	0.72	0.73
$MOED_{B3}$	0.85	0.96	0.73	0.73
$MOED_{B4}$	0.87	0.98	0.73	0.74

The influence of density when calculating $MOED_L$ was verified (Fig. 6). When using real density, the correlation with MOR is $r = 0.75$ (Fig. 6a). When using a fixed density $\rho_1 = 700 \text{ kg m}^{-3}$, there is a significant decrease of Spearman correlation coefficient to $r = 0.42$ (Fig. 6b). The results show the fundamental importance of real wood density when using the FRM in the wood industry.

4. Discussion

Moisture content 60.6% corresponds to standard moisture content of roundwood in log yards before the beginning of summer, when Ravoajanahary et al. (2025) recorded an average heartwood moisture content 25% and an average sapwood moisture content 110% for spruce in May. According to Rais et al. (2020), moisture above the fiber saturation point does not significantly affect MOED. This condition was also met for the measured logs, so it is not necessary to consider any correction coefficients. The high coefficient of variation is a result of irregular supplies to the sawmill's log yard, where some of the logs were delivered immediately after logging, while others have been stored for a longer period. The average dry sawn timber density and samples density after static testing was in the range between 420 kg m^{-3} and 450 kg m^{-3} , which corresponds to standard values. According to Simic et al. (2019), Sitka spruce sawn timber MOR was 31 MPa, which is significantly lower than the 42.6 MPa measured in presented study. However, based on the below-average density (377 kg m^{-3}), it can be assumed that the material used in this referred research was generally lower in quality. An interesting trend was observed for $MOED_L$, where similar values were measured at both log and dry sawn timber levels. Rais et al. (2014) recorded an increase for Douglas fir between logs and dry sawn timber from approx. 10,500 MPa to

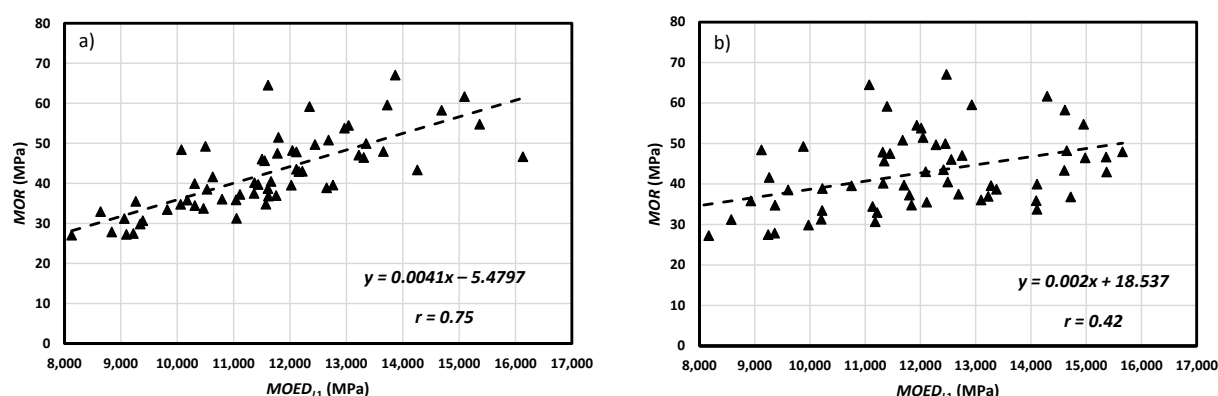


Fig. 6. Relationship between $MOED_{L1}$ of sawlogs and MOR of sawn timber: $MOED_{L1}$ calculation using actual log density, $r = 0.75$ (a); $MOED_{L1}$ calculation using fixed log density 700 kg m^{-3} , $r = 0.42$ (b).

