INTERDISCIPLINARY DOCTORAL SCHOOL

Faculty of Furniture Design and Wood Engineering

Iulia-Teodora DEACONU

Researches regarding the drying behaviour of Turkey oak (*Quercus cerris* L.) lumber

SUMMARY

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BRAȘOV, 2025

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INTRODUCTION

Drying oak wood has always been a challenge for the industry because it is is a high-density wood species with an inhomogeneous structure, characterized by annular pores, which develop high internal stresses during drying, making them prone to cracking. Even when mild drying conditions are applied, cracking is common, especially in thick varieties.

The novelty and relevance of this doctoral thesis lie in investigating a less studied species of oak, namely the European oak (*Quercus cerris* L.) to find solutions for its superior valorization. Currently, European oak is mainly used as firewood, despite being a high-density and durable wood with a distinctive appearance. Based on these premises, this research focuses on optimizing the drying process of this species, specifically on establishing drying schedules that both minimize defects and reduce drying time.

In Romania, oaks cover about 18% of the total forested area (source: https://www.qdidactic.com/bani-cariera/agricultura /silvicultura/specii-foioase-autohtone-fagul-cvercineele-castanul-557.php). The oak species found in Romanian forests include: the pedunculate oak (*Quercus robur* L.); the sessile oak (*Quercus petraea* (Matt.) Liebl.); the Turkey oak (*Quercus cerris* L.*)*; the Hungarian oak (*Quercus frainetto* Ten.); the downy oak (*Quercus pubescens* Willd); the red oak (*Quercus rubra* L.); and *Quercus pedunculiflora* (K.Koch) Menitski).

The oak species found in Romanian forests include: the pedunculate oak (Quercus *robur* L.); the Sessile oak (*Quercus petraea* (Matt.) Liebl.); the Turkey Oak (*Quercus cerris* L.*)*; the Hungarian oak (*Quercus frainetto* Ten.); the downy oak (Quercus *pubescens* Willd); the red oak (Quercus *rubra* L.) and Quercus *pedunculiflora* (K.Koch) Menitski.

Among these, the first three species are of industrial importance: Sessile oak represents approximately 10.8% of Romanian's total forested area, the Turkey Oak 2.9%, and the pedunculate oak 2.2%, (source: https://silvanews.ro/silvicultura/silvotehnica/cata-padure-mai-avem-romania/). The volume of wood harvested annually is approximately 2.2 million m^3 (source: https://insse.ro/cms/sites/default/files /field/publicatii/statistica_activ itatilor_din_silvicultura_in_anul_2022.pdf).

The wood of these species produces high-quality lumber, which, when properly dried, becomes a valuable raw material for furniture making, artistic woodworking, yacht construction, railway sleepers, as well as for building and interior design.

This underscores the economic significance and relevance of the topic, which aligns with the 2022-2027 National Research, Development and Innovation Plan, under the thematic priority "National areas of smart specialization" - a priority focused on strengthening research and innovation to better meet business needs (source: https://www.mcid.gov.ro/wp-content/uploads/2022/12/hg-aprobare-pncdi-iv.pdf).

CHAPTER 1. CURRENT STATUS OF RESEARCH ON THE STRUCTURAL FEATURES, PROPERTIES AND DRYING BEHAVIOR OF OAK WOOD

1.1 Oak wood – distribution area

The genus *Quercus* is the most important tree genus in the Northern Hemisphere. There are approximately 600 species belonging to this genus (Mabberley 2008), of which only four species are native to Central Europe: the pedunculate oak, the Sessile oak and the downy oak (Leuschner and Ellenberg 2017).

Pedunculate oak and Sessile oak have a wide distribution in Europe, ranging from southern countries to Scandinavia. The oak's range is more restricted, being concentrated in southern Europe and Asia Minor (De Rigo *et al* 2016), but it also includes countries such as England, Italy, Turkey, the Balkans and Lebanon (Stafasani and Toromani 2015; Najib *et al* 2021).

In Romania, it is difficult to delineate an exact distribution area for the pedunculate oak and the Sessile oak. These two species are widespread across the country, thriving in deciduous forests, on hills, and mountainous regions. The Turkey oak is widespread in the forest-steppe zone, particularly in the plains of Muntenia and Oltenia. In Transylvania and Banat, this species is found in the hilly areas. Additionally, it is also present in the Western Carpathians and southern Dobrogea.

1.2 Research on the structure, chemical composition and properties of oak species

1.2.1 Anatomical structure

According to the classification made by Richter and Dalwitz (2000), the Turkey oak belongs to the red oak group, with a reddish-brown-gray heartwood, while the pedunculate and Sessile oak belong to the white oak group, with a lighter, yellowish-brown heartwood.

According to Ghelmeziu's (1959) macroscopic identification key for woody species, both the Turkey oak and the pedunculate oak are hard deciduous species, with a complex and heterogeneous structure, characterized by annular pores and a sudden transition in pore size from earlywood to latewood.

The annual rings are clearly delineated, generally with a regular outline, showing a distinct difference between earlywood and latewood.

The medullary rays are clearly visible to the naked eye and come in two sizes: broad rays, easily noticeable, and narrow, fine rays, barely visible under a magnifying glass. On the radial section, they appear as wide, continuous, or interrupted, shiny bands ("mirrors") crossing the annual rings. On the tangential section, they appear as thick, dense, longitudinal lines, reaching up to 25 mm in length, though more commonly around 10 mm in the Turkey oak. In pedunculate oak, these lines can sometimes exceed 30 mm.

It exhibits apotracheal, fine woody parenchyma arranged in thin tangential rows, visible under a magnifying glass.

For Turkey oak, Manetti (2002) measured the ring width in 46 trees from five different regions in central and southern Italy, obtaining values of 2.2-2.9 mm for the first 15 years of growth. The ring width then decreased to 1.5-1.7 mm over the following 10 years.

For Turkey oak from four different locations in Hungary, Govina *et al* (2023) reported lower values, ranging from 1.1-1.6 mm in sapwood and 1.6-2.3 mm in heartwood. Even lower values were indicated by Nunes (2017), who studied the anatomical elements of Turkey oak from two regions in Kosovo, finding annual ring widths of 1.21-1.76 mm

Nunes (2017) also measured the pore diameter in latewood (72-73 μm) and earlywood (274-279 μm), obtaining an average value of 134–135 μm, slightly lower than those obtained by Carvalho (1997): 150-210 μm, for the same species. Govina *et al* (2023) determined the vessel diameter for Turkey oak from plantations located in the Vas region of western Hungary. His measurements were higher than those in the previously cited studies, reporting values of 111.44-236.87 μm in latewood and 307.31-448.74 μm in earlywood.

Microscopic images published by Merela and Cufar (2013) for the heartwood of Sessile oak and Turkey oak reveal a key anatomical difference between these two species: the vessel walls are thicker in Turkey oak wood.

1.2.2 Chemical composition

According to Holzatlas (2008), oak/alder wood is composed of cellulose (37.6…42.8%), lignin (24.9…34.3%) and hemicelluloses, with a total polysaccharide content (holocellulose) of 73.2…78.7%. In addition, oak wood also contains extractable substances, mainly tannins (3…13%) and ash (0.3…0.6). For alder wood, Fodor and Hofmann (2024) obtained the chemical composition presented in Table 1.1.

Table 1.1
Chemical composition of Turkey oak wood (mean value and standard deviation) (Fodor and Hofmann 2024)

	Holocellulose	**Hemicelluloses**	**Alpha-cellulose**	**Lignin**	**Extractable substances**
Sapwood	77.87 (0.08)	29.66 (0.95)	48,21 (0.87)	16.27 (0.23)	4.89 (0.09)
Heartwood	75.96 (1.91)	31.73 (4.65)	44,23 (2.74)	16.20 (1.60)	5.09 (0.11)

For heartwood, Bajraktari (2018) reported a total content of substances extractables of 6.7%. Stefasani *et al* (2018) analysed the extractable content of extractable substance using warm water on sawdust samples (50% sapwood, 50% heartwood), obtaining a value average of 7.03± 1.83%.

1.2.3 Physical and mechanical properties

By synthesizing values from specialized literature regarding physical and mechanical properties of Turkey oak, it can be concluded that:

- The density of Turkey oak heartwood is higher than the heartwood of the oak/alder, ranging from 720-870 kg/m^3, with an average of 802 kg/m^3 compared to pedunculate oak wood which has an anhydrous density of 390…650…930 kg/m^3 (Holzatlas 2008);
- Turkey oak shrinkage is greater than pedunculate oak/sessile oak wood, with volumetric shrinkage in the range of 16.0-19.2%, averaging 17.9% compared to oak which has a volumetric shrinkage coefficient of 12.6-15.6%;
- The fiber saturation point for oak heartwood is around 22% (Trendelenburg and Mayer-Wegelin, 1955). No data were found in the literature for Turkey oak wood;
- Regarding the anisotropy coefficient, the only source that provides data for oak wood is the Wood Database which indicates $\beta_t/\beta_{r,\,oak}$ = 1.7, lower than the values reported Holzatlas (2008) for oak wood ($\beta_t/\beta_{r,\,oak}$ = 1.95... 2.17);

Given its higher density, it is expected that Turkey oak wood will dry slowlier than oak wood. Higher shrinkage coefficients indicate a higher risk of cracks during drying. However, due to the lower shrinkage anisotropy of Turkey oak wood, it is possible that this species has lower deformability compared to oak wood.

1.3 Current state of research regarding dry oak wood

Wood drying aims to remove water from wood in order to reduce the wood moisture content to a value corresponding to practical conditions of use (for example: 10±2% for furniture and other interior products).

Oak wood is recognized as being among the most difficult European species to dry (*e.g.,* Cividini 2001, Denig *et al* 2000, Ferrari *et al* 2013, Hildebrand 1979, Janic 1965, Joyet and Meunier 1996, Marinescu 1979, Trübswetter 2006). This difficulty is due to its inhomogeneous structure and the large density variation characteristic of ring-porous deciduous species, where earlywood vessels are larger and more numerous and contain very few fibers. As a result, the wood develops high internal stresses during drying, which facilitates the formation of cracks (Câmpean and Lăzărescu 2016).

