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Analysis of Wood Defects in Norway spruce (*Picea abies* (L.) Karsten) from Mixed Uneven-Aged Forest Stand

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ABSTRACT

Norway spruce (*Picea abies* (L.) Karsten) is one of the most economically important conifer species in Europe. Efficient utilisation and processing of its wood require detailed knowledge of its technical properties, as well as the most common wood defects that substantially affect both properties and utilisation. Given the crucial role of wood defects in the roundwood classification system, the primary objective of this study was to identify defects in Norway spruce and to analyse the influence of forest assortment characteristics (diameter and position along the stem) and tree attributes (diameter at breast height and position within the stand) on the size of wood defects. The research was conducted in Bosnia and Herzegovina, within a forest compartment of an uneven-aged, mixed beech and silver fir stand with spruce. Trees were felled and processed into assortments using a chainsaw, predominantly applying the cut-to-length method. After measuring the assortment dimensions, the occurrence of defects was assessed, and their sizes were determined. The analysis showed that, following knots, the most common wood defect was rot, followed by pith eccentricity, compression wood, scars, mechanical damage, and resin pockets. Statistically significant differences were found in the size of knots, ellipticity, and taper among different diameter classes of assortments ($p<0.05$), as well as assortment positions along the stem ($p=0.0000$). Also, a statistically significant difference was observed in the size of the knots and ellipticity in relation to both diameter at the breast height and tree position within the stand ($p<0.05$). Overall, the findings align with previous studies, confirming the higher quality of the lower stem section, as reflected in smaller defect sizes critical for roundwood quality classification, such as knots, rot, ellipticity, and taper.

Keywords: quality classification; roundwood; wood defect; knots; rot

INTRODUCTION

Norway spruce (*Picea abies* (L.) Karsten) is one of the most economically significant conifer species in Europe. Its high productivity and wood quality across diverse site conditions distinguish it from other species (Skrøppa 2003). Owing to its favourable mechanical properties and low density, Norway spruce wood is widely used in construction and the furniture industry (Šoškić et al. 2008). The proper use and processing of wood require knowledge of its technical properties, as well as of the most common wood defects that significantly affect its performance and utilisation. The quality structure of forest wood assortments depends on numerous factors, primarily the dimensions of the assortment and the size of external defects (knots, etc.), and to a lesser extent internal defects (rot, etc.), as well as damage incurred during tree felling and processing (Krajnc et al. 2023). The external appearance of a tree and its properties, such as stem form, branching, bark features, anatomical structure, and wood colour, are determined by a range of characteristics that develop during its normal life cycle. Environmental factors, including temperature fluctuations, precipitation, snow, wind, and light, also affect tree growth. Biological influences, such as attacks by fungi, insects, animals, parasitic plants, and human activities, likewise play a significant role (Richter 2015).

Wood defects thus result from the combined effects of biotic, abiotic, and anthropogenic factors, and can occur on the stem, branches, and roots.

A particular characteristic of a tree resulting from growth under varying conditions may sometimes be regarded as a defect, and at other times not. When viewed from the perspective of tree growth, only those features that shorten the expected lifespan of the tree, such as rot or stem breakage, are considered defects. Irregular stem shape and knots, for example, are not regarded as defects from a biological standpoint. However, from the perspective of wood utilisation, defects are characteristics that make the use of wood for a specific purpose difficult or impossible (Richter 2015). In forestry practice of Bosnia and Herzegovina, wood defects are commonly defined according to Gurda and Musić (2015) as deviations from the normal structure, form, colour, or properties of wood, particularly those that reduce its usability. The quality classification of wood, according to the applicable standards in Bosnia and Herzegovina (Yugoslav standards), is based on the presence, size, and frequency of wood defects, as well as the dimensions of the wood assortments (diameter and length).

