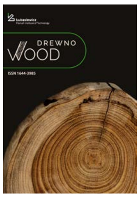
Article citation info:
Wieruszewski M., Wdowiak-Postulak A., Brol J., Krzosek S., Trociński A., Gocál J., Bahleda F., Prokop J., Nowak T. 2025. Qualitative and Strength Analysis of Pine (Pinus Sylvestris L.) Wood Materials – Study of Pallet Elements. *Drewno. Prace naukowe. Doniesienia. Komunikaty* 68 (215): 00042. https://doi.org/10.53502/wood-196536

Łukasiewicz
Poznań
Institute of
Technology

Drewno. Prace naukowe. Doniesienia. Komunikaty
Wood. Research papers. Reports. Announcements

Journal website: https://drewno-wood.pl



Qualitative and Strength Analysis of Pine (*Pinus Sylvestris* L.) Wood Materials – Study of Pallet Elements

Marek Wieruszewski[a]
Agnieszka Wdowiak-Postulak[b] *
Janusz Brol[c]
Sławomir Krzosek[d]
Adrian Trociński[a]
Jozef Gocál[e]
František Bahleda[e]
Jozef Prokop[e]
Tomasz Nowak[f]

[a] Poznań University of Life Sciences, Poznań, Poland
[b] Kielce University of Technology, Kielce, Poland
[c] Silesian University of Technology, Gliwice, Poland
[d] Warsaw University of Life Sciences, Warsaw, Poland
[e] University of Žilina, Žilina, Slovakia
[f] Wrocław University of Technology, Wrocław, Poland

Article info
Received: 23 April 2024
Accepted: 27 November 2024
Published: 17 February 2025

Keywords
wood packaging
Pinus sylvestris L.
lumber
durability
sorting

The manufacture of packaging products requires determining the strength requirements of the components that make up the structural elements of pallets, crates and other packaging. Wood, as a renewable material, is the basic raw material for manufacturing wooden pallets. The premise of this research is that the strength of pallets is derived from the characteristics of their subcomponents. Strength tests of lumber were carried out to evaluate the suitability of sawn materials. The measurement of raw material properties assists in the adaptation of individual components to static and dynamic force loads. Pine (*Pinus sylvestris* L.) lumber was analyzed, taking into account the part of the cross-sectional area from which the wood was taken and the presence of anatomical structure features. The results of the study confirm the influence of cross-sectional location on the strength properties of pine wood and consequently on its suitability for wood packaging. It was found that wood density is not a critical parameter for evaluating the strength of lumber and of the product. Tests of separated types of structural lumber for wood packaging indicate significant differences in the condition of the wood and the magnitude of the strength parameter.

DOI: 10.53502/wood-196536

Introduction

Research relating to wooden packaging includes the analysis of packaging components of wooden structures with respect to strength and durability. This study is carried out with the aim of improving the mechanical properties and durability of finished products and of the components of wooden packaging, and consequently increasing the life cycle of the product and reducing damage in the logistical process of transporting goods

---

[*] Corresponding author: awdowiak@tu.kielce.pl

[Biebl and Querner, 2020; Dixon-Hardy and Curran, 2009; García-Durañona et al., 2016].

We can categorize packaging based on its use as either direct packaging – mainly unitary packaging covering a certain amount of product, improving shipping, sales and turnover – and shipping packaging or transport-protection packaging, of which the most significant purpose is to protect the product during transport and storage [Trevisani et al., 2014; Hellström et al., 2011].

The role of direct packaging is to protect the goods from the adverse effects of mechanical factors, damage, etc., and to increase the logistical capacity to improve the product's safety. Packaging should be closely matched to the commodity's requirements. Transport packaging is subject to high requirements. Wooden pallets are products in which the wooden components have defined cross-sectional dimensions and a specified maximum distance between layers of lumber. They are used for transporting products with a solid and compact structure. To increase the durability of pallets, it is necessary to strengthen them by modifying the structure or introducing an increased number of wooden components. Even when the top and bottom bearing planes are made of suitable boards, they need to be fixed by introducing supports. The use of particular types of fasteners guarantees that the load-bearing capacity is maintained. To strengthen pallet-boxes, which are used to transport heavy loads, metal fittings are additionally utilized, which are attached to the sides of the pallet and fasten the individual elements together [Vlkovský et al., 2021; Vendl et al., 2021].

Today, wooden packaging plays a significant role in transportation logistics. In the past, no attention was paid to the construction of such packaging, which, first of all, protected the goods from the risks arising during transport, while also providing possible savings in raw material and improving its durability. It should be remembered that the principal material used for packaging was and still is wood, which has many of the characteristics necessary for this form of packaging [Hoefnagels et al., 2014]. Wood is a renewable, lightweight material that is easy to work with, has considerable mechanical strength, and is relatively resistant to weathering. All of these characteristics make wood the best material for constructing protective packaging. High-quality wood is a scarce raw material due to the constantly increasing demand for wood and the impossibility of increasing its production. Therefore, optimizing the use of wood must be considered in all areas of wood management focused on reducing the carbon footprint with an extended product Life Cycle Assessment (LCA). This concerns the time from product manufacture to disposal, often incineration. It is affected by the packaging's resistance to damage and biological degradation. Replacing wood with another material does not solve the problem of demand for packaging materials, as other materials, such as metals and plastics, are also scarce and at the same time pose an environmental burden [Deviatkin et al., 2019; Khan et al., 2021]. In addition, they are more expensive than wood material, are more difficult to process, and do not combine the positive characteristics that wood has. Therefore, a solution should be sought in improvements to wooden packaging. Such improvements first of all require research or laboratory trials, based on which it is possible to produce appropriate and effective packaging on a larger scale [Kvočka et al., 2020].

It should also be noted that more than 90% of products manufactured worldwide require appropriate transportation packaging, confirming that packaging plays a vital role in the global economy. Meanwhile, the complex processes of moving all kinds of goods and ensuring fast yet safe distribution also make it necessary to design such packaging that will meet the requirements faced by the product on its journey from the manufacturer to the customer. Cargo damage during transportation results from many factors [Zajac et al., 2021; Patricio and Maravall, 2003]. Among the most critical design features of packaging are shape and dimensions, weight, and distribution conditions. The principal exposures to which packaging is subjected throughout the distribution process are mechanical exposures during storage, transportation, or handling operations. Automatic exposures arising in storage are primarily related to the action of static loads – a package placed on the bottom layer of the stack is subject to the pressure force of a package located on the top layer. In turn, the magnitude of the pressures is determined by the weight of the loads in the upper layers and the stacking height. The tools used or human factors represent mechanical exposures during handling. Automatic exposures incurred during road transport are related to dynamic loads caused by vibrations of the drive train operation, changes in the direction of travel, and poor road surfaces. Exposures caused by sudden changes in speed or driving on mountainous terrain are also critical [Song, 2021].

The origins of the wooden pallet are dated to the first half of the 20th century. However, a major impetus for its development was the outbreak of World War II. With the development of the economy, pallets began to be adapted not only to the requirements of handling equipment, but also to the dimensions of containers or trucks. In 1950, a carrier was created with dimensions of 800 x 1200 x 144 mm [McKeever et al., 1986]. In turn, the first owner of the EUR trademark was the International Railway Organization. The EUR and EPAL markings appeared on pallets until August 1, 2013. Since then, due to the absence of an agreement between

UIC and EPAL, the railroad's trademark has disappeared from newly created Euro pallets in favor of the EPAL organization's markings. A cargo pallet forms a load-bearing platform, which can be supplemented with a superstructure. Based on the primary raw material of the platforms, several distinct types of pallets can be distinguished. The most commonly used in the market are wooden carriers. They are distinguished from each other by their external dimensions. In the case of certified pallets, they are approved and adopted based on the EUR pallet criteria and UIC Charter 435. Each pallet is assigned a marking indicating the layout on the supports, the spacing of brackets and nails, and the manufacturer's license number [Tornese et al., 2021; Deviatkin and Horttanainen, 2020]. Based on external dimensions, four types of EUR pallets can be distinguished [Buehlmann et al., 2009; Jedlinski and Sowa, 2021; EN-ISO 8611-1:2022]: EUR pallets 1 (800 × 1200 × 144 mm); EUR pallets 2 (1200 × 1000 × 144 mm); EUR pallets 3 (1000 × 1200 × 144 mm); and EUR pallets 6 (800 × 600 × 144 mm). A further important issue is the procedure of strengthening structural elements to increase the durability and strength of the final elements, following visual sorting for strength, as described in previous works [Wdowiak-Postulak, 2021, 2022, 2023; Wdowiak-Postulak et al., 2024].