The main defects that may occur after wood drying, along with their causes and methods of prevention and remediation, include: non-uniform final moisture content, surface case-hardening, surface cracks (Fig.1.12, a), internal cracks (Fig.1.12, b), end cracks (Fig.1.12, c), deformations (Fig.1.12, d), lath stains (Fig.1.12, e), condensation stains (Fig. 1.12, f), other abnormal discolorations (Fig.1.12, g).

a.

b.

c.

d.

e.

f.

g.

h.

Fig.1.12 Drying defects. a- surface cracks; b- internal cracks; c- end cracks; d-deformations; e-lath stains; f- condensation stains (Trübswetter 2006);
g- metal reaction stains (Trübswetter 2006); h- enzymatic stains

Air drying, also called natural drying, is the oldest drying process, known and applied since antiquity. This process consists of stacking lumber properly outdoors or under open sheds, allowing the wind to remove moisture.

The final moisture content that wood can reach through natural drying depends on seasonal and climatic factors specific to the area, which determine the equilibrium moisture content. In Romania, considering annual averages, the equilibrium moisture content is 12-15%.

The duration of outdoor drying for hardwood species can exceed over three years (e.g., in the case of oak), as drying practically stagnates during the winter (November-March). For this reason, natural drying alone cannot be used to achieve the final required moisture content, except in warm climates.

In Europe and Romania, natural drying is mainly used as a pre-drying method (air seasoning), especially for dense hardwood species. Once moisture is reduced to a value close to the fiber saturation point, the stacks are transferred to drying facilities for artificial drying to achieve the desired final moisture content.

Kiln drying. To reduce storage time and overall drying duration artificial drying is widely used, including for oak species. Artificial drying can be performed from the fresh-cut (green) state. The main artificial drying methods include: conventional drying, dehumidification drying (condensation method), high temperature drying, vacuum drying in CIF and microwave drying (Câmpean 2002).

For various species of oak, the most effective drying methods is vacuum and superheated steam drying as they ensure a short duration and very good quality.

The tendency of wood to crack during drying has led to industry in its large-scale processing (Todaro *et al* 2012, Tolvaj *et al* 2016, Ferrari *et al* 2013). To reduce internal drying stresses, steaming has been tested (Todaro *et al* 2012). This heat treatment reduces wood hygroscopicity and evens out colour differences between heartwood and sapwood. The best results in reducing equilibrium moisture and colour uniformity were obtained when steaming was performed at 120°C for 18 hours. Steaming has a beneficial effect on drying, particularly for hardwoods, as it unclogs vessel pores, temporarily plasticizes the wood, facilitates water removal, and reduces the risk of cracking.

Ferrari *et.al.* (2013) applied a combined steaming and vacuum drying Turkey oak wood. Freshly cut logs were used as wood material. It is steamed at a temperature of 110°C and a pressure of 140 kPa for 24 h, then cooled for 5 days and sawn into lumber. The boards were fanned for 5 months, until a humidity of 20-25% was reached. Half of them were vacuum dried by pressing (Press Vacuum Plant), and the other half of the pieces were heat-treated in vacuum and superheated steam (through the Termovuoto® process). The press-dried boards remained stable (no warping), whereas the heat-treated boards darkened. Initial steaming significantly reduced equilibrium moisture content. The drying and treatment processes were carried out without defects, except for boards containing knots, which developed severe cracks along their entire length.

Since vacuum drying is not widely used in Romania, this doctoral thesis focuses primarily on optimizing conventional drying (hot-air drying) and investigating optimal drying schedules for this process.

Conventional drying is a convective drying process using hot air below 100°C and atmospheric pressure. The drying process is controlled based on wood moisture content with key parameters including: temperature, air humidity and air speed.

For oak wood, reference literature does not provide data on specific drying schedule. Most companies rely on general drying recommendations for the Quercus genus provided by commercial drying software. This thesis, therefore, focuses on documenting recommended drying schedule for oak.

Older literature (Dumitrescu *et al* 1969, Hildebrand 1979, Janik 1965, Marinescu 1979, Sergovski 1968, STAS 10349/1-87) recommends: initial heating with high temperatures of 50-60°C and relative humidity φ = 100% (achievable only with steam humidification, not cold-water humidification).

Since modern drying systems use cold-water humidification, newer sources (Cividini 2001, Trübswetter 2009) recommend: lower values of relative air humidity, around 85%, and lower temperatures (30-35°C). During the drying process itself, older literature recommends high temperatures for both free and bound water removal with a drying gradient GU≥2. Newer limit the temperature to approximatively 30-35°C until reaching critical moisture content, while keeping equilibrium moisture at 18% (φ =85%). Only in the bound water elimination phase is the temperature raised to 60°C (or 70°C for pieces with thicknesses below 40mm), with a controlled drying gradient GU=1.5.

Hildebrand (1979) is the only bibliographic providing separate drying schedule for pedunculate oak and Sessile oak. His research indicates that oak drying should be milder, with: a starting temperature of 51°C compared to 60°C for alder, and the maximum temperature at the end of the process is 67°C compared to 72°C proposed for alder.

Drying time is a regulated parameter only during the heating, conditioning (balancing) and cooling phases, whereas the actual drying time depends on the moisture reduction rate for each specific batch. The drying time of heating period depends on the heat installation capacity and carrier fluid parameters, typically 1.5h per cm of thickness for hardwoods. Conditioning the duration period is recommended to be one tenth of the actual drying time. Drying time for cooling period will considerate equal with drying time of heating period.

The total drying time significantly impacts energy. Joly (1980) and Hess (1987) report specific energy consumption of 375 kWh/m^3 for thermal energy, 170 kWh/m ^{3} for electric and a total specific consumption of 545 kWh/m ^{3} for conventional hardwood lumber drying. For oak with a thickness of 25mm dried from green to a humidity final grade of 8%, literature indicates a total specific energy consumption of 560-700 kWh/m ^{3} (Câmpean and Lăzărescu 2016) or 2.5kWh/ kg of water (Joyet 1996).

Specialized literature served as a reference and foundation for developing optimized drying schedule for Turkey oak, which are addressed in Chapter 5 of this doctoral thesis.

CHAPTER 2. OBJECTIVES OF THE DOCTORAL THESIS

The general objective of this research was to investigate the drying behavior of oak wood compared to other oak species. The specific objectives proposed are schematically presented in Fig. 2.1.

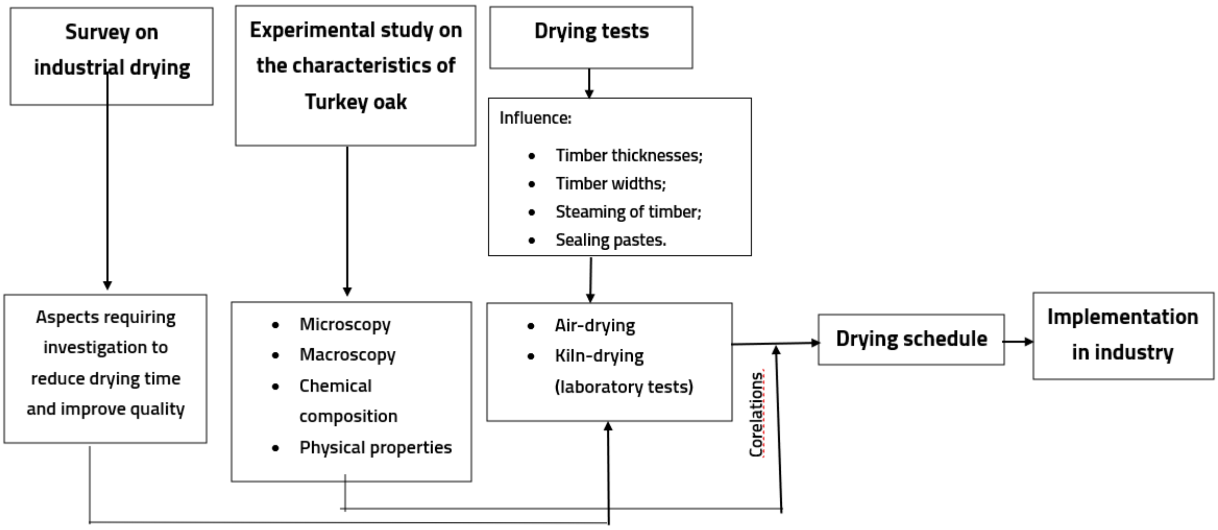


Fig. 2.1 Objectives of the doctoral thesis

CHAPTER 3. SURVEY ON INDUSTRIAL DRYING OF OAK LUMBER

3.1 Motivation and goals

This chapter presents the results of a survey conducted on ten companies in Romania that dry oak lumber (mainly alder and oak, but also Turkey oak). The aim of this survey was to establish the actual conditions applied in the industry when drying these species, but also to identify aspects that could be improved according to the opinions of the industry.

3.2 Method

To determine the current level of applied knowledge regarding the drying of these species, after consulting the specialized literature (*e.g.,* Brace 2018; Kasunic 2005), a questionnaire was developed and distributed to ten wood processing companies in Romania that dry oak lumber, located in different regions of the country.

The questionnaire includes ten questions, most of them multiple-choice (with answer options), to be as suggestive, user-friendly, and quick to complete as possible.

The questions aimed to assess:

- the Quercus species dried;
- the amount of dried lumber annually, in m ^{3} /year;
- the drying experience of enterprises, in years;

- the drying process applied (with air or in vacuum);
- whether it is an exclusive kiln-drying or air-drying followed by kiln-drying; for air-drying, the interval for decreasing the wood moisture content was also requested;
- the process control system used (manual or automatic);
- details regarding the drying schedule (temperature, humidity, drying gradient, duration);
- drying defects found;
- the percentage of compliant parts in a batch;
- aspects that can be optimized.

3.3 Results and discussions

The analysis of the completed questionnaires showed the following:

- 70% of companies dry only alder and oak, while only 30% dry Turkey oak lumber;
- 50% of respondents dry a quantity of lumber greater than 1500 m^3/year;
- 80% of companies have over ten years of drying experience, 10% between five and ten years and 10% less than five years;
- none of the interviewed companies dry in a vacuum.