Knots, rot, scars, curvature, compression wood, spiral grain, hazel wood, sunburn bark, resin pockets, burls, ring shakes, mechanical damage and damage caused by insects are cited as the most common wood defects in Norway spruce (Ugrenović 1950, Karahasanović 1992, Barszcz and Michalec 2007). Previous studies of Norway spruce identify knots and rot as the wood defects with the greatest negative impact on wood quality (Barszcz et al. 2010a, 2010b, Michalec et al. 2013, Kadunc 2013, Vlad et al. 2018, Noordermeer et al. 2023, Lara et al. 2024).

Spruce wood contains resin pockets, which can reduce its usability and commercial value. Resin pockets directly affect the aesthetic quality of wood products. The leakage of resin produces a sticky layer on contact with objects or people, which poses a greater disadvantage for carpentry applications than for construction wood. These negative effects have led to the number and size of resin pockets being regulated in national standards for wood classification (Gjerdrum and Bernabei 2006). Gryc and Horáček (2007) found that the density of Norway spruce wood is higher when compression wood is present. In cases where compression wood accounts for 80% of the stem, the wood density is 1.5 times greater compared to wood without this defect. Due to the higher density, working with compression wood results in increased energy consumption. Additionally, products containing compression wood exhibit a different colour, which may be considered an undesirable trait unless otherwise specified. Gryc and Vavrčík (2009) reported that the compressive strength parallel to the grain of Norway spruce compression wood is slightly higher than that of wood without the defect, reaching a value of 50 MPa.

The effects of bark beetle infestation on the tensile and compressive strength of Norway spruce wood were studied by Löwe et al. (2022). They reported that the longer trees remain in the stand after infestation, the greater is the reduction in these strength properties. In trees infected three years prior to analysis, tensile strength decreased by 14% compared to healthy trees (from 93.185 MPa to 80.709 MPa), while compressive strength declined by 25.6% (from 46.144 MPa to 34.318 MPa).

Lojo et al. (2021) found that the proportion of Norway spruce logs increases significantly with tree diameter. They also highlighted the influence of tree height on assortment volume, noting that taller trees produce a greater volume of high-quality assortments within the same diameter class.

Considering the previously emphasized importance of wood defects in the classification system of roundwood, the primary aim of this study was to identify wood defects in Norway spruce and to analyse the influence of forest wood assortment characteristics (diameter and position along the stem), as well as tree attributes (diameter at breast height and position within the stand), on the size of specific wood defects.

MATERIALS AND METHODS

The research was conducted in Bosnia and Herzegovina, in a forest compartment within an uneven-aged, mixed beech and silver fir forest with spruce, growing on shallow cambisol, leptosol and their complexes on limestone and dolomite, and phaeozems on saccharoid limestone and dolomites. The study area is located at 43°45'16'' N and 18°14'47'' E. Average elevation in forest compartment is 1,310 m, with terrain slope ranging from 10° to 25°. In 2023, trees were selected for felling according to the group selection system principles, with a total of 2,766 m^3 of merchantable wood (not smaller than 7 cm over-bark) marked. Field research focused on wood defect analysis was carried out in November 2024. A total of 30 Norway spruce trees were included in the study. To minimise sampling bias, trees were analysed consecutively along the felling lines, regardless of their external characteristics. Before tree felling, the diameter at breast height (DBH) and position within the stand were recorded for each analysed tree. DBH (measured at 1.3 m above ground level) was determined using a caliper. Tree position within the stand was classified according to Kraft's classification (1884), assigning each tree to one of five categories: predominant, dominant, co-dominant, suppressed, or overtopped.

The trees were felled and processed into forest wood assortments using a chainsaw. The cut-to-length processing method was predominantly applied, while the half-tree length method was used to a lesser extent. Length and diameter of all processed assortments were measured immediately after felling. Length was measured at the shortest point of each assortment using a measuring tape. Diameters were measured with a caliper at designated points crosswise (maximum and minimum), with values rounded down to the nearest centimeter. The reduction from over-bark to under-bark diameter was performed by subtracting double bark thickness in the amount of 1 cm for forest wood assortments with diameters up to 35 cm at the middle of length, and 2 cm for those with diameters exceeding 35 cm, in accordance with the internal regulations of the enterprise managing the forests in the study area. Diameters were recorded at three positions along each wood assortment: the thicker end, the middle of the length, and the thinner end. For the first assortment taken from the base of the tree, two crosswise diameters were measured at the root collar end, located at a maximum distance of 1 m from the thicker end instead of measuring diameter at the thicker end. The volume of forest wood assortments was determined using Huber's formula (Equation 1) cited in Banković and Pantić (2006).

$$V = g_{½} \cdot L \quad (1)$$

where V is volume of wood assortment (m^3), $g_{½}$ is basal area at the middle of length (m^2), and L is length of wood assortment (m).