The material justification for using raw wood materials from different species is subject to research evaluation. Among the most commonly used types of wood are poplar, pine, spruce, and other species with significant levels of availability [Karaçalı and Taner Ulguel, 2014; Waseem et al., 2013; Masis et al., 2022]. In the process of sorting and using wood raw material, a decisive factor in selection in terms of ensuring adequate physical and mechanical properties of the product is the origin of the raw material [ISO Standard No. 8611-1:2011].

An evaluation is made of the influence of the sorting of the starting raw material based on the required quality characteristics and cross-sectional dimensions determining selected physical and mechanical properties. Previous studies [Dunno and Symanski, 2021; Clayton et al., 2019; Iždinský et al., 2021; Zhu et al., 2022] include verification of strength tests for batches of lumber during loading. The results of these tests form the basis for the design of transport pallet structural elements. Considering all of these aspects, pine wood of defined quality enabling the production of wooden packaging with high strength and increased durability for use in automated production lines was proposed for production [Ponis and Efthymiou, 2020].

Considering all of these problems, this study proposes to evaluate the requirements that must be met by innovative wooden packaging with high strength and excellent durability. The work aimed to analyze the production of selected types of wooden packaging. It was decided to verify the state of knowledge about wood packaging and to investigate the problem of selection and the impact of quality and type of wood on performance indicators. The goal of the study was to evaluate the effect of lumber quality on semi-finished products, and to determine the influence of roundwood species group and processing directions on specific sawn materials and semi-finished products intended for use in wooden packaging in a given plant.

Materials and methods

Wooden transport pallets are made from the indicated types of softwood lumber with defined dimensions:

- 22 mm x 100 mm (rough), length of section 1200 mm;
- 22 mm x 145 mm, length of section 1200 mm.
- From each dimensional type, lumber was separated:

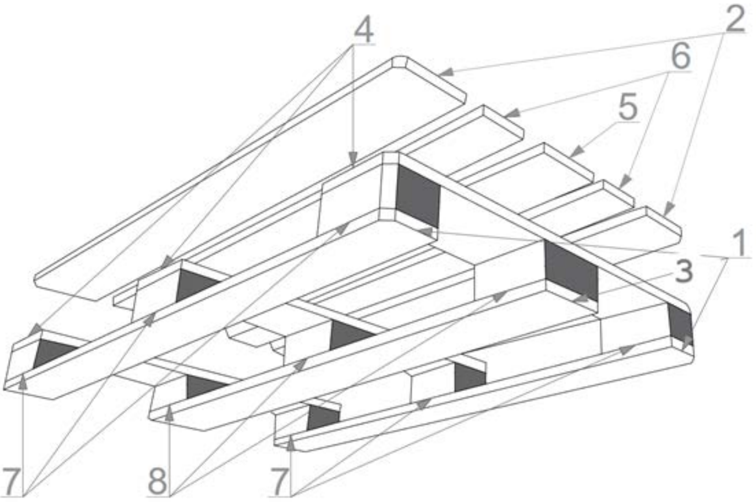


Fig. 1. Diagram of wooden packaging – wooden pallet (description of the components given in Table 1)

Table 1. Dimensions of the lumber included in the wooden pallet

No.	Component	Number of components pcs.	Dimensions at 22% moisture content Length	Width	Thickness
			mm		
1	Bottom edge board	2	1200	100	22
2	Top edge board	2	1200	145	22
3	Lower middle board	1	1200	145	22
4	Longitudinal board	3	800	145	22
5	Top center board	1	1200	145	22
6	Intermediate top board	2	1200	100	22
7	External wood bracket	6	145	100	78
8	Center wood bracket	3	154	145	78

- Top board heartwood lumber 10 pcs. / bottom board sapwood lumber 10 pcs.
- Top board sapwood lumber 10 pcs / bottom board heartwood lumber 10 pcs.

The subject of study was a set of elements of a wooden pallet structure made of solid wood [EN 13382], pine wood (*Pinus sylvestris* L.) with exclusive use for elements with a required usable moisture content of about 22%. The timber material is pine wood (*Pinus sylvestris* L.) harvested from trees of cutting age (80 years), with an average density of more than 480 kg/m^3.

The structure of the wooden package (Fig. 1) is made as mechanically connected elements of the top and bottom plate structure linked by a core or support that performs the load-bearing function of prefabricated pine wood. Table 1 characterizes the components of the pallet shown in Fig. 1.

The evaluation was conducted on sawn material in rough (unplaned) condition. The scope of the study included verification of the properties of lumber for the construction of the pallet board, as components of the structure's external bracing. The evaluation was carried out through strength tests according to EN 408:2012, EN 14081-1 and EN 384, and visual testing, including checking for moisture content and quality control by assessing knots, grain bias, degree of cracking, rot, insect holes, and curvature of inaccessible structural members (EN 336; EN 13183-2; PN-D-94021).

Tests of supplied timber were carried out using the available testing equipment of the SAM 50 testing machine to verify data on the impact of the zone of the cross-section of raw timber from which the material was taken. For some structural components, this zone can translate into changes in performance characteristics.

Three primary zones were separated along the length of the log: the pith zone (A – heartwood, D – sapwood), the middle zone (B – heartwood, E – sapwood), and the mixed heartwood-sapwood top zone (C). It was evaluated how an increase in the severity of defects affects the material's strength. The last zone was excluded from the study due to the mixed proportion of heartwood and sapwood zones and the significant severity of knots.

The qualitative variation of lumber was determined by directly measuring the samples, considering defects in the anatomical structure. The research was conducted by subjecting the samples to comprehensive testing and visual analysis, measuring features along the length of the structural elements. Measurements and visual inspection of representative aspects of the pallet structure were carried out, measuring secondary defects, including cracks, and their intensity, size, and extent.

The study was completed by undertaking the following:

- analysis of the influence of the zone of the cross-section of round timber from which the wood was taken;
- analysis of the influence of this zone on the technical condition of the structural timber, through the evaluation of bending strength and modulus of elasticity;
- measurement of identified defects and damage during bending of solid wood and their effect on the mechanical properties of the wood.

1. Principles of solid wood sample preparation

The material for the study was solid pine wood in the form of rough lumber of undeclared strength. The timber consisted of sawn wood from a separated fresh forest habitat (LŚw class), Bolewice Forestry location 10-04-10. The mixed oak–beech–pine stand generated pine timber with a cutting age of 117 years, characterized by an average height of 27 m and an average breast height of 42 cm (data from the managing organization). For evaluating the delivered batches of lumber, the

Table 2. Markings of test batches of lumber

No.	Dimensional parameters mm	Batch designation	Cross-sectional zones			
			Top layer board		Bottom board	
			heartwood	sapwood	heartwood	sapwood
1	22x145x1200	Z145	A	D	B	E
2	22x100x1200	W100	A	D	B	E

principles of sorting by mechanical and visual methods were adopted (according to PN-D-94021, EN 338 and EN 14081-1. The structural elements of the top and bottom pallet boards were pretreated by drying to serviceable conditions, characterized by a moisture content of 22±3% in the material. The material was machined by longitudinal and transverse sawing to the assumed usable dimensions.

Selected dimensional batches of lumber for research purposes were labeled according to dimensional groups and zones of origin for the indicated types of lumber:

- 1200 mm length for cross-section 22 mm x 100 mm inner board, W100
- 1200 mm length for cross-section 22 mm x 145 mm outer board, Z145

Markings were made for each set of the test batch (Table 2).