Regarding whether or air-drying is applied before artificial drying: 30% of respondents apply kiln-drying from the green state, and 60% practice air-drying first before introducing the lumber into the dryer. Only one company buys pre-dried lumber (with a humidity of 38%), which it artificially dries.

The average drying time of wood drying from green to U=30-40% varies between two months for thinner lumber (25mm) and four months for the thickest (50mm).

For pedunculate oak/ Sessile oak, the drying rate values varied between 0.16%/day for 50mm thickness and 0.5%/day for 25mm. The low number of responses for Turkey oak did not allow for a conclusive statement regarding this species, but the value obtained from the only respondent who naturally dries this species indicates a much longer time than for pedunculate/ Sessile oak.

Half of the companies interviewed use installations with a capacity of 50-80 m^3/batch, 20% with a capacity of less than 50 m^3/batch, and 30% with a capacity of more than 100 m^3/batch.

Regarding the conditions applied in kiln-drying, the following observations were made:

- 100% of respondents use an initial temperature of 30...35°C; this temperature is correlated, in 80% of cases, with an equilibrium moisture content (EMC) of 15...17%, while 20% choose U_e<14%;

- 30% of respondents use a maximum temperature of 50°C after reaching the fiber saturation point; the majority (50%) use t_{max} =60°C and only 20% go up to a temperature of 70°C;
- the drying gradient (GU) varies between 1.5 and 2.5: 40% of companies apply a gentle drying schedule, where GU=1.5; 30% dry with a drying gradient of 2 and 30% practice a harsh drying schedule with GU=2.5 or even 3.

Comparing the drying time of kiln-drying from the green state (60%...8-10%) with the drying time from the pre-dried state (40%...8-10%), it was found that in the first scenario, drying time are 33% longer (10 days) for 25mm lumber and 40% longer (40 days) for 50mm lumber.

Comparing the total drying time obtained in the green drying variant with the wind-up followed by artificial drying variant, it was found that in the second case the duration is 167% longer (80 days compared to 30 days) for 25mm lumber and 89% longer (170 days compared to 90 days) for 50mm lumber. Thus, from a strict time-efficiency perspective, air-drying before artificial drying is not justified for any of the thicknesses. Regarding the drying defects reported by the respondents, most of the responses indicated end cracks as the most common defect, followed by deformations. Only 10% of them indicated internal cracks as the most common defect encountered in the drying of slatted lumber. This case concerns an enterprise that dries only slatted lumber. Businesses that dry oak lumber have not reported problems with this drying defect.

The result obtained indicates a high degree of satisfaction of the respondents regarding the quality obtained. This unexpected result is also due to the fact that most of the respondents are furniture manufacturers, who can also make use of cracked pieces. In many cases (especially in case of Turkey oak), the final product is represented by rustic tables, in which the cracks create the impression of “weathered patina”.

In terms of optimization directions, 70% of respondents requested solutions to reduce drying time and the proportion of end cracking; 60% of respondents would like better uniformity of final moisture content and 50% of respondents requested solutions to avoid drying discoloration.

Reducing the drying time was requested by both companies that apply air-drying followed by kiln-drying and those that apply artificial drying from the green state. The same request was reported by both companies that apply a gentle drying schedule (long drying time) and those that apply a harder drying schedule. It should be noted that these two companies dry alder lumber and it is clear that for this species the schedule applied must be gentler than for pedunculate/Sessile oak.

3.4 Conclusions

According to the results of the survey conducted in ten wood industry enterprises in Romania that dry oak lumber, the following conclusions can be drawn:

- 60% of respondents apply air-drying before kiln- drying;
- the average drying time for pedunculate/ sessile oak from green to 30-40% humidity varies between two months for thin lumber (25mm) and four months for thicker lumber (50mm);
- kiln-drying from the green state, the drying duration is 63% longer compared to the air-dried to 30-40% followed by artificial drying;
- kiln-drying starts, in all cases, with an initial temperature of 30...35°C. In 80% of cases, a humidification is present, thus leading to U_e = 15...17%; in the other cases a U_e value <14% is maintained during the initial heating- in these cases, companies indicated uneven final humidity and cracks as the main defects;
- the maximum temperature applied during kiln-drying for pedunculate/Sessile oak varies between 50°C and 70°C, but the majority response (60%) indicated t_{max} =60°C;
- for oak lumber, further research is needed regarding the maximum temperature supported by this species; applying a temperature of 60°C or 70°C generates more drying defects;
- the average rate for kiln-drying from 30% to 8% (bound water range) is 1.3%/day for 25mm thickness and 0.5%/day for 50mm thickness for pedunculate/Sessile oak lumber. For the Turkey oak, insufficient data were obtained to formulate a clear hypothesis;
- the main optimization requests from the industry focus on reducing drying time, minimizing end cracking, and achieving better uniformity of final moisture content.

CHAPTER 4. EXPERIMENTAL RESEARCH ON THE ANATOMICAL PARTICULARS AND A SELECTION OF PHYSICAL AND CHEMICAL PROPERTIES OF TURKEY OAK WOOD RELEVANT TO THE DRYING PROCESS

4.1 Motivation and objectives

In addition to the very long drying time, drying oak lumber is also a challenge from a qualitative point of view.

Adapting drying schedule to the structural peculiarities and properties of each individual species is the key to achieving high-qualitative drying, with minimal wood mass losses, in the shortest possible time. Therefore, in-depth research on the structure and properties of wood is highly beneficial for any species in order to better understand its drying behavior.

4.2 Structural features

4.2.1 Material, method, apparatus

Area of origin of the material. The samples required for the experimental research were obtained from a freshly cut Turkey oak tree and a sessile oak tree, originating from the Getic Subcarpathians area (45°N 24°E).

Cutting of samples. The logs were cut according to the standard currently in force (SR ISO 4471-93) into three sample logs, each measuring 2m in length: the first was cut at a distance of 1.3m from the base, the second at a distance of one-third of the trunk length starting from the base towards the crown and the third at one meter below the crown. From the base of each sample log, a 15cm thick disk was first cut for macroscopy, and then another 10cm thick disk for the determination of secondary chemical components, physical properties and from which samples for microscopy were also taken.

Determination of macroscopic characteristics

The characteristics of the annual rings were determined according to the requirements of STAS 2557-88. Along the main diameter, the following characteristics were measured using a graduated ruler:

- width of annual rings, b;
- width of the latewood zone in each growth ring, bl_{tz};

and then determined by calculation:

- average width of annual rings, b_m;
- regularity index, r;
- the proportion of latewood and earlywood, Pl_{tz} and Pl_{tp}.

The proportion of heartwood was evaluated according to the number of annual rings contained in the heartwood/sapwood area, relative to the total number of rings and based on the area occupied by the heartwood in relation to the total area (excluding bark) on the cross-section of the disk.

To verify the results obtained, a graphical method of determining the area was also applied, using the ImageJ program. The obtained images were first converted to black and white (Fig.4.4), then calibrated based on a known dimension: the size (in cm) of the main diameter marked on the cross-section.

Then, the contour of the areas of interest was traced (Gurău *et al* 2013), and the software calculated the area of the respective regions, with the data being be saved in an Excel file.

The color difference between sapwood and heartwood was evaluated using the CIELab coordinate system, with an AvaSpec-USB2 spectrophotometer (from Avantes Apeldoorn, The Netherlands), equipped with an 80mm diameter AVA sphere and AVA Soft Version 7.7 software for data acquisition and processing. Measurements were performed on the cross-section of specimens measuring 180 x 20 x 18 mm, with a humidity of 8%.

Microscopic characteristics. Microscopic images were obtained from the cross-section of the Turkey oak and Sessile oak wood using a NIKON SMZ18 stereomicroscope (Tokyo, Japan). A magnification of 22.5x was used to determine the pore diameter in the earlywood, sapwood and heartwood. A total of 15 measurements were made in the heartwood of Sessile oak wood, 6 measurements in the sapwood of Sessile oak wood, 16 measurements in the heartwood of Turkey oak and 18 measurements in the sapwood of Turkey oak.

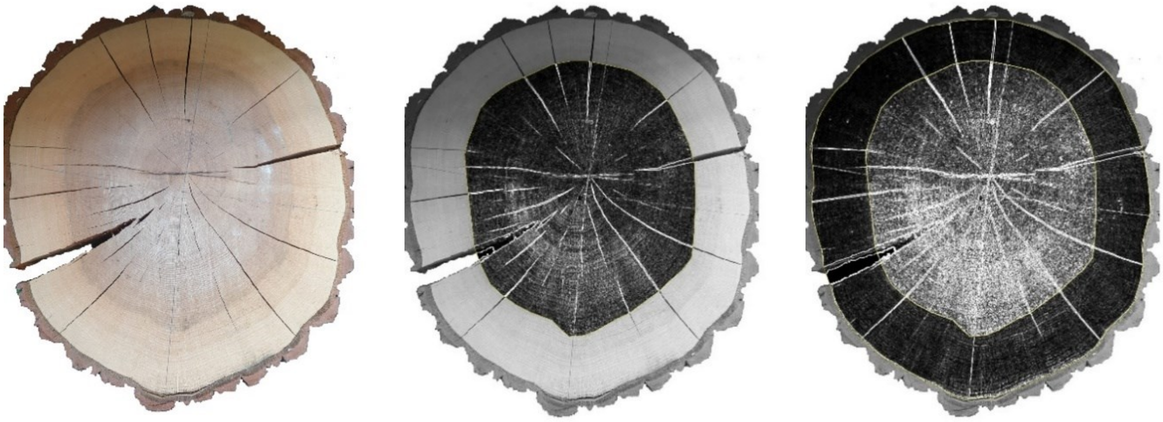


Fig. 4.4 Converting the cross-sectional image of the roundel to black and white for evaluating the sapwood/heartwood area in ImageJ

4.2.2 Results and discussions

Characteristics of annual rings. The values obtained are summarized in Table 4.3.

Table 4.3
Characteristics of annual rings in alder and alder wood

No. Specimen	Characteristics of annual rings				
	b_{max} [mm]	b_m [mm]	R [%]	Place [%]	P_{ltp} [%]
TURKEY OAK	4	1.98	120.91	56.36	43.63
SESSILE OAK	6	3.64	228.08	58.17	41.82

Heartwood and sapwood proportion. From Fig. 4.8 it can be seen with the naked eye that the heartwood proportion is lower in the case of the Turkey oak wood than in the sapwood. The exact calculated values lead to a value of approx. 50% in the Turkey oak tree, by both methods applied.

a.

b.