After measuring the assortment dimensions, the presence of wood defects was analysed and their sizes were determined. Defects were measured according to the national Yugoslav standard from 1969 (JUS D.A0.101 - Wood Defects: Terminology, Definitions, and Measurement). The formulas used to calculate the size of individual defects are presented in Table 1.

For some defects (split tree stem, compression wood, resin pockets, ingrown bark, and insect damage), only their presence or absence was determined.

Knots were classified according to the following criteria: mutual position (individual knots; knots in a whorl), degree of their tightness with the surrounding wood (tight or intergrown; partially intergrown; encased or loose knots), health status (sound; partially rotten; rotten), and size (pin knots <6 mm; small knots 7–20 mm; medium knots 21–40 mm; large knots >41 mm). A similar classification of knots can be found in Barszcz et al. (2010a, 2010b). For knot size classification, the smallest diameter of an individual knot was recorded, whereas for knots in a whorl, the smallest diameter of the largest knot was measured.

Statistical data processing was performed using the Statgraphics Centurion XVII software package. After testing for data normality (Shapiro-Wilk W-test) and homogeneity of variance (Levene's test), the ANOVA or Kruskal-Wallis non-parametric test was applied to analyse the influence of forest wood assortment and tree characteristics on the size of wood defects. $\chi 2$ test was used to determine compression wood occurrence depending on wood assortment and tree characteristics.

RESULTS AND DISCUSSION

The research included 30 Norway spruce trees with an average DBH of 71.17 cm (±15.39 cm), ranging from 22 to 94 cm. The total gross volume of all analysed trees was 141.289 m^3, corresponding to an average of 4.710 m^3 per tree. From these trees, 133 wood assortments were processed (Table 2). Sawlogs accounted for 76.58% of the total volume of processed forest assortments, followed by pulpwood with 21.18% and round pit timber with 2.24%.

Table 1. Formulas for calculating wood defect sizes.

Wood defect	Formula
Ellipticity (%)	((LD–SD)/LD) · 100
Taper (%)	(((TKD-THD)/L)/TKD) · 100
Double heart (%)	(DP/D) · 100
Pith eccentricity (%)	(DC/D) · 100
Curvature (%)	(HC/L) · 100
Rot (%)	(DR/D) · 100
Scars and damage caused by physical and mechanical factors (mm^2)	Scar/damage length (mm) · Scar/damage width (mm)

LD – larger diameter; SD – smaller diameter; TKD – thicker end diameter; THD – thinner end diameter; L – length; DP – distance between piths; D – diameter; DC – distance from centre; HC – height of curvature arc; DR – diameter or depth of rot

Table 2. Features of processed wood assortments.

Feature	Number of data	Minimum	Average	Maximum	Standard deviation
N	30	2.00	4.43	6.00	±1.28
V_t (m^3)	30	0.20	4.45	8.10	±1.91
L (m)	133	1.10	6.05	11.10	±1.51
D_m (cm)	133	11.00	45.90	86.00	±18.20
D (cm)	103	19.00	47.47	83.00	±14.09
D_r (cm)	30	26.00	80.77	99.00	±15.62
d (cm)	133	10.00	40.65	83.00	±17.89
V_i (m^3)	133	0.03	1.00	2.87	±0.73

N – number of assortments per tree; V_t – volume of all assortments per tree; L – assortment length; D_m – diameter at the midlle of length; D – diameter at the thicker end; D_r – diameter at the root collar end; d – diameter at the thinner end; V_i – Volume of individual assortment

Analysis of the processed forest assortments revealed that after knots, the most prevalent defect was rot, observed in 56.67% of the analysed trees. Pith eccentricity and compression wood were each recorded in 50% of the trees. Scars were observed in 26.67% of trees, whereas damage from physical and mechanical factors and resin pockets were present in 20% of cases each. Other recorded wood defects (double heart, curvature, split tree stem, ingrown bark, and insect damage) were present in 10% or fewer of the analysed trees (Figure 1). The most frequent wood defects are presented in Figure 2.