Using the numbering adopted in the documentation, the individual elements were labeled correctly and subjected to qualitative evaluation based on the methodology for testing dominant features in the form of knots, fiber twists, desorption cracks and curvatures, and traces of insect feeding and rot.

2. Test methodology and measurements of lumber used in wooden pallets

According to the requirements used in the classification for solid structural timber in force at the time of the tests (PN-D-94021 and EN 14081), along with the current normative provisions (EN 13382), we describe the confirmation of strength parameters taking into account the obtained parameters of the softwood used.

Visual evaluation criteria for strength-graded structural timber according to PN-D-94021 and EN 14081-1 assigned to a strength class above C14 determine the maximum share of significant defects in the structure of lumber. The study focuses on the share of knots on the section, fiber twists, and cracks. These tests are analyzed based on moisture content at the time of sorting of the lumber intended for use, and the evaluation of the characteristics is carried out on a plane available for verification. In the review conducted for pine wood according to EN-338, where knots are present on the cross-section and in the marginal zone, cracks of a certain thickness of lumber and diagonal course of fibers are allowed.

3. Moisture content of wood

Moisture content testing was carried out in accordance with EN 13183-2. The moisture content of solid pine wood was determined as the average value of the individual moisture contents of the test samples (three measurement points along the length of each of 10 pieces of lumber) in a given sample. The Tanel (TANEL Elektronika i Informatyka Spółka Jawna, Poland) moisture meter type HIT-3, purchased in the course of the project, was used to obtain direct reading values of individual measurements to determine the moisture content of the test material. All test results presented in the paper were converted to values corresponding to a moisture content of 12%.

4. Mechanical properties of the tested pine lumber

Measurements of the mechanical properties of the tested material were carried out on an SAM 50 testing machine and measuring apparatus. Testing of the modulus of elasticity under bending, bending strength, and destructive force under bending were carried out according to EN 380 and EN 408. The tests were carried out with the lumber in flat position, where the thickness of the board is the height of the test piece (preserving the natural direction of loads in the elements of the pallet structure). The displacement during loading was 3.96 mm/minute (the loading head's speed of movement should not be greater than (0.003 h) mm/s).

5. Modulus of elasticity in bending

The static bending modulus test was performed with an increasing load in four-point bending until the proportional limit was reached. The deflection arrow was determined using a dial gauge with an accuracy of 0.01 mm at a thrust spacing equal to 1/3 of the support spacing.

The test procedure for the elasticity coefficient for the 4-point method in bending along the fibers corresponded to the provisions of EN 408. The thrust was placed symmetrically between the supports, with the value of the loading force increased in steps of 100 N. Preloading of the specimen was omitted.

During subsequent tests of solid specimens, the modulus of elasticity in bending was determined based on the formula [1]:

$$E_{gw} = \frac{3(P_{n+1}-P_n)l^3}{64bh^3(f_{n+1}-f_n)}\ [\mathrm{MPa}] \tag{1}$$

where:
$P_{n+1} - P_n$ is the difference between successive loads [N],
$f_{n+1} - f_n$ refers to the deflection arrows corresponding to successive load increments [mm],
l is the distance between centers of supports [mm],
b is the width of the specimen [mm],
h is the height of the specimen [mm].

To convert the value of the elastic modulus E_w of the tested samples with different absolute moisture content *w* to the so-called reference value (for samples with normative moisture content $w = 12\%$), the conversion formula given in PN-63/D-04117 [2] was used:

$$E = E_w\left(1+\alpha\left(w-12\right)\right) \tag{2}$$

where:
E_W is the modulus of elasticity at moisture content *w* [N/mm^2],
α is a conversion factor, $\alpha = 0.02$ (according to PN-63/D-04117),
w is the absolute moisture content of the sample [%].

According to literature sources, pine wood's bending strength and bending modulus of elasticity with a moisture content (m.c.) of about 12% are 75–87 MPa and 12 GPa [Mielczarek, 1994; Krzysik, 1974]. Studies indicate that small samples, free of defects, give much higher results than large samples, which contain a quantity of defects that is acceptable in construction lumber.

6. Strength classification of structural elements made of Scots pine wood

According to the guidelines of EN 338, the strength classification of structural timber is based on three indices: modulus of elasticity, bending strength, and the density of the tested wood. The values of other properties can be read from the table provided in EN 338. The present work provides a determination of selected values of the listed characteristics of wood by a laboratory method. However, the provisions of the indicated standard and other related standards suggest that the strength classification of structural timber is based on a comparison of the so-called "characteristic values" of the listed characteristics with standard values. The characteristic values on which such an assessment can be made for solid wood are presented in abbreviated form in EN 338 and EN 384. The typical value for bending strength and density is based on the statistical distribution of the results obtained and is the value of the 5% quantile of a given sample. In turn, the characteristic value for the modulus of elasticity is the average value from the sample [Krzosek, 2009; Pajchrowski et al., 2009]. The exact method of determining typical values is described in EN 384. A strength classification based on the expressed distinct values would lead to the assignment of a strength class C, corresponding to relatively low results from a given test (5% quantile). Such a classification implies a significant detriment to the actual properties of the entire population of samples in a given trial. One method of strength selection is to group all samples by visual sorting. The principle of optical sorting is to carefully visually inspect each piece of lumber and assign it to a specific class based on the defects present in the wood's anatomical structure, its shape, and processing [Krzosek, 1998; Szukała and Szumiński, 2003; Dzbeński, 2005]. Because of the prior labeling of all samples obtained from three different locations on the cross-section of the log, it will be possible to later identify the origin of a given sample assigned to a sorting class. The adopted methodology also made it possible to compare the properties of the tested pine elements based on laboratory test results with the results of the classification carried out by the visual method.

All test equipment met the following requirements:

- when designing the test equipment, the tolerances for all dimensions did not exceed ± 2%;
- the accuracy of the test equipment was ± 0.5 mm;
- the accuracy of the position of each component, excluding the test load, was ± 2 m; the measuring instruments were positioned to an accuracy of to ± 4 mm;
- the accuracy of the position of the center of application of the test load was within ± 3% of the recommended value.

Results and discussion

The tested pine wood (*Pinus sylvestris* L.) elements, part of the pine raw material sample, were analyzed based on the adopted procedure for testing pallet elements. Various qualitative and strength characteristics were determined for the tested elements. Visual examination of the boards did not reveal the presence of desorption cracks, rot, or insect holes. In the examined elements in the plane of the lumber, elements were shown to have limitations in terms of the proportion of knots on the cross-section.

Table 3. Summary of average physical properties for wooden elements from pine (*Pinus sylvestris* L.) lumber Z145

Properties	Batch of lumber							
	A		B		D		E	
	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]
MIN	6.3	470	6.3	386	6.6	544	6.7	412
5% quantile	6.5	470	6.4	389	6.7	546	6.8	413
MEAN	7.7	552	7.6	472	8.5	571	8.35	499
MAX	9.8	638	8.5	629	9.7	649	9.6	645
SD	1.1	48	0.7	53	0.9	25	0.7	67

* Calculation for 12% moisture content

Table 4. Summary of average physical properties for Z145 pine (*Pinus sylvestris* L.) lumber, with separation of zones along the length of the log

Properties	Batch of lumber			
	A/D		B/E	
	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]
MIN	6.3	470	6.3	386
5% quantile	6.5	470	6.4	389
MEAN	8.1	565	8.0	491
MAX	9.8	648	9.6	645
SD	1.1	40	0.7	63

* Calculation for 12% moisture content

Table 5. Summary of average physical properties for pine (*Pinus sylvestris* L.) lumber W100

Properties	Batch of lumber							
	A		B		D		E	
	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]	Moisture m.c. [%]	Density* ρ [kg/m³]
MIN	6.2	470	6.3	425	6.1	511	6.1	406
5% quantile	6.2	470	6.4	427	6.2	515	6.1	407
MEAN	**7.1**	**553**	**7.5**	**497**	**7.5**	**554**	**7.4**	**529**
MAX	8.6	643	8.7	602	9.2	609	8.9	609
SD	0.6	51	0.6	52	0.8	28	0.8	45

* Calculation for 12% moisture content

The results obtained for physical properties of lumber of 145 mm width are presented in Tables 3 and 4, and those for lumber of 100 mm width in Tables 5 and 6.