Fig. 4.8 Proportion of heartwood and sapwood in: a- Turkey oak; b-sessile oak

Chromatic characterization. Table 4.5 presents the values of the color coordinates obtained on the sapwood and heartwood areas of the Sessile oak and Turkey oak wood, respectively, and then the color difference (ΔE) between sapwood and heartwood was determined for both species.

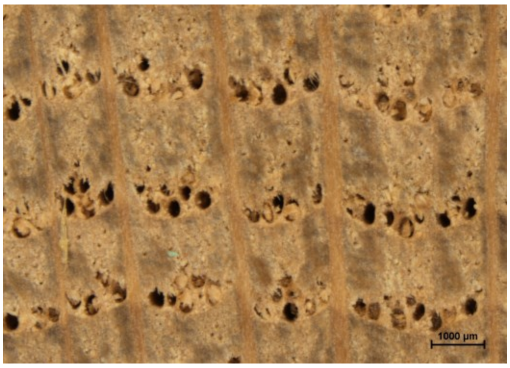
Table 4.5

Color coordinates (mean values and standard deviation) and color difference between sapwood and heartwood of Turkey oak wood and gorun

Type of wood	L*		a*		b*		ΔE *
	Sapwood	Heartwood	Sapwood	Heartwood	Sapwood	Heartwood	
Turkey oak	73.67 (0.90)	61.55 (0.99)	4.05 (0.16)	6.34 (0.28)	15.77 (1.26)	16.07 (0.31)	12.33
Sessile oak	76.5 (3.15)	60.35 (2.80)	3.05 (0.58)	5.94 (0.75)	16.48 (1.32)	18.72 (1.52)	16.55

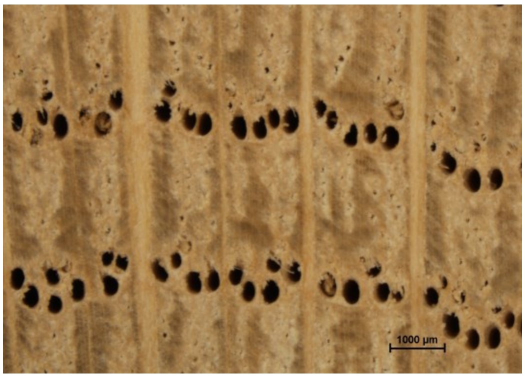
Color measurements in the CIELab system indicated a reddish hue for the Turkey oak wood and a less pronounced contrast between sapwood and heartwood, compared to the sessile oak wood.

Microscopic characteristics. The images obtained on the cross-section of the wood of the Turkey oak and the Sessile oak are presented in Fig.4.9.

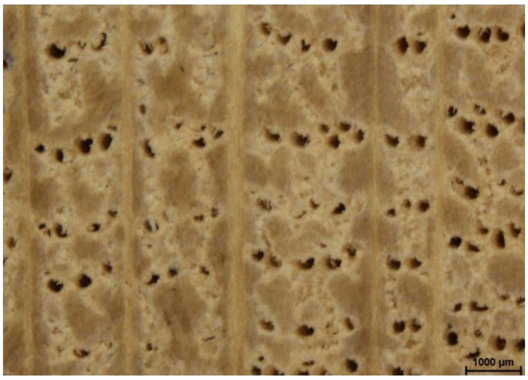


a. Turkey oak heartwood

b. Sessile oak heartwood



c. Turkey oak sapwood



d. Sessile oak sapwood

Fig. 4.9. Images of cross-section of the wood of Turkey oak and sessile oak wood, sapwood and heartwood (magnification 22.5x)

The difference with the sessile oak, at a microscopic level, is the much larger diameter of the pores in the early wood, both in the heartwood and in the sapwood, but also their different arrangement. In the sapwood, both species have completely empty pores, but in the heartwood they are partially filled with tyloses.

4.3 Chemical composition

4.3.1 Material, method, apparatus

Comparative aspects of the chemical composition for Turkey oak and sessile oak, as well as differences between the sapwood and heartwood of these species, were determined on sawdust samples collected differentially during the mechanical processing of the wood material.

Sample preparation for analysis consisted of sieving sawdust samples in the existing facility within the Chemistry Laboratory of the Faculty of Furniture Design and Wood Engineering. In the present research, the sawdust fraction that passed through the 0.5mm mesh sieve, but was retained on the 0.25mm mesh sieve, was used.

Then the moisture content of the sawdust was determined by the anhydrous drying method (STAS 83-89), with the samples being dried to constant mass in an electric oven with thermostat, at a temperature of 103±2°C. For each determination, four samples were used, two samples of heartwood sawdust and two samples of sapwood sawdust.

Main chemical compounds - FTIR investigations. To evaluate and compare the chemical composition of the wood of the two species, as well as to make a comparison between sapwood and heartwood, the FTIR (Fourier Transformed InfraRed Spectroscopy) method was used. The measurements were performed using an Alpha-Bruker spectrometer (Germany) equipped with an ATR (Attenuated Total Reflectance) module.

Extractables content. In addition to the main chemical compounds (cellulose, hemicelluloses and lignin), secondary chemical compounds, especially extractables, are important when characterizing a wood species. Extractables are a mixture of compounds with different molecular weights, which can be extracted from wood with cold/hot water and/or organic solvents.

Extractable substances affect the properties and also the drying behavior of wood (drying colors). As a result, in the present research, it was deemed appropriate to determine the content of extractable substances. Extractions were carried out in different media (cold water, hot water and 1% NaOH) on samples from the four assortments.

The extract obtained from the cold-water method contains the soluble part of the ash (inorganic compounds soluble in water), saccharides, starch, pectins, certain hemicelluloses (galactan), various gummy substances, etc. If a previous extraction with alcohol had not been performed, then the extract would also contain some of the amines and pigments present in the wood (Petrovici and Popa 1997).

The extract obtained by the hot water method contains the same substances, but in a larger quantity, due to the increased solubility of the water temperature. In this case, sugars and tannins are also found in the extract.

The extract obtained in an alkaline aqueous medium (1% NaOH solution) additionally contains vegetable resins, waxes, fats, coloring substances, glycosides, proteins, alkaloids, phytosterols (Petrovici and Popa 1997).

Presence of tanning substances. To highlight the presence of tannins, an original method was used based on the color reaction between tanning substances and iron cations (Fe^{+2}, Fe^{+3}). The semi-quantitative assessment of the concentration of tannin substances was made in correlation with the intensity of the coloration, respectively the evaluation of the color differences associated with the reaction of tanning substances in the samples with Fe^{+3} cations in a ferric chloride solution $FeCl_3$.

Three solid wood samples were analyzed, with dimensions of 180 x 20 x 18mm in the radial, tangential and longitudinal directions, respectively, containing both the sapwood and heartwood areas. The determinations were carried out comparatively for the sapwood and the heartwood using the AvaSpec-USB2 spectrophotometer (Fig. 4.6), the color coordinates in the CIELab system in the initial state (L_1*, a_1*, b_1*) were determined. The color measurements were performed at several precise points (circular areas with a diameter of 8mm) on each sample, starting from the outer sapwood area towards the inner heartwood area. The measurement positions were located at 20mm intervals. Due to the difference in the width of the sapwood of the two species, two measurements were performed on the sapwood and five on the heartwood in the sapwood area and one, respectively seven measurements in the case of the heartwood. Then a layer of $FeCl_3$ (5% concentration) was applied to each sample. After 24 hours the color was measured again at the same points.

4.3.2 Results and discussions

Main chemical compounds - FTIR investigations. A first analysis of the spectra indicates a qualitatively similar chemical composition (similar absorption bands) for both species, both in sapwood and heartwood.

A noticeable distinguishing feature is the small absorption from 1644 to 1647 cm^{-1} attributed to conjugated carbonyl groups. This absorption is present as a shoulder at 1647cm^{-1} in the spectra of the Turkey oak wood, slightly more distinct in the sapwood compared to the heartwood, while in the case of the sessile oak a small absorption at 1644 cm^{-1} is found only in the sapwood 1644cm^{-1} . Also, in the case of the sessile oak wood the absorption at 1368cm^{-1} (CH in Cel, Hcel) appeared as a distinct peak for the sapwood, being reduced to only a shoulder for the heartwood. At the same time, the absorption at 1323 cm^{-1} (L with a contribution of Cel) appeared as the highest in the sessile oak heartwood, while at 1233 cm $^{-1}$ the lowest value was recorded, in the sessile oak heartwood. A high relative intensity at the 1323cm^{-1} absorption band compared to the absorption from 1732 to 1738cm^{-1} marks a difference in the sapwood of sessile oak compared to the heartwood of the same species, which is in accordance with the FTIR database created by Traore *et al* (2018).