Some of the commonly reported wood defects in Norway spruce trees (Ugrenović 1950, Karahasanović 1992, Barszcz and Michalec 2007, Sandak et al. 2020) were also observed in this study, including compression wood, resin pockets, curvature, rot, scars, mechanical damage, and insect damage. Other defects frequently cited in the literature, such as spiral grain, hazel wood, sunburn bark, burls, and ring shakes, were not observed in the analysed trees.

Knots were predominantly in whorls (80.76%), tight (87.09%) and sound (92.87%) (Figure 3). Barszcz et al.

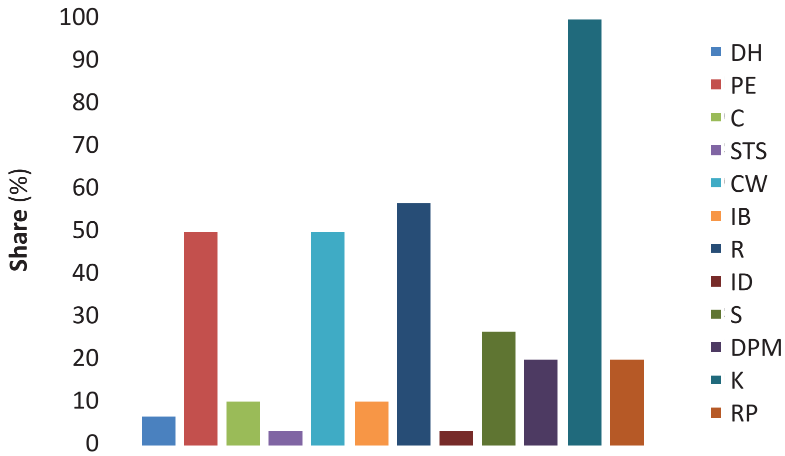

Figure 1. Proportion of wood defects in the analysed trees. DH – double heart; PE – pith eccentricity; C – curvature; STS – split tree stem; CW – compression wood; IB – ingrown bark; R – rot; ID – insect damage; S – scars; DPM – damage caused by physical and mechanical factors; K – knots; RP – resin pockets.

Figure 2. Some of the recorded wood defects in Norway spruce. **(a)** knots; **(b)** rot; **(c)** pith eccentricity and compression wood; **(d)** scar; **(e)** damage caused by mechanical factor; **(f)** resin pockets.

(2010a) also found that sound-tight knots prevailed (60%) in mature 150-year-old Norway spruce stands situated at an altitude of 1,450-1,740 m above sea level in northern Italy. Medium-sized knots (21–40 mm) and large knots (>41 mm) were the most frequently found. Small knots (7–20 mm) comprising 15.28% of the total. Based on measurements of 1,263 individual knots and knots in a whorl, it was determined that its size ranged from 10 mm to 75 mm, with an average of 33.81 mm. The average knot diameter was higher than 20.3 mm reported by Barszcz et al. (2010a) in 150-year-old Norway stands situated at an altitude of 1,450–1,740 m above sea level in northern Italy.

Rot was measured at both the thicker and thinner ends of the logs. The average extent of rot at the thicker end of the assortments was 51.65%, ranging from 10.19% to 100%. At the thinner end, the average extent of rot was slightly higher, 67.63%, ranging from 10.19% to 94.34%.