The measured physical properties confirm the variability of lumber density depending on the zone within the roundwood. The average density of heartwood (Table 3) in the case of raw material for the top layer (550 kg/m³) is similar to the density obtained for the sapwood zone (570 kg/m³). This is due to the identical location of the assortments harvested, the larger cross-sectional dimensions of the sawn roundwood, and the required usable width of the semi-finished

Table 6. Summary of average physical properties for W100 pine (*Pinus sylvestris* L.) lumber elements with separation of zones along the length of the log

Properties	Batch of lumber			
	A/D		B/E	
	Moisture m.c. [%]	**Density*** ρ [kg/m^3]	**Moisture** m.c. [%]	**Density*** ρ [kg/m^3]
MIN	6.2	470	6.1	406
5% quantile	**6.2**	**470**	**6.1**	**407**
MEAN	**7.3**	**554**	**7.4**	**513**
MAX	9.2	643	8.9	608
SD	0.7	41	0.7	50

* Calculation for 12% moisture content

products obtained. As expected, the density index for wood in the near-edge zone is higher than that of the heartwood zone. The density values, both average and maximum, for pine wood are relatively high and correspond to grades C50, C30, C50, and C35, respectively for zones A, B, D, and E. The characteristic value describing the assumed mechanical properties is the 5% quantile, for which the sample densities correspond to the values determined by the average density. These values are significantly higher than those reported in the literature [Kharrat et al., 2019; Roszyk et al., 2020].

In a general analysis of the density distribution of the tested lumber, a high average density of 560 kg/m^3 was found for the wood of the upper layer zone. The average density of pine lumber from the lower zone has a value around 490 kg/m^3 (Table 4). The density values for pine lumber, both average and 5% quantile, qualify the raw material for the C50 class. The middle zone of the raw material, heartwood lumber, is placed in class C30 due to the lower 5% quantile of density. The lumber destined for the bottom plane zone of the pallet has average properties that allow the wood to be assigned a strength class of C40. Of course, physical properties can only give a small indication of the actual strength of the tested wood [Šilinskas et al., 2020].

The measured physical properties of the tested W100 lumber with dimensions of 22 x 100 x 1200 mm (Table 5) confirm the tendency of the raw material to vary in density depending on the zone of the cross-section of round logs, similarly as in the previous series. The average density of heartwood for the raw material of the top boards was 560 kg/m^3, while the density for the near-edge zone was slightly lower at 550 kg/m^3. The peripheral zone of the cross-section of sawn roundwood exhibits similar densities of 530–550 kg/m^3. The density index for the wood of the peripheral zone is higher than that for the heartwood zone, excluding the top plane. The average and characteristic density values of pine wood are relatively high and correspond to grades C50, C35, C30, C50, and C35, respectively for zones A, B, C, D, and E. This trend is consistent with the assumption of a change in juvenile wood proportion in coniferous species, especially in pine wood [Irby et al., 2020; Garbachevski et al., 2022].

In a joint analysis of the density distribution for the lumber tested (Table 6), a high average density of 560 kg/m^3 of the wood of the upper pallet plane zone was obtained. This result is consistent with that for wood of the 22 x 145 x 1200 mm sample for the same zone. The average density of the raw material of the bottom layer has similar minimum values of about 410 kg/m^3. The density values, both average and 5% quantile, qualify the raw material of the upper layer for the C50 class. The middle zone corresponds to the C35 class due to the lower 5% quantile of density.

1. Mechanical properties of the tested wood

The results of the fundamental strength tests presented in this paper characterize the variability and, simultaneously, the quality potential of the pine raw material. The values obtained represent the modulus of elasticity and bending strength of the tested material of Z145 lumber with dimensions 22 x 145 x 1200 mm and W100 with dimensions 22 x 100 x 1200 mm (Tables 7–10).

In comparative studies for technical evaluation of pine (*Pinus sylvestris* L.) raw material, the characteristic values of the elastic modulus and the bending strength index alone were used as criteria (Table 7). In the analyzed batch (EN 338) of pine material with dimensions of 22 x 145 x 1200 mm, high strengths were indicated for the sapwood of the pith zone, reaching C35 grade, and comparable strength properties (C20) were obtained for the wood of the top zone and the sapwood of the middle zone part of the tested logs. The weakest was the heartwood material of the pith zone (C14) and middle zone (C16). Non-destructive evaluation conditions, used to determine the elastic

Table 7. Summary of average strength properties for Z145 pine (*Pinus sylvestris* L.) lumber components

Batch of lumber	A		B		D		E	
	MOE*	**MOR***	**MOE***	**MOR***	**MOE***	**MOR***	**MOE***	**MOR***
	N/mm^2							
MIN	7 390	15.76	5 350	17.13	8 410	35.04	9 920	20.93
5% quantile	**7 390**	**15.76**	**5 350**	**17.13**	**8 410**	**35.04**	**9 920**	**20.93**
MEAN	12 950	36.68	11 420	34.08	13 170	55.45	13 140	44.98
MAX	17 240	82.27	15 050	58.22	15 180	84.46	15 870	77.37
SD	1 100	48	2 250	12.06	1 360	12.64	1 600	13.98

* Calculation for 12% moisture content

Table 8. Summary of average mechanical properties for Z145 pine (*Pinus sylvestris* L.) lumber elements with separation of zones along the length of the logs

Batch of lumber	A/D -		B/E -	
	MOE*	**MOR***	**MOE***	**MOR***
	N/mm^2			
MIN	7 390	15.76	5 350	17.13
5% quantile	**7 390**	**15.76**	**5 350**	**17.13**
MEAN	13 060	46.06	12 280	39.53
MAX	17 240	84.46	15 870	77.37
SD	2 380	17.19	2 110	14.02

* Calculation for 12% moisture content

Table 9. Summary of average strength properties for W100 pine (*Pinus sylvestris* L.) lumber disk elements

Batch of lumber	A		B		D		E	
	MOE*	**MOR***	**MOE***	**MOR***	**MOE***	**MOR***	**MOE***	**MOR***
	N/mm^2							
MIN	8 010	16.80	7 350	26.61	8 700	27.80	10 100	37.21
5% quantile	8 080	16.80	7 390	26.65	8 720	27.83	10 100	37.26
MEAN	12 220	44.72	10 750	45.51	13 550	56.00	14 270	66.67
MAX	20 620	70.54	13 620	75.38	15 960	92.62	16 600	114.05
SD	2 920	12.52	1 930	16.08	1 900	14.27	1 880	19.03

* Calculation for 12% moisture content

Table 10. Summary of average mechanical properties for W100 pine (*Pinus sylvestris* L.) lumber elements with separated zones along the length of the logs

Zone along the length of the logs	A/D – butt timber		B/E – middle timber	
	MOE*	**MOR***	**MOE***	**MOR***
	N/mm^2			
MIN	8 010	16.80	7 350	26.61
5% quantile	**8 080**	**16.80**	**7 390**	**26.65**
MEAN	12 880	50.36	12 210	56.09
MAX	20 620	92.62	16 600	114.05
SD	2 530	14.43	2 390	20.42