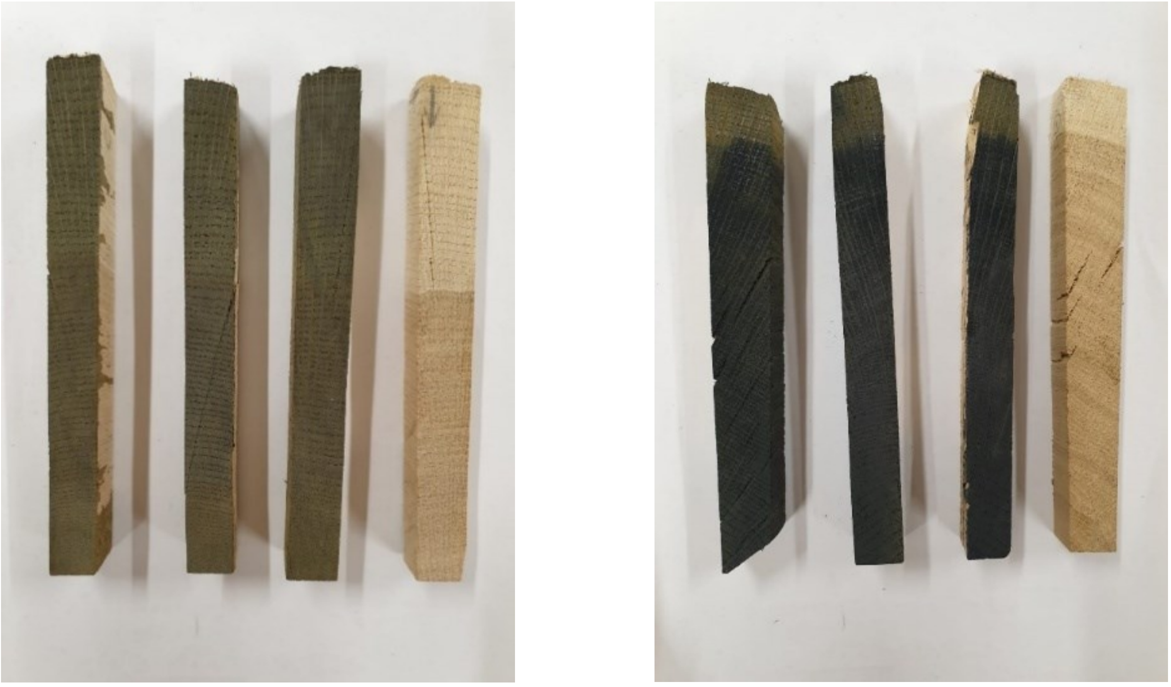
The most obvious difference is observed in the case of the spectra of the sapwood and heartwood of the Turkey oak, which reflect a lignin absorption around the values 1504, 1456, 1420 and 1323 cm^{-1} , for which the heartwood/sapwood ratios were calculated: 1.18, 1.17, 1.63 and 1.36, all suggesting a high lignification of the heartwood compared to the sapwood. At the same time, the ratio 0.39 calculated for the absorption band 1368 cm^{-1} (Cel+Hcel) for the heartwood/sapwood of the Turkey oak reflects a low holocellulose content in the heartwood compared to the sapwood, while the value of 0.99 (heartwood/sapwood) for the absorption at 1368 cm^{-1} (Hcel) suggests a similar content of hemicelluloses in the heartwood and sapwood. This shows a lower cellulose content in the more lignified heartwood compared to the sapwood.

By comparison, in the case of sessile oak, the heartwood/sapwood ratio for the most characteristic lignin absorption band 1504 cm^{-1} was 1.10 (possibly a slightly higher lignin content in the heartwood), while the ratios most different from 1 (±0.1) were those calculated for the bands 1456cm^{-1} (2.36), 1323cm^{-1} (1.52), with the highest values, and at 1233cm^{-1} (0.38) with the lowest value.

Extractable substances content. As expected, among the three extraction methods, the lowest values were obtained with cold water extraction and the highest with 1% NaOH extraction for all four wood types. Regarding the comparative results between Turkey oak and Sessile oak wood, the values are generally higher for Sessile oak wood with one exception, in the case of NaOH extraction for sapwood.

Presence of tanning substances. Fig. 4.15 shows the color change after application of the $FeCl_3$ solution to the four wood types.

The strongest color darkening was recorded for the heartwood of the Sessile oak
(-39.42±3.56) and the lowest for the heartwood of the Turkey oak (-26.58±0.68). The largest decrease in the b* coordinate (Δb*=-20.96±0.89) was obtained for the heartwood of the Sessile oak, and the smallest (Δb*=-4.36±1.88) was that of the Turkey oak sapwood. The total color change ΔE* is 14.5% higher for the Turkey oak sapwood compared to the heartwood.



a. **b.**

Fig. 4.15 Color change of Turkey oak wood (a) and Sessile oak wood (b) after application of $FeCl_3$

4.4 Physical properties

4.4.1 Material, method, apparatus

To determine the physical properties, samples were taken from three different tree heights to evaluate the variation of each property along the length of the log. From these rounds, 20mm thick logs were cut along the main diameter, containing both heartwood and sapwood. From these logs, 20 x 20 x 20mm samples were cut, containing only sapwood and heartwood, respectively.

A total of 102 specimens (83 from heartwood and 19 from sapwood) were obtained from the Turkey oak wood and 134 from the Sessile oak wood (118 from heartwood and 16 from sapwood).

4.4.2 Results and discussions

A summary of the results obtained regarding the main physical properties of Turkey oak and Sessile oak wood is presented in Table 4.27.

Table 4.27
The physical properties of Turkey oak wood presented in comparison to Sessile oak wood (mean value and standard deviation)

Properties	Turkey oak			Sessile oak		
	Sapwood	Heartwood	Total	Sapwood	Heartwood	Total
Oven-dry density ρ_0 (kg/m^3)	666,04...732,99...783,53 (34,45)	638,95...723,75...886,81 (51,25)	**728,44**	616,09...652,49...714,33 (24,63)	570,69...667,87...779,07 (46,24)	**666,56**
Conventional density ρ_c (kg/m^3)	576,07...624,37...667,49 (29,71)	554,95...619,02...743,01 (38,24)	**621,66**	532,30...562,40...622,72 (20,10)	463,56...563,31...636,83 (30,71)	**563,19**
Radial shrinkage coefficient β_r (%)	3,81...5,08...6,79 (0,86)	3,55...4,83...6,89 (0,65)	**4,96**	3,36...4,51...6,64 (0,75)	3,91...5,26...7,76 (0,69)	**5,24**
Tangential shrinkage coefficient β_t (%)	8,36...9,54...10,65 (0,68)	7,25...9,37...15,72 (1,25)	**9,45**	7,50...9,19...10,26 (0,70)	7,40...10,26...12,73 (1,36)	**10,16**
Volumetric shrinkage coefficient β_v (%)	13,44...14,81...17,77 (1,10)	11,69...14,40...20,42 (1,58)	**14,60**	12,31...13,79...16,16 (1,47)	11,69...15,56....19,02 (1,69)	**15,54**
Shrinkage anisotropy (β_t/β_r)	1,34...1,94...2,74 (0,39)	1,06...1,96...2,84 (0,31)	**1,948**	1,45...2,083...2,78 (0,32)	1,276...1,967...2,981 (0,28)	**1,997**
Fiber saturation point(%)	20,64...23,79...27,87 (2,27)	19,67...23,30...32,31 (2,44)	**23,54**	20,59...24,55...28,55 (2,16)	22,15...27,59...32,66 (2,28)	**27,57**

4.5 Conclusions

Following studies conducted on the structure, chemical composition and physical properties of Turkey oak wood compared to sessile oak wood, the following conclusions can be drawn:

- The pores in the early wood of the Turkey oak wood are larger than those in the Sessile oak wood; in the heartwood they are partially filled with tyloses in both species;
- the heartwood of the Turkey oak has a smaller proportion of heartwood than the sapwood, covering only half the cross-sectional area (ca. 50%); in both species, the heartwood has a distinct color, darker than the sapwood. The color difference is greater in the case of the sapwood than in the heartwood;
- in both species, the width of the annual rings is greater in the central area, decreases towards the periphery and increases again in the sapwood area;
- the sapwood of the Turkey oak wood has a higher content of extractable substances than the heartwood of this species, close to the value obtained for the heartwood of the sessile oak wood;
- the green moisture content of Turkey oak lumber is around 60-70%, similar to the green moisture content of pedunculate/ sessile oak lumber;

- The density of the wood of the Turkey oak is significantly higher than that of the wood of the Sessile oak. The values obtained for the sapwood and heartwood of this species are very close, slightly higher in the sapwood;
- the linear and volumetric total shrinkage coefficients of Turkey oak wood were lower than those of Sessile oak wood;
- the anisotropy coefficient has close values in both species, both in sapwood and heartwood, with no significant differences between groups.

Chapter 5. EXPERIMENTAL RESEARCH ON THE DRYING BEHAVIOR OF TUKEY OAK LUMBER IN COMPARISON WITH OTHER OAK SPECIES

5.1 Exploratory research on the drying of oak lumber

The laboratory test was carried out in the conventional SEBA type drying plant. In a false stack, 8 planks of oak lumber were dried, two of each species: pedunculate oak, sessile oak, turkey oak and Hungarian oak, having the following dimensions: length of 150 cm, width of 12cm, and thickness of 25cm. The schedule applied was that of the original SEBA plant software for oak lumber.

To measure the moisture content in wood during drying, a V2A type resistive transducer was inserted into each sample board up to half the thickness.

The drying process was monitored by completing the drying record sheet and by recording the drying parameters daily: humidity indicated by the eight transducers (corresponding to the eight sample boards), air temperature, equilibrium humidity.

After completing the drying record sheet, it was first observed that the initial humidity of the boards was more varied than desired. Thus, the two boards of Hungarian oak had a lower initial humidity (32…48%) compared to the other species (54…76%). Even the boards within the same species showed a significant variation, for example, for Turkey oak 54% and 76%, and for Sessile oak 58% and 74%. This non-uniformity in initial humidity led to different drying dynamics, but by the end, the final humidity content converged towrds the target value of 10%.

The drying time was 20 days. The values obtained for the drying rate indicate a higher drying rate for oak and alder (0.115%/h) compared to Turkey oak (0.11%/h) and alder (0.065%/h).

The quality control of drying consisted of: determining the average final moisture content on each sample board, determining the degree of case-hardening and visual analysis of the pieces to identify cracks, deformations and discolorations.

The final moisture content was measured according to SR EN 13183-3:2005 using a capacitive moisture meter (BROOKHUIS, Netherlands). The measurement was taken at three points along the length of each board: one point located 0.25m from each end and at one point in the center. The average of these three values was then calculated to obtain the average humidity of each board.

The evaluation of case-hardening degree (as an indicator of the presence of stresses in wood) was carried out according to SR ENV 14464:2004, using a specimen cut from the middle of each board with a width of 2cm and a length equal to the width of the lumber pieces. Each specimen was split in two at half the thickness (Fig. 5.7).