The average scar size was 561.55 cm², with the majority of scars (81.82%) observed on the first and second assortments, moving upward from the base of the tree toward the crown. The average size of damage caused by physical and mechanical impacts was 598.11 cm². The highest incidence of damage caused by physical and mechanical impacts was also recorded in the lower part of the stem, specifically on the first assortment (44.44%) and second assortment (44.44%). These findings support the well-established fact that the lower stem section is the most susceptible to injuries during timber extraction by cable skidders, which are commonly used in forest harvesting in Bosnia and Herzegovina. Kadunc (2013) notes that mechanical damage is a significant factor influencing the occurrence of wood rot in Norway spruce. Also, Michalec et al. (2013) stated that Norway spruce is highly susceptible to mechanical stem damage, which can rapidly lead to rot. Several researchers have investigated fungi affecting Norway spruce trees. Lara et al. (2024) stated that the presence of fungi from genera *Heterobasidion* and *Armillaria* results in financial losses and a reduction in the usable wood volume. Also, Noordermeer et al. (2023) report that butt end rot is the most significant defect in Norway spruce, causing substantial financial losses. In a study of 140,000 m³ of felled spruce wood in Norway, 16% of trees showed rot, with a higher incidence in larger-diameter trees. When root rot is present, the volume of sawlogs is reduced by 48%. The same authors also reported that the presence of wood rot reduces timber revenue by 7%, corresponding to approximately 18.5 million euros in Norway. According to Kadunc (2013) wood rot in Norway spruce can reduce timber value by up to 19 €·m^{-3}, with the most significant losses observed in the 50–70 cm diameter class. Therefore, careful consideration is required when conducting harvesting operations in spruce stands. In this study, injuries (damage caused by physical and mechanical impacts and/or scars) were observed in 41.18% of trees in which rot was recorded.

Compression wood was found in 23.31% of wood assortments. The χ^2 test was used to analyse the occurrence of compression wood in relation to the characteristics of processed wood assortments and the tree (Table A1, Table A2, Table A3, and Table A4). A statistically significant difference was found in the proportions of assortments with and without compression wood across different stem sections (p=0.0206). For the other analysed factors (assortment diameter, DBH, and position within the stand), no statistically significant effects were observed (p>0.05). This wood defect was most frequently observed in the first assortment (45.16%), while in the upper parts of the stem, in the fourth and fifth assortments, it was recorded in only 19.63% of cases. No defects were observed in the sixth assortment. The distribution of compression wood along the stem is consistent with the findings of Warensjö (2003), who reported that this wood defect is typically