* Calculation for 12% moisture content

Table 11. Summary of the effect of knots on the strength index for Z145 elements

No.	A			B			D			E		
	Mechanical properties		Share of knot surfaces	Mechanical properties		Share of knot surfaces	Mechanical properties		Share of knot surfaces	Mechanical properties		Share of knot surfaces
	MOE*	MOR*		MOE*	MOR*		MOE*	MOR*		MOE*	MOR*	
	N/mm^2		%	N/mm^2		%	N/mm^2		%	N/mm^2		%
1	17 240	35.77	1.79	8 920	27.31	1.79	13 240	65.36	0.45	13 030	32.33	0.89
2	16 490	46.23	3.57	16 490	46.23	2.68	8 410	54.27	1.34	14 270	43.03	0.89
3	16 020	53.61	3.57	16 020	53.61	2.68	13 450	65.49	1.34	12 400	53.17	0.89
4	9 880	38.45	4.02	9 880	38.45	3.13	14 030	47.18	1.79	12 960	34.02	0.89
5	11 240	22.26	4.46	15 820	51.08	3.57	13 180	51.47	2.23	11 320	32.23	1.34
6	15 960	35.15	4.46	15 960	35.15	3.57	14 230	38.95	2.68	9 920	48.86	1.79
7	8 920	27.31	5.36	10 700	37.24	4.02	13 070	59.19	2.68	12 340	31.76	2.23
8	15 820	51.08	5.80	17 240	35.77	4.91	12 180	49.76	3.57	11 490	53.31	2.68
9	7 390	15.76	5.80	11 240	22.26	4.91	13 740	61.87	4.02	13 680	20.93	4.02
10	10 700	37.24	6.25	7 390	15.76	6.25	14 140	41.14	4.46	11 130	41.48	4.46
MEAN.	12 970	36.29	4.51	12 970	36.29	3.75	12 970	53.47	2.46	12 250	39.11	2.01
SD	3 500	11.50	1.28	3 500	11.50	1.25	1 630	9.00	1.22	1 240	10.10	1.27

* Calculation for 12% moisture content

Table 12. Summary of the effect of knots on the strength index for W100 elements

No.	A			B			D			E		
	Mechanical properties		**Share of knot surfaces**	**Mechanical properties**		**Share of knot surfaces**	**Mechanical properties**		**Share of knot surfaces**	**Mechanical properties**		**Share of knot surfaces**
	MOE*	**MOR***		**MOE***	**MOR***		**MOE***	**MOR***		**MOE***	**MOR***	
	N/mm^2		%	N/mm^2		%	N/mm^2		%	N/mm^2		%
1	11 560	44.43	2.78	12 600	66.62	0.00	14 170	72.75	0.00	14 680	64.68	0.00
2	10 880	38.63	2.78	11 400	27.27	0.00	12 500	56.33	0.00	12 920	76.20	0.00
3	10 850	39.15	3.70	11 100	26.65	2.78	8 720	43.12	0.00	10 100	37.26	1.85
4	8 690	45.59	3.70	11 700	75.38	2.78	12 120	45.39	0.00	14 480	59.42	1.85
5	11 350	40.22	3.70	9 300	55.17	3.70	15 300	54.03	2.78	11 210	70.50	2.78
6	10 070	36.78	4.63	7 720	31.79	4.63	13 120	52.35	2.78	13 180	43.46	2.78
7	9 480	16.80	7.41	9 300	46.09	4.63	13 380	43.21	2.78	12 500	57.52	2.78
8	11 210	36.08	8.33	11 000	35.83	4.63	12 340	45.64	2.78	15 610	56.46	2.78
9	20 620	38.71	8.33	8 700	47.74	4.63	13 350	48.64	2.78	14 050	69.68	3.70
10	8 080	25.75	16.67	9 900	26.97	8.33	9 220	27.83	3.70	12 010	43.89	3.70
MEAN.	11 280	36.21	6.20	10 270	43.95	3.61	12 420	48.93	1.76	13 070	57.91	2.22
SD	3 310	8.24	4.06	1 450	16.51	2.32	1 940	10.93	1.46	1 600	12.30	1.26

* Calculation for 12% moisture content

modulus parameter, caused the entire batch of sapwood to be graded C30, and the sapwood of the lower layer to be graded C35. The heartwood of the upper pallet zone was in the C24 class and the heartwood of the lower layer was in the C16 class. It is noticeable that there is a significant discrepancy between the verified strength and the modulus of elasticity of the tested raw material.

In the case of the exclusive analysis of the zones of origin of the tested sawn materials (Table 8), by far the lowest technical quality was confirmed for the wood of the upper layer (C14), where the strength characteristics of the wood to be used for both planes indicate the lower strength of the raw material [Mustefaga et al., 2019; Wieruszewski et al., 2022]. The negative influence of the wood of the central (heartwood) zone is significant in the batch of material tested [Durmaz et al., 2019].

In the study of the technical properties of the pine (*Pinus sylvestris* L.) raw material, the modulus of elasticity and the flexural strength were taken as the decisive indicators (Table 9). In the analyzed batch of pine material W100, with dimensions of 22 x 100 x 1200 mm, high strengths were indicated for sapwood E of the lower zone, reaching grade C35, and lower strength properties for batch D sapwood (C27) and batch B heartwood of the lower zone (C25). In the wood of the heartwood part of the upper zone of the tested sawn materials, the characteristic strengths corresponded to C16 (A). The experimental material of the heartwood part of the pith zone A and the middle zone D had an average strength at an equivalent level of about 42–45 N/mm^2. Non-destructive evaluation conditions, used to determine the elastic modulus parameter, caused the heartwood raw material and the entire batch of sapwood to be classified higher than C30. Only the heartwood of the middle zone would fall into the C22 class based on the elastic modulus assessment. A significant discrepancy between the verified strength and the modulus of elasticity of the tested raw material is confirmed [Fundova et al., 2019; Wieruszewski et al., 2022].

In measurement of the strength properties of lumber from different application zones (Table 10), by far the lowest technical quality was confirmed for the wood of the top layer of material (C16). A significant bending strength index was found for the wood of the bottom layer of the pallet (C24 grade). A leveling off of the average bending strength and, more importantly, the average modulus of elasticity (about 13 kN/mm^2) is evident. The average moduli caused the raw material to be graded from C30 for the top layer of wood to C24 for the bottom layer. Here, too, there is a noticeable negative effect on strength from defects in the central (heartwood) zone of lumber in the batch of material referred for testing, where this strength characteristic testifies to the lower strength of the tested raw material.

2. Evaluation of wood quality based on test results

As a result of the measurements and visual inspection of solid wood elements in the process of analyzing knots as additional factors affecting the strength of lumber, the variable correlation of the occurrence of significant quantities of knots with the mechanical properties of pine wood was confirmed [Roszyk et al., 2020]. This led to consideration of the permissible dimensional sections of knots, as defined in Polish subject standards PN-D-94021:2013, to assess their impact on the assignment to strength classes.

Proportions of knots occurring on critical sections of structural timber were measured and observed. Defects were identified and evaluated in the cross-section and length of the analyzed elements (Tables 11 and 12) using the strength evaluation system.

Significant decreases in strength were noted for both Z145 and W100 lumber as the proportion of area occupied by knots increased. For heartwood lumber from zones A and B (exception: batch 145), the decrease in strength was linear. The decrease averaged about 2.5 N/mm^2 per 1% increase in the proportion of knot area. An exceptional response was observed for B-core lumber in batch Z145, where the knot factor did not affect strength. A much stronger response in the form of decreased strength was observed for D and E sapwood lumber. Strength decreases in this layer of lumber reached about 5 N/mm^2 for a 1% increase in the proportion of knot area.

In the case of destructive testing, the vast majority of damage occurred in the knot or knot grouping zone. This reflects the direct effect of weakening of the lumber by irregularities in the structure of the tested wood, both in the form of the knot itself and the collapses around it. In the case of knotless zones, damage and delamination occurred most frequently at the boundary of annual growth, in the earlywood zone [Wieruszewski et al., 2022; Hong et al., 2014].

The study of the proportion of knots of various sizes and positions resulting from taking lumber from different parts of the cross-section and length of experimental timber pieces indicated a variable distribution of this feature and its influence on the strength indices. Visual assessment of the degree of influence of the severity of knots as the main factor affecting the strength of lumber corresponds to changes observed in laboratory tests (Figs. 2 and 3) [Lam et al., 2005; Lin et al., 2011; Wright et al., 2019; Mirski et al., 2021].