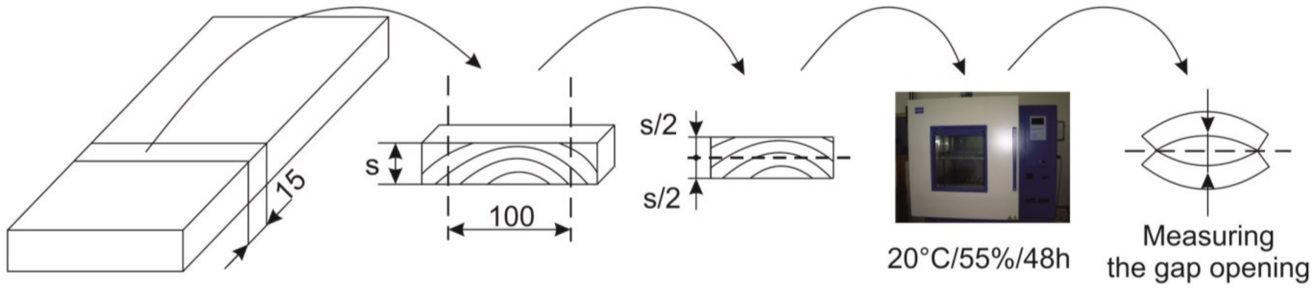


Fig. 5.7 Method for establishing the case-hardening degree after drying

The two halves were conditioned in a climatic chamber at t=20°C and relative humidity φ=55% for 48h, after which the deflection was measured. The higher it is, the more severe the degree of case-hardening. If the value exceeds 3mm, the wood is considered cemented.

Following the drying of this batch, the following conclusions were drawn:

- The pedunculate oak wood was dried correctly, with a final moisture content of 8.61%. The process was carried out without stress accumulation, as the degree of case-hardening being below 3mm;
- The sessile oak wood dried correctly, reaching a final moisture content of 8.36%, but accumulated stresses during the drying process (opening size >3mm);
- Of the four species, Turkey oak wood dried the slowest, with a final moisture content of 10.25%. This indicates that this species requires a longer drying time. The high degree of case-hardening (4.5mm) showed that this species accumulated high stresses during drying, which led to cracking of the wood;
- The wood of the Hungarian oak tree dried the fastest, reaching a final moisture content of 8.17% at the end of the drying process. The degree of case-hardening is, as in the case of the Turkey oak tree, high, which indicates a high accumulation of internal stresses, but in the case of this species no cracks were recorded;
- A gentle drying schedule should be applied to Turkey oak; by testing different combinations of temperature and air humidity, at various humidity levels, it must be established whether the drying schedule should be gentler in the first stage of the actual drying, in the second, or in both.

Industrial batch. To evaluate the current experience in the production of industrial drying of Turkey oak lumber, an analysis of a dried batch was carried out at a wood processing company in Romania. The drying was carried out in a NARDI-type kiln (Italy). The wood material consisted of unedged Turkey oak lumber, with a length greater than 2.0m, a width greater than 10cm, a thickness of 40mm. The lumber was stacked horizontally using 20mm thick lime slats. The drying was automatically conducted using the SIRIO 9000 software.

The drying process started with an initial wood moisture content of 60-65%. The initial temperature was 36-38°C and, the equilibrium moisture of 15-18%. These parameters were maintained until the wood moisture reached 30%. The maximum temperature reached during the actual drying phase was 65°C. Conditioning was carried out for 24-36 hours. The total duration of the process was 102 days, and the final moisture content reached 8%.

As in the laboratory batch drying, eight sensors were used to monitor the humidity in the drying chamber during the process. The temperature was measured by a resistive sensor, and the equilibrium humidity was measured using a cellulose pad sensor.

The drying quality assessment was performed as in the laboratory test according to the standards SR EN 14298:2005 and SR ENV 14464:2004. The number of pieces measured was 200, randomly selected from 4 stacks (out of a total of 48 stacks).

The final humidity was measured at three points using a HM9 type hygrometer from Merlin Superior Humidification Technologies (Germany) and the average final humidity was calculated for each piece.

The average final moisture content obtained in this batch was 7.06%, thus falling within the permissible moisture content range according to the SR EN 14298:2005 standard, of 7.0-9.0%. Out of the total of 200 pieces tested, 113 pieces (56.6%) had a moisture content outside the permissible range: 79 pieces had a moisture content below 7%, while 34% had a moisture content above 9%. The wide range of variation in the final moisture content, between 4.67% and 12.33%, indicates uneven drying.

For the case-hardening evaluation, 15 pieces were randomly selected from the 200 used for measuring the moisture content These pieces were also sectioned to observe the presence of internal cracks.

An average value of 1.85 ± 0.33 mm of the case-hardening degree was obtained.

The visual analysis of the 200 pieces revealed that: 57.5% showed end cracks (Fig. 5.13), 57 pieces showed surface cracks, 48 pieces showed both end and surface cracks. Among the 15 pieces, two (13.3%) showed internal cracks.


Fig.5.13 Pieces with end cracks

Following the results obtained from the analysis of the industrial batch, it can be concluded that:

- The total recorded drying time of 102 days (3.4 months) from an initial humidity of 60-65% to a final humidity of 8% is long;
- The temperature applied during the heating period (36-38°C) seems to have been too high, as indicated by the high proportion of surface cracks was high (28.5%);
- The maximum applied temperature of 65°C seems to impose too harsh a drying schedule, considering the large number of cracks recorded as well as the wide range of final moisture content (4.67%-12.33%);
- There was a high percentage of end cracks (57.5%), likely due to the lack of protection of the lumber ends as well as the large width of the dried boards.

The conclusions obtained from the drying process of the two batches allowed the development of an experimental plan for the continuation of the research on the drying of the Turkey oak lumber. This plan includes four phases:

I. Air-drying – to determine whether this would allow drying in better quality conditions than kiln-drying; these tests also verified the effectiveness of two types of paste used to cover the ends in order to avoid end cracks;
II. Kiln-drying – conducted on a laboratory scale to test different combinations of air temperature and humidity at various drying stages. Additionally, the efficiency of lumber pre-steaming was examined;
III. Proposal of an optimized drying schedule for each of the two analyzed thicknesses, based on the results obtained in the first two phases;
IV. Industrial-kiln-drying of a batch - for verification and validation of the proposed drying schedule .

5.2 Experimental research on the drying behavior of Turkey oak wood

5.2.1 Material, method, apparatus

The wood samples subjected to experimental tests consisted of edged boards of Turkey oak (*Quercus cerris,* L) and pedunculate oak (*Quercus robur* L). For comparison, several additional oak boards were included in each batch. The samples measured 0.6m in length, 15-30cm in width, and were cut from industrial lumber grades, with thicknesses of 28 mm and 50 mm.

For both lumber thicknesses, two drying methods were tested: air-drying under a shed for 7 months and conventional kiln-drying, from green state to a moisture content of approx. 10%.

Mini-stacks of lumber were built, following industry-standard stacking rules. The naturally dried pieces were tied with elastic straps to avoid deformation.

The **air-drying** it was done between November 30, 2022 and July 3, 2023, during which the ambient temperature varied from -4°C to 24.9°C, with an average of 9.48°C. The relative humidity ranged from 39% to a maximum of 98%, with an average of 73.43%.

When forming the stack, the pieces were numbered and pre-existing cracks were marked with chalk. The initial moisture content of each piece was measured using a resistive moisture meter LG9 NG from Holzmeister (Italy).

Kiln-drying of the parts was carried out within the Heat Treatment Laboratory of the DMIL Faculty, in a KPK 200 climatic chamber from the FEUTRON company (Germany).

To monitor wood moisture during the initial drying phase (above 30% moisture content), pieces were removed individually from the climatic chamber and measured with a resistive moisture meter. This approach was necessary since transducers are not accurate for moisture levels above 30%.

For monitoring moisture levels below 30%, eight resistive transducers (V2A type from Gann, Germany) were used. For 50mm-thick lumber samples, both shorter transducers (10mm) – to measure surface moisture – and longer transducers (25mm) – to measure core moisture – were utilized.

Based on the drying schedule recommended in the specialized literature (Câmpean 1997, Trübswetter 2009) for oak lumber, as well as conclusions drawn from preliminary research, several guidelines (Table 5.7) were established regarding the drying schedule and process management during climatic chamber tests.

Table 5.7
Guidelines on experimental drying schedule for Turkey oak lumber

Phase	Recommendation
Initial heating	Considering that when heated at t=35°C the Turkey oak pieces were case-hardened, t=30°C was considered optimal for this phase, combined with high air humidity (φ=85%, respectively U_e =18%). The duration of the heating phase was considered 1.5h per each cm of thickness, respectively: D_1 = 5h for lumber with a thickness of 28mm and D_1 = 8h for a thickness of 50mm.
Actual drying	After the heating period (D_1), in order for the wood humidity to begin to decrease, it was considered appropriate to decrease the air humidity to φ=83%, respectively U_e =17.5%, maintaining the temperature constant at t=30°C. This temperature should not only ensure the conditions for the gradual adaptation of the wood to the drying environment so as not to produce tensions in the wood, but also to prevent drying colorations specific to species with tannin. As the wood moisture content decreases during the actual drying process, the schedule parameters must be adapted so that the drying does not stagnate. When the wood moisture content remains constant from one day to the next, a decision must be made regarding their modification. There are two solutions: either gradually increase the temperature (in steps of max. 5°C), keeping the air humidity constant (φ=83%, respectively U_e=17.5%), or gradually reduce the relative air humidity (in steps of 2- max. 5%), keeping the temperature at the value of t=30°C. This process management strategy will be applied until the average wood moisture values, measured in the center of the test pieces, reach the value of 24%, corresponding to $U_{sf,\ Turkey\ oak}$. At the end of this stage, the equilibrium moisture content (U_e) should be ≥12%, so that the drying gradient (GU=U/U_e) does not exceed the value of 2. Ideally, GU=1.5 (U_e =16%). From this point on, since there is only bound water in the wood, the drying process must be accelerated, otherwise the decrease in humidity will stagnate again. Depending on the strategy adopted in the first stage of the actual drying, it is recommended to either decrease the air humidity (if the temperature has already reached t=50°C) or gradually increase the temperature, up to a maximum of 60°C, given that a temperature of 65°C has been shown to be

	detrimental to the quality of the material in the case of an industrial batch. Again, the change is made gradually in order to be able to monitor the effect on the quality and stop the measure if the wood starts to crack.
Conditioning Cooling	Since the climatic chamber was located in the hall, neither conditioning nor cooling treatment was considered necessary. When the wood moisture reached the desired final moisture content, the climatic chamber was turned off, the door was opened and the pieces were allowed to cool gradually, with quality control being performed after 1 week.