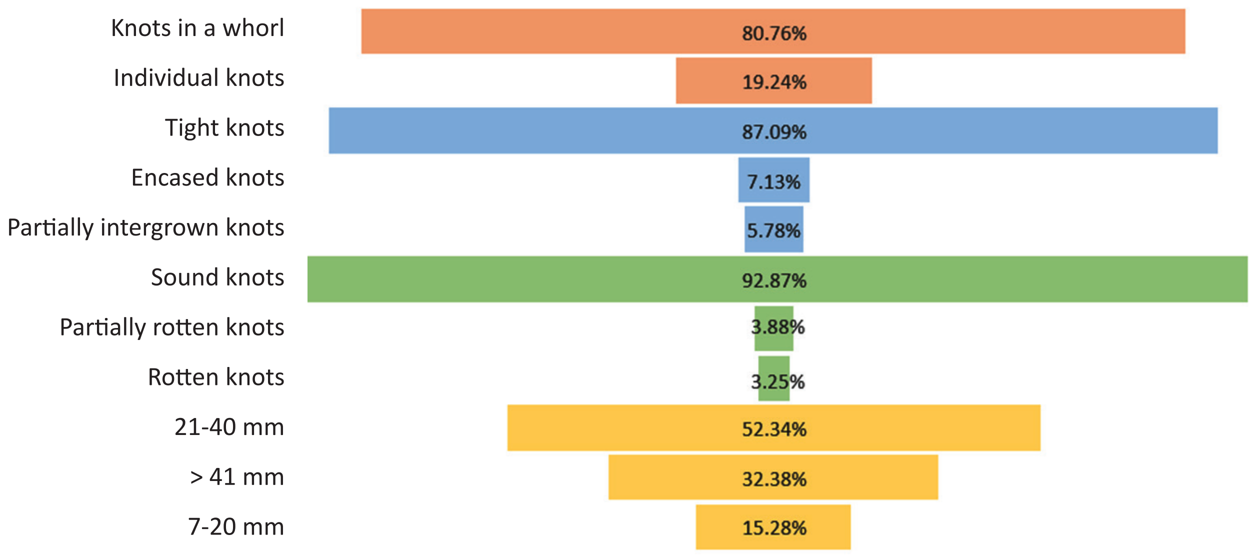

Figure 3. Distribution of knots by mutual position, degree of their tightness with the surrounding wood, health status, and size.

most pronounced near the ground and decreases toward the upper parts of the stem.

The pith eccentricity varied from 6.77% to 24.47% at the thicker end, and from 6.77% to 24.14% at the thinner end. The lower number of defects recorded at the thinner end (16) compared to the thicker end (29) supports the observation that these defects tend to disappear at a certain height of the tree.

Resin pockets were found in 5.26% of the wood assortments. The defect was recorded at tree heights ranging from 6.54 m to 25.11 m, with an average height of 14.99 m. These results are consistent with the findings of Gjerdrum and Bernabei (2006), Temnerud (1997), and Seifert et al. (2010), which report an increased occurrence of resin pockets with increasing height in Norway spruce trees.

The ellipticity at different positions (thicker end, root-collar end, mid-length, and thinner end), as well as the taper for each wood assortment, were determined. Ellipticity ranged from 0% to 9.09%. The applicable JUS standard defines a section as regular if its ellipticity is less than 10%. Analysis of ellipticity measured along different lengths of the wood assortments showed that this defect did not exceed the threshold value in any case. Taper ranged from 0.96% to 19.41%, with a mean of 5.01%.

The relationship between the wood defect size and the diameter of processed forest assortments, as well as their position along the stem, was analysed. The analysis focused on the most frequent wood defects identified in this study (knots, rot, and pith eccentricity) and on ellipticity and taper, which were determined for each wood assortment. The diameter at mid-length of the forest wood assortment was considered in the analysis. The position along the stem was defined by the assortment's ordinal number (1–6), with assortment 1 corresponding to the lowest position on the stem, closest to the ground.

A statistically significant difference (Table 3 and Table 4) was found in the size of knots, ellipticity and taper for different diameter classes of processed forest wood assortments ($p< 0.05$), as well as for different assortment positions along the stem ($p=0.0000$). Larger knots were observed in thinner assortments originating from the upper part of the stem. The smallest knot sizes were recorded within assortments with diameters from 81 cm to 90 cm, as well as the first assortment in the stem, near the ground. Similar results regarding the size of the knots along the stem were obtained by Barszcz et al. (2010a). Ellipticity decreases with increasing assortment diameter. On the other hand, with respect to position within the stem, the relationship is inverse: ellipticity increases from the root collar toward the crown. Exceptions are 71–80 cm the 81–90 cm diameter classes, as these assortments belong to the first stem section of old trees, where the root collar deformation caused higher ellipticity. Taper decreases from thinner to thicker assortments and increases from the root collar toward the crown. The deviation from trend is expressed in the 81-90 cm diameter class, and the first assortment from the stem, similar to ellipticity.

The relationship between the size of wood defects and tree characteristics (DBH and position within the stand) was also analysed (Table 5 and Table 6). A statistically significant difference was observed in the size of the knots and ellipticity in relation to both DBH and tree position within the stand ($p<0.05$). The largest knots were found in trees with DBH >81 cm and in "predominant trees". The largest size of ellipticity was observed in trees with DBH from 21 cm to 30 cm, and in "co-dominant trees". The result of the previous study (Noordermeer et al. 2023) showed that root collar rot in Norway spruce is more common in trees with larger DBH. Also, Chomicz (2013) emphasised the relationship between tree age and the occurrence of butt end rot in Norway spruce under comparable stand and site conditions, reporting that the probability of rot increases with tree age. However, in this case, no statistically significant effect of DBH on rot occurrence was observed.