12,000 MPa, so in our case, the decrease in density due to drying was evenly compensated by an increased natural frequency in the longitudinal direction. On the contrary, drying resulted in an expected significantly increased natural frequencies in bending, with dry sawn timber having $MOED_{B3} = 9,405 \text{ MPa}$ compared to $MOED_{B1} = 7,664 \text{ MPa}$ for roundwood. The dataset is limited to roundwood originating from a single enterprise in the South Moravian Region (Mendel University Forest) harvested in May–June 2025, with relatively uniform mid-diameter (approx. 30 cm) and length (3 m). Therefore, the results should be interpreted with regard to this regional and size-specific context.

4.1 Visual classes

According to the results, visual quality grades of sawlogs are not a suitable indicator for the physical and mechanical properties of future sawn timber. A statistically significant difference was confirmed in only 3 out of 18 cases. It is therefore not possible to say with sufficient accuracy that higher quality grades will produce sawn timber with the highest strength. Similar conclusions have been reached by other authors using different standards for visual quality log grading (Edlund et al. 2006; Denzler et al. 2015). The main cause of such inaccuracy is primarily the assessment of characteristics that have a negative impact on the visual appearance of future sawn timber, volume yield, log manipulation and processing, or subsequent processability of sawn timber. These defects do not necessarily affect the physical and mechanical properties. Such defects may include, for example, resin pockets, reaction wood, shallow insect damage, or blue stain. Considering the current situation of sawmill industry in the Czech Republic, which focuses on the production of commercially graded sawn timber, visual assessment of roundwood can be considered appropriate. However, for

the production of strength-graded sawn timber, it would be advisable to employ alternative methods of sawlog pre-sorting.

4.2. Knot parameters

The examined dataset of sawlogs did not contain any significant defects other than knots that would have a significant impact on mechanical properties, such as rot (Witowski et al. 2016). The research therefore provided an opportunity to assess the impact of knots on the properties of sawn timber. The total number of knots proved to be suitable parameter, which contradicts the results of Wieruszewski et al. (2022). However, this author conducted the assessment on sawn timber, where the total number of knots is generally lower. The dimensions of knots are often an assessed parameter for logs, but contrary to expectations, lower correlations with mechanical properties were achieved. Inaccuracies may have been caused by the human factor, as in some cases it is difficult to visually determine the boundary of a knot, and errors may also occur when reading values from a steel ruler. Compared to dimensions, the total number of knots is a simpler parameter, where inaccuracy due to the human factor is significantly reduced. Moving windows, various versions of which are used in some studies (Ravoajana-hary et al. 2025), have proven to be very effective. When predicting mechanical properties, the summed number of knots in the worst window or in the 2 to 3 worst windows has again proven to be a good indicator. On the contrary, the summed dimensions of knots in the worst windows correlated better with the $MOED_{L1}$. Based on these results, it can be concluded that the FRM is a good indicator to detect the local presence of larger knots. $MOED_L$ generally described the knottiness of the logs better than $MOED_B$. Interesting findings were provided by Fig. 5. While the total number of knots correlates rel-

actively well with the board's strength, there are several deviations. For example, in log number 33, only two knots were detected on the surface, but after sawing, many enclosed knots were visible, which led to low strength. In contrast, 18 knots were detected in log number 48, but these knots were not large and were evenly distributed, so the resulting board strength exceeded the average. These results clearly show that in some cases, external visual assessment cannot provide accurate information about the actual knottiness of a log. In such cases, high accuracy can be expected when using CT scanners, primarily due to their ability to accurately detect hidden defects (for example, the above-mentioned enclosed knots). An alternative option for automated knot measurement is the use of photometry, which can significantly reduce human error. However, this technique is limited to surface analysis and cannot identify subsurface irregularities.