At the end of each batch, quality control was performed, consisting of determining the uniformity of the final moisture content, the size of the case-hardening and visual analysis of the pieces to identify any cracks, deformations and discolorations. All observations were recorded in the drying quality analysis sheet.

5.2.2 Experimental results on the air-drying of Turkey oak wood

a) Air-drying of 28mm thick Turkey oak lumber

Following the initial evaluation of the pieces, it is observed that:

- the Turkey oak lumber had a higher average initial humidity (59%) compared to that of the oak lumber (45%);
- half of the Turkey oak pieces were 30cm wide (called "wide" pieces) and half were 15cm wide (called "narrow" pieces);
- of the 8 pieces of Turkey oak wood, 5 pieces showed a high proportion of heartwood (over 70% of the surface on both sides), and 3 pieces had a higher proportion of sapwood;
- no pieces showed cracks before drying.

A paraffin-based paste was applied to the ends of half of the pieces.

Based on these wood moisture values, the drying diagram presented in Fig. 5.23 was drawn up.

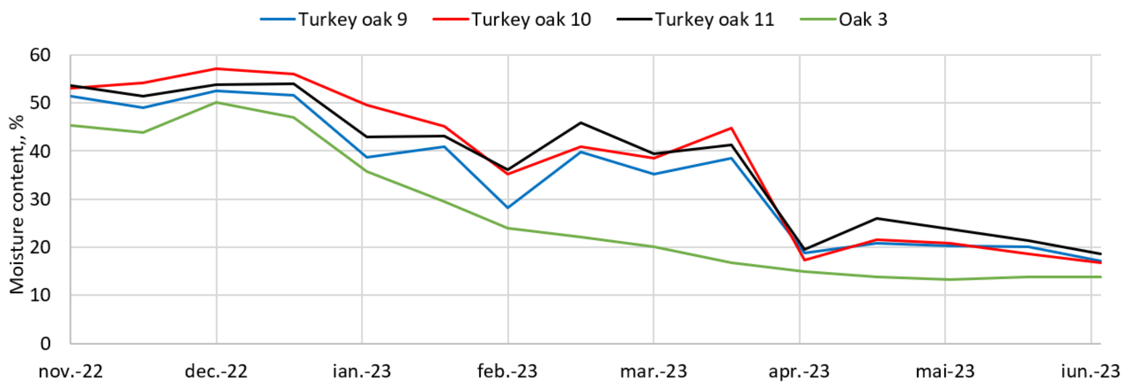


Fig. 5.23 Drying diagram for air-drying

It is observed that both the oak and the Turkey oak pieces experienced an increase in humidity at the beginning of the exposure (until mid-December). From this date on, the humidity of the oak piece decreased continuously and at an accelerated rate, while that of the Turkey oak pieces fluctuated and began to decrease more consistently only after mid-April.

After six months of outdoor exposure, the oak piece reached a moisture content of 13.2%, after which drying stagnated. In the same interval, the Turkey oak pieces reduced their moisture content to 20.3%-23.7%, and in the following month, drying continued down to 16.7-18.6%. The values for the drying indicate that during the free water removal phase, the difference between the two species is quite small, while during the bound water phase, the drying rate of Turkey oak wood is almost twice as slow as that of oak wood of the same thickness, exposed to exactly the same drying environment.

In order to assess the quality of drying, the pieces were visually examined at the end of the seven months of outdoor exposure. It is noted that none of the oak pieces cracked. However, the five broadleaf pieces, all with a high proportion of heartwood, developed cracks.

In the case of the Turkey oak pieces, the end protection ineffective. The determining factor influencing the cracking was the width of the pieces and the fact that they contained a high proportion of heartwood (over 70%).

The absence of internal cracks and the relatively low proportion of surface cracks show that the schedule was mild.

For the evaluation of stresses after drying, four tangential pieces were selected to determine the degree of case-hardening. It was observed that the values obtained from the case-hardening test showed a good correlation between the degree of case-hardening and the degree of cracking.

Following the warping test of edged lumber with a thickness of 28mm, the following findings were made:

- The winter months (December, January, February) do not provide favorable conditions for drying;
- From February onward, the decrease in relative air humidity and the increase in temperature facilitate the elimination of free water, allowing the wood to reach 30% humidity. For Turkey oak wood, this value was reached approximately 15 days later than for oak wood;
- It was observed that, unlike oak wood, the humidity in the Turkey oak continues to fluctuate in the following period, possibly even increasing again;
- The final moisture content reached by Turkey oak wood after seven months of exposure was 17.5±1%, while for the oak wood it was 13.2±0.2%;
- 62.5% of the Turkey oak pieces (the wide ones) developed end cracks;
- 37.5% of the Turkey oak pieces (the wide ones) developed surface cracks;

- No pieces had internal cracks;
- A strong correlation was found between the value of the degree of case-hardening and that of the degree of cracking.

In conclusion, it can be stated that 28mm-thick cedar lumber can be air-dried to moisture levels below the fiber saturation point. However, this process requires a drying time of more than six months and carries the risk of drying defects.

b) Air- drying of 50mm thick Turkey oak lumber

Following the initial evaluation of the pieces, the following observations were made :

- The Turkey oak lumber had an initial humidity of 58%, while the oak planks had an initial humidity of 54%;
- Five pieces of Turkey oak were narrow (15cm wide) and 3 pieces were wide (30cm wide);
- all the pieces of wood showed a heartwood proportion of over 50%;
- half of the Turkey oak pieces developed cracks even before they were exposed to the air.

A paraffin-based paste was applied to the ends of half of the pieces.

Based on these moisture values, the drying diagram was drawn up (Fig. 5.25).

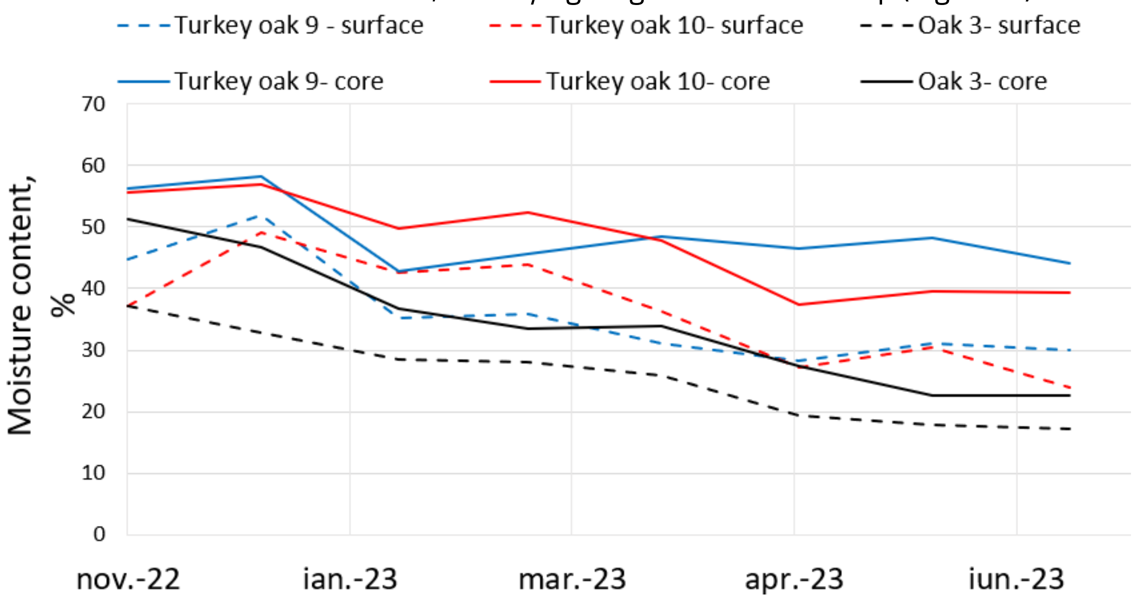


Fig. 5.25 Drying diagram for air-dried 50mm lumber

It is noted that in the case of the oak piece, the humidity decreased continuously, from the beginning of the exposure, while for the Turkey oak pieces it increased (particularly on the surface) between November and February and only then began to decrease with fluctuations.

The difference between core and surface moisture was at its maximum (11-18%) at the beginning of the process for all three pieces. Starting in late December, it decreased to 7-8%, a value that was maintained even further reduced to 5% in May-June for the oak piece.

However, it increased again in mid-March for the Turkey oak pieces, reaching 17-18% once more.

After seven months of outdoor exposure, the oak piece had an internal moisture content of 22.6% and a surface moisture content of 17.3%, while both Turkey oak pieces only managed to reduce their internal moisture to 39% and 42%, respectively, and their surface moisture to 24% and 30%, respectively.

The values for the drying rate show that the seven months time interval was insufficient for the moisture content of the Turkey oak pieces to drop below the fiber saturation point, whereas the oak pieces dried to approx. 20%. The drying rate within the free water range is almost twice as fast for oak than for Turkey oak wood.

To assess the drying quality, the pieces were visually examined again at the end of the seven-months outdoor exposure period. All wide pieces (including oak) suffered surface and end cracks. No narrow pieces showed cracks.
No pieces showed internal cracks. This result was predictable, given that drying only occurred in the free water range, and internal cracks are typically caused by excessively harsh drying conditions during the bound water removal stage.

The Turkey oak pieces tested for case-hardening revealed larger opening sizes than the 28mm pieces by up to 2.5mm.

Following the warping test of edged lumber with a thickness of 50mm, the following findings can be formulated:

- After exposure to air for 7 months, the Turkey oak pieces removed 14% of their moisture, failing to reach the fiber's restoration moisture content;
- The drying speed of Turkey oak wood in the free water area is about 2 times slower than that of oak wood of the same thickness;
- All wide pieces showed both surface and end cracks. The narrow pieces did not crack.
- The proportion of heartwood was not a decisive factor for the occurrence of cracks;
- In the case of 30 cm pieces, protecting the ends with paraffin-based paste did not help avoid end cracks.