Tukey's HSD procedure was used to compare the parameters of Z145 lumber within the ANOVA data (Table 13). The f-ratio statistic is 5.44537, which means that there is an overall risk between baths with use. The Tukey HSD test shows differences in MOR between pairs A and D, B and D, and D and E. It is worth paying

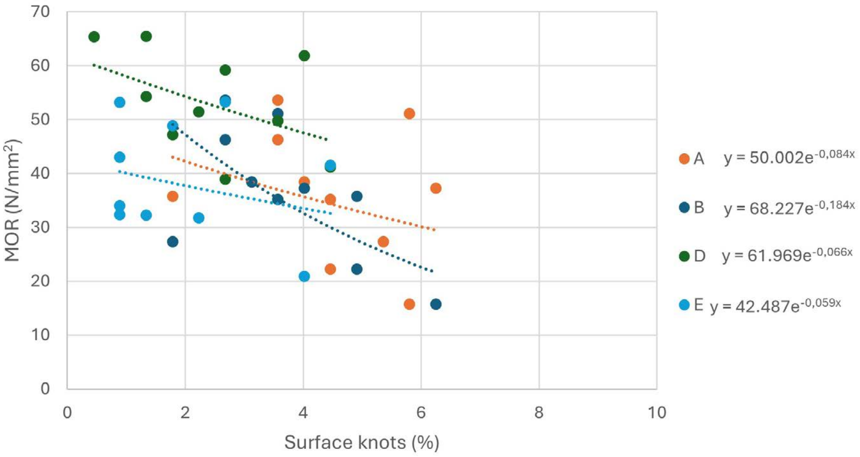


Fig. 2. Effect of knots on flexural strength for Z145

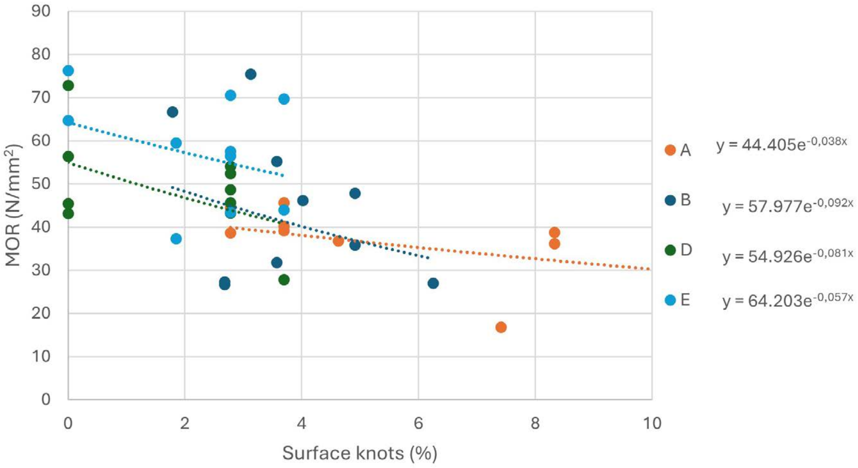


Fig. 3. Effect of knots on flexural strength for W100

Table 13. Post hoc Tukey HSD for Z145

Pairwise comparisons		$\mathbf{HSD_{.05} = 13.4307}$	$\mathbf{Q_{.05} = 3.8088}$
T_A:T_B	$A_A = 36.29$ $M_B = 36.29$	0.00	Q = 0.00
T_A:T_D	$M_A = 36.29$ $M_3 = 53.47$	17.18	Q = 4.87
T_A:T_E	$M_A = 36.29$ $M_E = 39.11$	2.83	Q = 0.80
T_B:T_D	$M_B = 36.29$ $M_D = 53.47$	17.18	Q = 4.87
T_B:T_E	$M_B = 36.29$ $M_E = 39.11$	2.83	Q = 0.80
T_D:T_E	$M_D = 53.47$ $M_E = 39.11$	14.36	Q = 4.07

Table 14. Post hoc Tukey HSD for W100

Pairwise comparisons		**$HSD_{.05}$ = 15.6962**	**$Q_{.05}$ = 3.8088**
T_A:T_B	M_A = 36.21 M_B = 43.95	7.74	Q = 1.88
T_A:T_D	M_A = 36.21 M_D = 48.93	12.72	Q = 3.09
T_A:T_E	M_A = 36.21 M_E = 57.91	21.69	Q = 5.26
T_B:T_D	M_B = 43.95 M_D = 48.93	4.98	Q = 1.21
T_B:T_E	M_B = 43.95 M_E = 57.91	13.96	Q = 3.39
T_D:T_E	M_D = 48.93 M_E = 57.91	8.98	Q = 2.18

attention to the result of the evaluation of the result equivalent to F of the required level of significance. The p-value is 0.003424. The result is significant at $p < 0.05$.

Tukey's HSD procedure within the ANOVA data for the f-ratio value of 4.869 from the W100 sample confirms the p-value to be 0.006063. The result is significant at $p < 0.05$. The F statistic indicates an overall difference between the means of samples A and E. The test result reached the level of significance (Table 14).

Conclusions

A detailed analysis of the range of strength values and effects of the severity of defects that occur in selected timber for the construction of wooden packaging is presented in the results, based on destructive testing and laboratory measurements. Through direct measurements of physical and mechanical properties of structural timber, the results confirmed the changes in properties of wood due to the zone of the cross-section of the raw material from which it was taken.

In conclusion, concerning the quality of lumber used as structural elements of solid wood packaging, the following final general statements can be made.

Detailed tests and measurements of physical properties confirm the high density of pine (*Pinus sylvestris* L.) wood from the studied habitat of fresh mesquite forest. For some of the structural elements, access to specific habitats can translate into changes in performance characteristics. The magnitudes of the studied parameter vary significantly between zones on the cross-section. This influence is significant due to the use in construction of lumber from near-edge zones with substantially higher density and, often associated with this, higher expected strength parameters. The average density of pine lumber exceeded 470 to 570 kg/m^3, which would cause this material to be graded from C30 up to the maximum C50. However, the density of the lumber is not a critical parameter determining the potential technical performance of the wood.

A study of available and separated structural lumber for the construction of wood packaging confirmed significant differences in the technical condition of the wood, resulting from its different origins on the wood cross-section. Strengths in the C14–C16 classes (EN 338) were found for core lumber, while sapwood lumber reached the highest strengths, from C30 to C35.

Analyses and measurements of the influence of the extent of knots confirmed the decline in the technical condition of lumber for solid wood elements in the examined batch of material. The degree of influence of the proportion of knots is particularly significant in sapwood, where, according to the detected trend, an increase of 1% in the proportion of knot area causes a decrease in flexural strength of about 5 N/mm^2. In the case of cored lumber, the reduction in strength on bending corresponding to an increase in the share of knot area is half as much, and at the same time, the average surface share of knots reaches a maximum of 8%.

Solid wood elements used for the construction of transport pallets require the introduction of grading. The selection of lumber to adequately strengthen the structure of pallet layers should be based on calculations according to the loads to be carried [Zhu et al., 2022].

The necessity of sorting the raw material becomes evident in evaluating the selection of quality and strength of the obtained sawn materials to be used in the production of wooden packaging [Hoefnagels et al., 2014]. The use of pine wood guarantees an improvement in the strength and reinforcement of the structural elements of wooden packaging, taking into account both the origin within the cross-section and the distribution of knots in the lumber.

This study tested flat wooden pallets, meeting and exceeding the requirements of EN ISO 8611-1 for compressive strength. The adjustment of quality and strength to the individual layers is due to the origin of the raw material within the cross-sectional area and the zones along the length of the timber logs. This is conducive to improving the cycle of use of the wood product [Kvočka et al., 2020].