Table 3. Analysis of the influence of assortment diameter on the wood defect size.

Diameter of wood assortment (cm)	**K** (mm)	**RTKD** (%)	**RTHD** (%)	**PETKD** (%)	**PETHD** (%)	**E** (%)	**T** (%)
11-20	35.54a	86.21		14.26	16.67	4.58a	7.87b
21-30	32.21a	75.86	93.33	15.51		3.69a,b	6.63b,c
31-40	35.84a	64.16	68.97	13.17	14.58	3.54a,b,c	5.31c,d
41-50	33.63a	53.66	68.29	11.13	12.74	2.53b,c,d	3.62d
51-60	32.74a	47.59	58.36	14.57	12.09	2.41c,d	3.82d
61-70	30.80a	45.03	75	20.35	19.05	1.77d	4.06d
71-80	32.93a	53.42		17.91	14.65	1.90d	3.97d
81-90	26.00b	22.32		16.67		2.34c,d	10.34a
p value	K-W 0.0003*	K-W 0.3743	A 0.9110	A 0.4384	A 0.7370	K-W 0.0000*	K-W 0.0000*
Total	33.81	51.65	67.62	15.49	13.83	2.92	5.01

K – knots size; RTKD – rot at the thicker end; RTHD – rot at the thinner end; PETKD – pith eccentricity at the thicker end; PETHD – pith eccentricity at the thinner end; E – ellipticity; T – taper; SD – standard deviation; * – statistically significant difference at the 95% confidence level; K-W – Kruskal-Wallis p value; A – ANOVA p value; different letters show significant differences among diameter classes according to the performed statistical test

Table 4. Analysis of the influence of assortment position on the wood defect size.

Assortment position along the stem	K (mm)	RTKD (%)	RTHD (%)	PETKD (%)	PETHD (%)	E (%)	T (%)
1	27.41b	44.97	53.52	18.23	15.30	2.49c	5.82b
2	33.05a	53.52	76.98	14.27	12.31	2.29c	3.04d
3	35.45a	69.50	72.53	12.25	13.64	2.59c	3.68c,d
4	35.67a	51.72	86.21	13.64	13.69	3.33b,c	5.42b,c
5	34.26a	86.21		11.89		4.08a,b	7.16a,b
6	34.75a					4.85a	8.18a
p value	K-W 0.0000*	K-W 0.3411	A 0.6749	A 0.1185	A 0.8136	K-W 0.0000*	K-W 0.0000*
Total	33.81	51.65	67.62	15.49	13.83	2.92	5.01

K – knots size; RTKD – rot at the thicker end; RTHD – rot at the thinner end; PETKD – pith eccentricity at the thicker end; PETHD – pith eccentricity at the thinner end; E – ellipticity; T – taper; SD – standard deviation; * – statistically significant difference at the 95% confidence level; K-W – Kruskal-Wallis p value; A – ANOVA p value; different letters show significant differences among positions according to the performed statistical test

Table 5. Analysis of the influence of DBH on the wood defect size.

DBH (cm)	K (mm)	RTKD (%)	PETKD (%)	PETHD (%)	E (%)	T (%)
21-30	33.25a,b		17.31	16.67	6.23a	7.54
31-50	29.44a,b	79.55			5.90a	6.59
51-80	32.91b	51.69	15.08	13.64	2.86b	4.96
>81	35.77a	42.05	17.61		2.76b	4.92
p value	K-W 0.0050*	K-W 0.4356	K-W 0.6526	K-W 0.2325	K-W 0.0183*	K-W 0.2648
Total	33.81	51.65	15.49	13.83	2.92	5.01

K – knots size; RTKD – rot at the thicker end; PETKD – pit eccentricity at the thicker end; PETHD – pit eccentricity at the thinner end; E – ellipticity; T – taper; SD – standard deviation; * – statistically significant difference at the 95% confidence level; K-W – Kruskal-Wallis p value; different letters show significant differences among DBH classes according to the performed statistical test.