4.3. Acoustic properties

Based on the results, the use of the FRM can be recommended. Strong relationships (correlation coefficients above $r = 0.70$) were found between the mechanical and acoustic properties of sawn timber. For both $MOED_L$ and $MOED_B$, the correlation coefficients did not change significantly with drying or shortening of the sawn timber. $MOED_B$ correlated slightly better in the final phase with the final length, when the most significant wood defects were located mostly in the centre of the boards. At the log level, $MOED_L$ correlated better with mechanical properties than $MOED_B$. Measuring acoustic properties in bending is generally more complicated due to the need to support and precisely position the log. It is therefore recommended to measure only frequencies in the longitudinal direction at the log level and to omit measurements in bending completely.

It was not possible to distinguish visual quality grades of sawlogs using the FRM. Other authors have reached similar conclusions (Straže et al. 2023; Nocetti et al. 2025). It should be noted that visual assessment of logs is based on many defects, not all of which affect physical and mechanical properties, including vibro-acoustic properties. It therefore depends fundamentally on both the quality assessment standard used and the set of logs being assessed. The results can be highly variable, with the acoustic method corresponding to visual grading for logs with significant knots and rot, but for another set with other defects, such as resin pockets, blue stain, or shallow insect damage, the acoustic properties will not correspond to the specified quality classes.

Knowledge of the actual wood density is essential for the proper application of the FRM. Measuring density can be problematic in practice, therefore some studies use fixed values (Edlund et al. 2006). However, based on our results, the use of fixed values is highly undesirable

and leads to a significant reduction in the applicability of this method. Another crucial parameter is knowledge of the wood moisture content. There are methodologies for correction of acoustic parameters at different moisture contents (Unterswieser & Schickhofer 2011; Llana et al. 2020), but the simplest solution is to use MOED while observing the sawlogs with a moisture content above the fiber saturation point (Rais et al. 2020), which was also fulfilled in the presented research.

5. Conclusion

Presented study verified the applicability of basic non-destructive methods for predicting the mechanical properties of sawn timber based on sawlog parameters. The results confirmed the fulfilment of the stated primary and secondary research objectives:

- A statistically significant relationship was found between the mechanical properties of sawn timber (MOR , MOE_{glob}) and the vibro-acoustic properties of logs ($MOED_{L1}$). The strongest correlations were observed between $MOED_{L1}$ and MOR ($r = 0.75$) and between $MOED_{L1}$ and MOE_{glob} ($r = 0.80$). The vibro-acoustic properties in the longitudinal direction proved to be a reliable predictor of strength-related properties (H1 was confirmed).
- At the log level, it is recommended to measure only longitudinal vibrations. Measurements in bending ($MOED_{B1}$) showed weaker correlations and are operationally more demanding, making them unsuitable for efficient industrial pre-sorting.
- Visual grading of sawlogs according to current industrial standards in the Czech Republic is not a reliable predictor of sawn timber mechanical properties. Strength and acoustic parameters (MOR , MOE , $MOED_{L1}$) could not be consistently distinguished across visual classes. Current approach remains suitable for commercial sawn timber grading, but not for strength prediction (H2 was confirmed).
- Knot-related parameters measured at the log level significantly contributed to predicting sawn timber strength (H3 was confirmed). The total number of knots (K_n) and parameters derived from sliding windows (KW_{n1} – KW_{n3}) showed the strongest correlations with MOR (up to $r = -0.73$). Surface-based knot assessment has limitations, particularly in cases with enclosed knots. Deviations observed in selected logs demonstrated that manual measurements may underestimate internal defects, which supports the integration of CT scanning in future research.
- After drying, a decrease in sawn timber density was observed ($\rho_1 = 687.9 \text{ kg m}^{-3}$ to $\rho_5 = 419.9 \text{ kg m}^{-3}$), whereas $MOED_B$ increased ($MOED_{B1} = 7,664 \text{ MPa}$ to $MOED_{B4} = 8,909 \text{ MPa}$). In contrast, $MOED_L$ values remained relatively stable across all stages ($MOED_{L1}$

= 11,611 MPa to $MOED_{L4} = 11,492$ MPa). While certain properties changed between production phases, others remained comparable, indicating that H4 was only partially confirmed.

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