References

Biebl, S., Querner, P. [2020]: Transportation of Wood Boring Beetles in Wooden Transport Boxes, Wooden Pallets, and Newly Bought Wood in Museums. Studies in Conservation, 1–7. doi:10.1080/00393630.2020.1756126

Buehlmann, U., Bumgardner, M., Fluharty, T. [2009]: Ban on landfilling of wooden pallets in North Carolina: an assessment of recycling and industry capacity. Journal of Cleaner Production 17[2], 271-275. https://doi.org/10.1016/j.jclepro.2008.06.002

Clayton, A. P., Horvath, L., Bouldin, J., Gething, B. [2019]: Investigation of the effect of column stacked corrugated boxes on load bridging using partial four-way stringer class wooden pallets. Packaging Technology and Science. doi:10.1002/pts.2438

Deviatkin, I., Horttanainen, M. [2020]: Carbon footprint of an EUR-sized wooden and a plastic pallet. E3S Web of Conferences, 158, 03001. doi:10.1051/e3sconf/202015803001

Deviatkin, I., Khan, M., Ernst, E., Horttanainen, M. [2019]: Wooden and Plastic Pallets: A Review of Life Cycle Assessment [LCA) Studies. Sustainability 2019, 11, 5750. https://doi.org/10.3390/su11205750

Dixon-Hardy, D. W., Curran, B. A. [2009]:. Types of packaging waste from secondary sources [supermarkets) – The situation in the UK. Waste Management, 29[3], 1198–1207. doi:10.1016/j.wasman.2008.06.045

Dunno, Kyle and Symanski, Maria [2021]: Evaluation of stretch film behavior during long-term storage under different atmospheric conditions. Journal of Applied Packaging Research 13 [1], 3. https://scholarworks.rit.edu/japr/vol13/iss1/3

Durmaz, E., Ucuncu, T., Karamanoglu, M., Kaymakcı, A. [2019]: Effects of heat treatment on some characteristics of Scots pine (*Pinus sylvestris* L.) wood. BioResources 14[4], 9531-9543. DOI: 10.15376/biores.14.4.9531-9543

Dzbeński, W., Kozakiewicz, K., Krzosek, S. [2005]: Wytrzymałościowe sortowanie tarcicy budowlano-konstrukcyjnej. Warszawa.

EN - ISO 8611-1:2022: Pallets for moving loads – Flat pallets - Part 1: Test methods.

EN ISO 13119:2022: Roundwood and sawn timber. Methods for measuring biological degradation.

EN 13183-2:2002/AC:2003: Moisture content of lumber - Part 2: Determination of moisture content using an electric resistance moisture meter.

EN 13382:2002: Flat cargo pallets – Basic parameters.

EN 14081-1:2016+A1:2019: Wooden structures – Strength-graded rectangular structural timber – Part 1: General requirements.

EN 15228; 2009: Structural wood - Structural wood protected against biological corrosion.

EN 336:2013: Structural wood - Dimensions, allowable deviations.

EN 338:2016: Structural wood - Strength classes.

EN 350-1; 2000: Durability of wood and wood-based materials – Natural durability of solid wood – Guidelines on the principles of testing and classifying the natural durability of wood.

EN 350-2; 2000: Durability of wood and wood-based materials – Natural durability of solid wood – Guidelines on the natural durability and susceptibility to saturation of selected wood species of importance in Europe.

EN 380:1993: Wooden structures – Test methods – General principles of tests under static load.

EN 384:2016+A2:2022: Structural wood – Determination of the values of characteristic mechanical properties and density.

EN 408:2012: Wooden structures – Solid and glued structural timber – Determination of certain physical and mechanical properties.

Fundova, I.; Funda, T.; Wu, H.X. [2019]: Non-Destructive Assessment of Wood Stiffness in Scots Pine (*Pinus sylvestris* L.) and its Use in Forest Tree Improvement. Forests 10, 491. https://doi.org/10.3390/f10060491

Garbachevski, É. M., Hillig, E., Abreu Neto, R. D., Retslaff, F. A. D. S., Koehler, H. S. [2022]: Physico-mechanical properties and growth characteristics of pine juvenile wood as a function of age and planting spacing. Revista Árvore 46. https://doi.org/10.1590/1806-908820220000027

García-Durañona, L., Farreny, R., Navarro, P., Boschmonart-Rives, J. [2016]: Life Cycle Assessment of a coniferous wood supply chain for pallet production in Catalonia, Spain. Journal of Cleaner Production 137, 178–188. doi:10.1016/j.jclepro.2016.07.032

Hellström, D. Nilsson, F. [2011]: Logistics-driven packaging innovation: a case study at IKEA. International Journal of Retail & Distribution Management 39 [9], 638-657. https://doi.org/10.1108/09590551111159323

Hoefnagels, R., Junginger, M., Faaij, A. [2014]: The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S. Biomass and Bioenergy 71, 443–454. doi:10.1016/j.biombioe.2014.09.00

Ho**ng, Z.; Fries, A.; Wu, H. [2014]**: High negative genetic correlations between growth traits and wood properties suggest incorporating multiple traits selection including economic weights for the future Scots pine breeding programs. Ann. For. Sci. 71, 463–472. https://doi.org/10.1007/s13595-014-0359-3

International Organization for Standardization. ISO Standard No. 8611-1:2011. Pallets for Materials Handling-Flat Pallets-Part 1: Test Methods. International Organization for Standardization: Geneva, Switzerland, 2011

Irby N. E., França F. J. N., Barnes H. M., Seale R. D., Shmulsky R. [2020]: Effect of growth rings per inch and density on compression parallel to grain in southern pine lumber. BioResources 15[2], 2310-2325. https://doi:10.15376/biores.15.2.2310-2325.

Iždinský, J.; Reinprecht, L.; Vidholdová, Z. [2021]: Particleboards from Recycled Pallets. Forests 12, 1597. https://doi.org/10.3390/f12111597

Jedlinski, M., Sowa, M. [2021]: The concept of the "Reverse Iceberg-RIB" in the application of account of total cost of ownership for a reusable wooden flat pallet in its operating phase. European Research Studies Journal 24[4], 199-210. https://www.um.edu.mt/library/oar/handle/123456789/84121

Karaçalı, Ö., & Taner Ulguel, A. [2014]: Finite Element Analysis of Pallet-Nail Materials Used in Pallet Joint Design for Material Handling Works. Acta Physica Polonica A 125[2], 183–185. doi:10.12693/aphyspola.125.183

Khan, M.H., Deviatkin, I., Havukainen, J. et al. [2021]: Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. Int J Life Cycle Assess 26, 1607–1622. https://doi.org/10.1007/s11367-021-01953-7

Kharrat, W.; Koubaa, A.; Khlif, M.; Bradai, C. [2019]: Intra-Ring Wood Density and Dynamic Modulus of Elasticity Profiles for Black Spruce and Jack Pine from X-Ray Densitometry and Ultrasonic Wave Velocity Measurement. Forests 10, 569. https://doi.org/10.3390/f10070569

Kozakiewicz, P.; Jankowska, A.; Mamiński, M.; Marciszewska, K.; Ciurzycki, W.; Tulik, M. [2020]: The Wood of Scots Pine (Pinus sylvestris L.) from Post-Agricultural Lands Has Suitable Properties for the Timber Industry. Forests, 11, 1033. https://doi.org/10.3390/f11101033

Krzosek, S. [1998a]. Wytrzymałościowe sortowanie tarcicy konstrukcyjnej, Lekkie Budownictwo Szkieletowe 4, 10–11.

Krzosek, S. [1998b]: Badanie gęstości jako kryterium wytrzymałościowej jakości iglastej tarcicy konstrukcyjnej. Rozprawa doktorska Wydział Technologii Drewna SGGW, Warszawa 1998.

Krzosek, S. [2009]: Wytrzymałościowe sortowanie polskiej, sosnowej tarcicy konstrukcyjnej różnymi metodami. Wydawnictwo SGGW, Warszawa.

Krzysik F. [1974]: Nauka o drewnie. PWN, Warszawa.

Kvočka, D.; Lešek, A.; Knez, F.; Ducman, V.; Panizza, M.; Tsoutis, C.; Bernardi, A. [2020]: Life Cycle Assessment of Prefabricated Geopolymeric Façade Cladding Panels Made from Large Fractions of Recycled Construction and Demolition Waste. Materials 13, 3931. https://doi.org/10.3390/ma13183931

Lam, F., Barrett, J. D., and Nakajima, S. [2005]: Influence of knot area ratio on the bending strength of Canadian Douglas fir timber used in Japanese post and beam housing," Journal of Wood Science 51[1], 18-25. DOI: 10.1007/s10086-003-0619-6

Landendorf G. [1983]: Holzvergütung. VEB Fachbuchverlag, Leipzig.