Table 6. Analysis of the influence of tree position within stand on the wood defect size.

Position within the stand	K (mm)	RTKD (%)	PETKD (%)	PETHD (%)	E (%)	T (%)
Predominant	37.19a	22.32	15.10	15.29	2.88b	4.98
Dominant	32.50b	52.93	15.45	13.04	2.81b	4.93
Co-dominant	31.88b	79.55	17.31	16.67	6.06a	7.07
p value	K-W 0.0000*	K-W 0.1173	K-W 0.9616	K-W 0.2320	K-W 0.0094*	K-W 0.1384
Total	33.81	51.65	15.49	13.83	2.92	5.01

K – knots size; RTKD – rot at the thicker end; PEKD – pit eccentricity at the thicker end; PETHD – pit eccentricity at the thinner end; E – ellipticity; T – taper; SD – standard deviation; * – statistically significant difference at the 95% confidence level; K-W – Kruskal-Wallis p value; different letters show significant differences among positions according to the performed statistical test.

CONCLUSIONS

The research results on the identified wood defects are consistent with previous findings of higher quality in the lower stem, as reflected in smaller defect sizes relevant to roundwood quality classification, such as knots, rot, ellipticity, and taper. Exceptions are pith eccentricity and compression wood, which are more frequent in the lower part of the stem. Additionally, the highest number of scars and damage from physical and mechanical factors was observed in the lower part of the stem, particularly in the first and second assortments from the ground. Given that scars and/or damage from physical and mechanical factors, most often caused by skidders during the wood extraction phase, were confirmed in a large number of trees affected by rot, the necessity of implementing protective measures to preserve the residual trees in the stand during forest harvesting is emphasised. The use of harvesters in uneven-aged mixed stands in Bosnia and Herzegovina requires mathematical models of individual tree species' morphology, as well as the occurrence and size of the most common wood defects, to enable accurate automatic bucking. Consequently, continued research is needed to expand the database of wood defects and to develop reliable mathematical models. Also, future research is planned to focus on assessing the importance of the analysed factors through their influence on the value structure.

Author Contributions

JK and AH conceived and designed the research and carried out the field measurements; JK, AH, EP and AK processed the data and performed the statistical analysis; JK and JM supervised the research and helped to draft the manuscript; JK, JM and VH wrote the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Apendix

Table A1. Analysis of the dependence of compression wood occurrence on diameter of wood assortment.

Diameter of wood assortment (cm)	Number of wood assortments		
	Compression wood present	Compression wood not present	Total
11-20	3	15	18
21-30	3	7	10
31-40	4	20	24
41-50	3	22	25
51-60	8	22	30
61-70	3	9	12
71-80	6	5	11
81-90	1	2	3
Total	31	102	133
χ^2 p value		0.2215	

Table A2. Analysis of the dependence of compression wood occurrence on assortment position along the stem.

Assortment position along the stem	Number of wood assortments		
	Compression wood present	Compression wood not present	Total
1	14	16	30
2	5	25	30
3	5	21	26
4	5	19	24
5	2	15	17
6	0	6	6
Total	31	102	133
χ^2 p value		0.0206*	

(*) – statistically significant difference at the 95% confidence level.

Table A3. Analysis of the dependence of compression wood occurrence on DBH.

DBH (cm)	**Number of wood assortments**		
	Compression wood present	**Compression wood not present**	**Total**
21-30	1	0	1
31-50	0	1	1
51-80	11	9	20
>81	3	5	8
Total	15	15	30
χ^2 p value	0.4402		

Table A4. Analysis of the dependence of compression wood occurrence on tree position within the stand.

Tree position within the stand	**Number of wood assortments**		
	Compression wood present	**Compression wood not present**	**Total**
Predominant	3	4	7
Dominant	11	10	21
Co-dominant	1	1	2
Total	15	15	30
χ^2 p value	0.9092		

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