Lin, W., Wang, J., and Sharma, B. [2011]: Development of an optimal three-dimensional visualization system for rough lumber edging and trimming in central Appalachia, Forest Products Journal 61[5], 401-410. DOI: 10.13073/0015-7473-61.5.401

Masis, J.; Horvath, L.; Böröcz, P. [2022]: The Effect of Forklift Type, Pallet Design, Entry Speed, and Top Load on the Horizontal Shock Impacts Exerted during the Interactions between Pallet and Forklift. Appl. Sci. 12, 7035. https://doi.org/10.3390/app12147035

McKeever, D. B., McCurdy, D. R., Kung, F. H., & Ewers, J. T. [1986]: Wood used in pallets manufactured in the United States, 1982. US Department of Agriculture, Forest Service, Forest Products Laboratory.

Mielczarek, Z. [1997]: Budownictwo drewniane. Arkady. Warszawa

Mirski, R., Wieruszewski, M., Trociński, A., Kawalerczyk, J., & Łabęda, K. [2021]: Elastic moduli of butt-end logs and the variable knots distribution in Scots pine from Western Poland. BioResources 16[1], 1842. DOI: 10.15376/biores.16.1.1842-1853

Mustefaga, E. C., Hillig, É., Tavares, E. L., Sozim, P. C. L., Rusch, F. [2019]: Caracterização físico-mecânica da madeira juvenil de Pinus. Physico-mechanical characterization of pine juvenile wood. Scientia Forestalis 47[123], 472-481. doi.org/10.18671/scifor.v47n123.09

Pajchrowski, G. Jabłoński, L., Szumiński, G. [2009]: Krajowa baza drewna tartacznego do produkcji drewna konstrukcyjnego spełniającego wymagania wynikające z Dyrektywy na wyroby budowlane (89/106/EEC). ETAP VII. Analiza kierunków rozwoju urządzeń do wytrzymałościowej klasyfikacji drewna konstrukcyjnego. Instytut Technologii Drewna, Zakład Badania i Zastosowania Drewna, Poznań.

Patricio, M.Á., Maravall, D. [**2003**]: Automatic Visual Inspection of Wooden Pallets. In: Chung, P.W.H., Hinde, C., Ali, M. (eds) Developments in Applied Artificial Intelligence. IEA/AIE 2003. Lecture Notes in Computer Science 2718. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-45034-3_28

PN-63/D-04117 Fizyczne i mechaniczne własności drewna - Oznaczanie współczynnika sprężystości przy zginaniu statycznym (Physical and mechanical properties of wood – Determination of the coefficient of elasticity under static bending).

PN-66/D-01000: Wady drewna (Wood defects).

PN-D-94021:2013-10: Tarcica konstrukcyjna iglasta sortowana metodami wytrzymałościowymi (Coniferous structural lumber sorted using strength methods).

Ponis, S.T.; Efthymiou, O.K. [**2020**]: Cloud and IoT Applications in Material Handling Automation and Intralogistics. Logistics 4, 22. https://doi.org/10.3390/logistics4030022

Roszyk, E., Mania, P., Iwańska, E., Kusiak, W., Broda, M. [**2020**]: Mechanical performance of Scots pine wood from northwestern Poland–A case study. BioResources 15[3], 6781-6794.

Šilinskas, **B.; Varnagirytė-Kabašinskienė, I.; Aleinikovas, M.; Beniušienė, L.; Aleinikovienė, J.; Škėma, M.** [**2020**]: Scots Pine and Norway Spruce Wood Properties at Sites with Different Stand Densities. Forests 11, 587. https://doi.org/10.3390/f11050587

Song, D. A [**2021**]: Literature Review, Container Shipping Supply Chain: Planning Problems and Research Opportunities. Logistics 5, 41. https://doi.org/10.3390/logistics5020041

Szczuka J., Żurowski J. [**1999**]: Materiałoznawstwo przemysłu drzewnego. Warszawa

Szukała, R., Szumiński, G. [**2003**]: Badanie podstawowych właściwości iglastej tarcicy konstrukcyjnej zgodnie z normami europejskimi. ITD, Poznań 2003.

Tornese, F.; Gnoni, M.G.; Thorn, B.K.; Carrano, A.L.; Pazour, J.A. [**2021**]: Management and Logistics of Returnable Transport Items: A Review Analysis on the Pallet Supply Chain. Sustainability 13, 12747. https://doi.org/10.3390/su132212747

Trevisani, A., Iaccheri, E., Fabbri, A., & Guarnieri, A. [**2014**]: Pallet standards in agri-food sector: a brief survey. Journal of Agricultural Engineering 45[2], 90. doi:10.4081/jae.2014.220

Vendl, T., Stejskal, V., Kadlec, J., & Aulicky, R. [**2021**]: New approach for evaluating the repellent activity of essential oils against storage pests using a miniaturized model of stored-commodity packaging and a wooden transport pallet. Industrial Crops and Products 172, 114024. doi:10.1016/j.indcrop.2021.114024

Vlkovský, M., Malíšek, J., & Kutil, R. [**2021**]: Influence of Shocks on Pallet Load and Cargo Securing. Transportation Research Procedia 55, 50-56. https://doi.org/10.1016/j.trpro.2021.06.005

Waseem, A., Nawaz, A., Munir, N., Islam, B., & Noor, S. [**2013**]: Comparative analysis of different materials for pallet design using ANSYS. International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, 13[2], 26138002-6767.

Wdowiak-Postulak A. [**2021**]: Basalt Fibre Reinforcement of Bent Heterogeneous Glued Laminated Beams. Materials;14[1]:51. https://doi.org/10.3390/ma14010051.

Wdowiak-Postulak A. [**2022**]: Ductility, load capacity and bending stiffness of Scandinavian pine beams from waste timber strengthened with jute fibres. Drewno Prace Naukowe, Doniesienia, Komunikaty = Wood Research Papers, Reports, Announcements 65. https://doi.org/10.12841/wood.1644-3985.417.01.

Wdowiak-Postulak A, Bahleda F, Prokop J. [**2023**]: An Experimental and Numerical Analysis of Glued Laminated Beams Strengthened by Pre-Stressed Basalt Fibre-Reinforced Polymer Bars. Materials;16:2776. https://doi.org/10.3390/ma16072776.

Wdowiak-Postulak A, Świt G, Dziedzic-Jagocka I. [**2024**]. Application of Composite Bars in Wooden, Full-Scale, Innovative Engineering Products—Experimental and Numerical Study. Materials 17, 730. https://doi.org/10.3390/ma17030730.

Wieruszewski, M.; Trociński, A.; Kawalerczyk, J.; Derkowski, A.; Mirski, R. [**2022**]: The Strength of Pine (*Pinus sylvestris* L.) Sawn Timber in Correlation with Selected Wood Defects. Materials *15*, 3974. https://doi.org/10.3390/ma15113974

Wright, S., Dahlen, J., Montes, C., and Eberhardt, T. L. [**2019**]: Quantifying knots by image analysis and modeling their effects on the mechanical properties of loblolly pine lumber, European Journal of Wood and Wood Products 77, 903-917. DOI:10.1007/s00107-019-01441-8

Zajac, P.; Dragasius, E.; Roik, T. [**2021**]: Energy Consumption When Transporting Pallet Loads Using a Forklift with an Anti Slip Pad Preventing Damage. Energies 14, 8423. https://doi.org/10.3390/en14248423

Zhu, X., Toyota, H., Ito, D., & Doi, K. [**2022**]: Structural Design for Improving the Strength of Flat Wooden Pallets. In Journal of Physics: Conference Series 2287[1], 012043. https://doi.org/10.1088/1742-6596/2287/1/012043

This research was supported by Research Project No. 1/0103/2024 of the Slovak Grant Agency.