5.2.3 Experimental results on artificial drying of Turkey oak wood

a) Artificial drying of 28mm thick Turkey oak lumber

Following the initial evaluation of the pieces, it is observed that:

- the Turkey oak planks had a higher average initial humidity (62%) compared to the oak planks (44%);
- only one piece showed cracks before drying.

Fig. 5.27 shows the drying diagram for this batch.

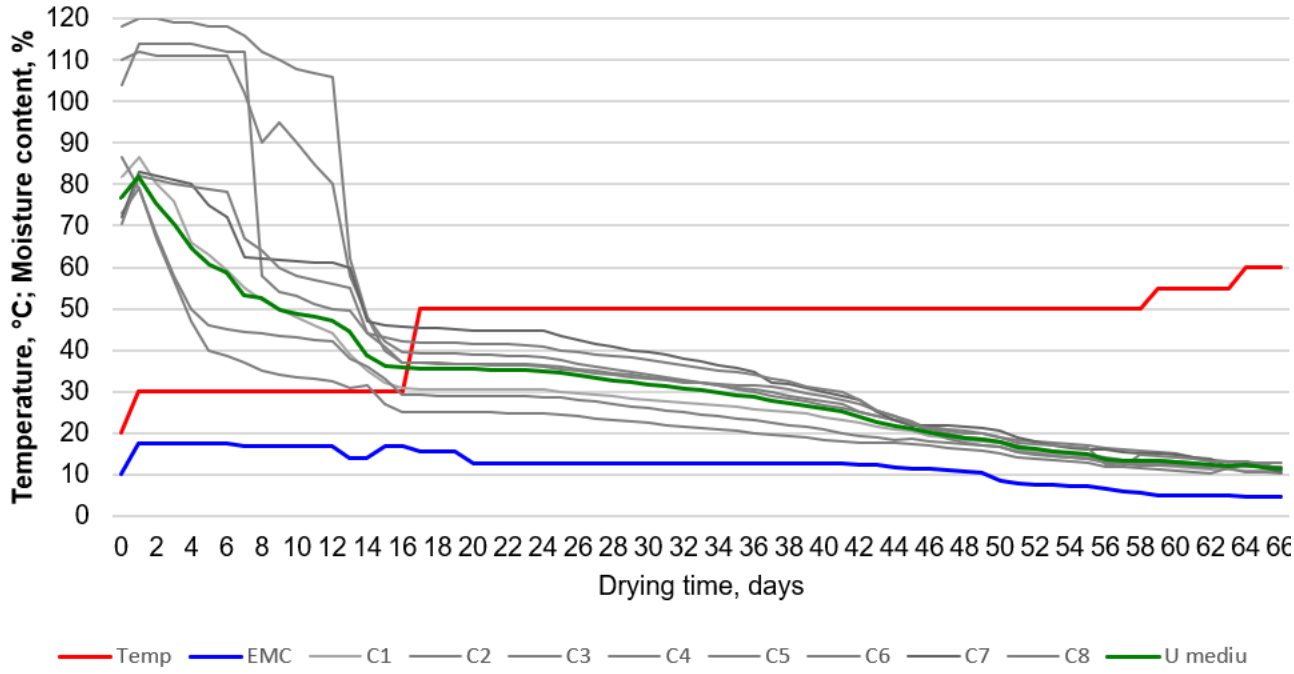


Fig. 5.27 Drying diagram for kiln-dried 28mm thick lumber

The total drying time was 67 days, of which 66 days were actual drying. The values obtained for the drying rate indicate that in the free water domain, the rate was 17% lower for Turkey oak wood (0.88%/day) than for oak (1.06%/day). In the domain of bound water elimination, the drying rate yielded close values for the two species (Turkey oak: 0.60%/day; oak: 0.62%/day). Also, over the entire interval of humidity decrease, the drying rate was identical for both species (0.8%/day).

In order to assess the quality of drying, the pieces were visually examined and the following were observed:

- no piece of oak cracked, unlikke in the case of natural drying;
- half of the Turkey oak pieces suffered cracks; all cracked pieces had a large width and a heartwood proportion greater than 60%;
- two pieces of Turkey oak showed surface cracks; in one of the pieces the cracks were observed and marked before drying, but during the process they increased;
- two pieces of Turkey oak showed end cracks; both pieces were free of defects in their original state; one of the pieces was protected on the end and the other was not;
- no piece showed internal cracks;
- all pieces showed bulging after drying. This shows that placing a weight on top of the stack is absolutely necessary at this thickness; in the case of natural drying, bulging was avoided by strapping the mini-stacks.

Four pieces were selected for the evaluation of post-drying stresses by the case-hardening test. It is observed that the opening size ranged between was 1.0-2.0 mm for the Turkey oak and was 1.0mm for the oak piece.

The results of the kiln-drying tests of 28mm-thick cedar lumber led to the following findings:

- as long as Ue is ≥18% (φ≥85%), the wood humidity does not decrease; only when it was reduced φto 83% (Ue=17%), did the wood humidity begin to decrease (the actual drying began);
- under these conditions (t=30°C, Ue=17%) drying proceeded without cracks, but was very slow (between 0.7-1.27%/day, with higher values at the beginning of the process);
- a harsher dying schedule (for example 30°C, φ= 74%, Ue=14%) was proven ineffective at thi stage, because 3 out of 8 pieces cracked when the air humidity in the climatic chamber accidentally decreased;
- during the bound water removal, drying took 22 days to reduce the moisture content from 20.6% (average) to 11% (average), resulting in a drying rate of 0.44%/day. Under the applied schedule (t=50°C and relative humidity gradually reduced from 70% to 40%), no cracks occurred. Once the humidity reached 12%, the process almost stopped. Raising the temperature to 60°C led to the cracking of another piece. As a result, the maximum temperature of 55°C was deeemed optimal when applying a drying gradient of 2.3;
- only 50% of the dried pieces remained free of cracks; the cracks occurred in the last phase of drying when an attempt was made to raise the temperature to 60°C;
- all the pieces have deformed (bulged); it is necessary to place weights on top of the stack;
- The case-hardening test revealed that the applied schedule is sufficiently mild, with the pieces only suffering a slight case-hardening (≤2mm); it should be emphasized that this result was obtained for lumber dried from a green state.

These conclusions, together with those previous drying tests, allowed the formulation of recommendations regarding the optimal drying schedule for 28mm-thick Turkey oak lumber.

b) Kiln-drying of 50mm thick lumber

For this thickness, two experimental batches were dried. In the first batch, due to the poor quality of the pieces, with numerous knots and pre-existing cracks (before drying) and the application of an excessively harsh schedule at a time when drying appeared to have stagnated, this batch was rejected, all the pieces suffering severe cracks. The main conclusions from this experience were:

- the relative humidity during the heating phase must be 87% (U_e =18%) to prevent case-hardening;

- Since it is a large thickness (>40mm), the humidity must be monitored both at the center of the piece and on the surface because, especially in the range above U_{sf}, the difference (ΔU) between the two values is very large; the batch management was carried out according to the average of the two values;
- Given the pronounced tendency to crack, even in mild conditions with high relative humidity and low temperature, it was decided for the tests at this thickness to pre-steam half of the pieces subjected to drying to determine whether this has a positive influence on drying.

Based on these findings, the test conditions for the second batch were established, the course of which is presented below.

Following the initial assessment, the following were observed:

- the Turkey oak boards had an average initial humidity of 68%;
- 2 narrow and 6 wide pieces were subjected to drying;
- 4 pieces had a heartwood proportion of over 70%;
- three out of 8 pieces showed small surface cracks from the initial state. During steaming, surface cracks appeared on all 4 steamed pieces; thus, at the start of drying, 6 out of 8 pieces showed cracks, but without irreparably affecting the quality of the material.

The drying diagram is shown in Fig.5.31.

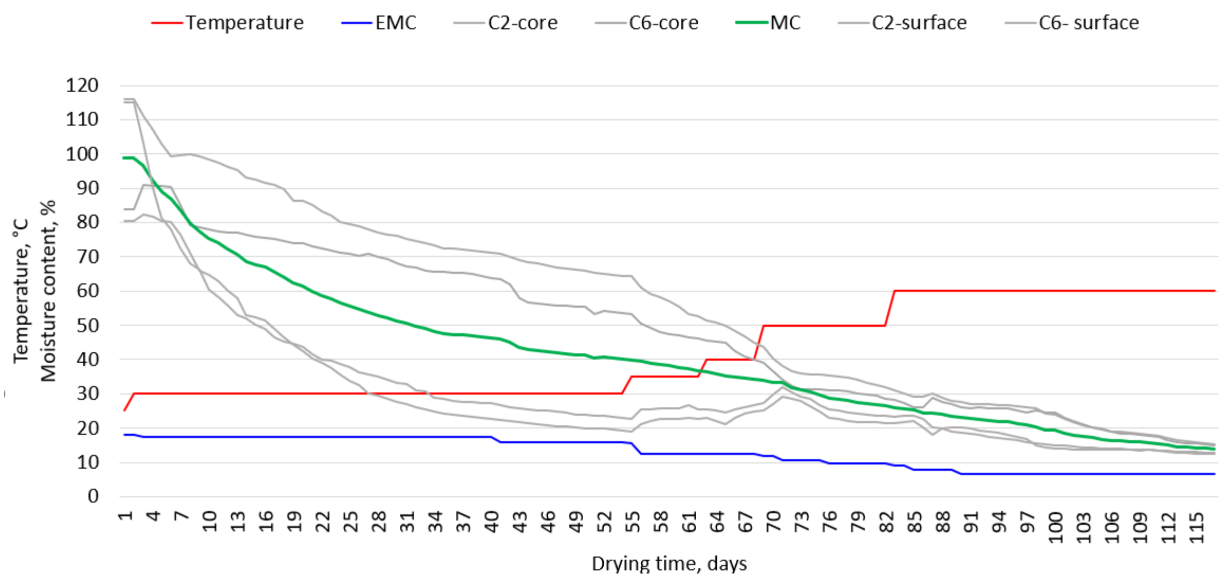


Fig. 5.31 Drying diagram for kiln-drying Turkey oak lumber 50mm thick

The total drying time was 116 days. The values obtained for the drying rate are presented in Table 5.24.

Table 5.24
Drying speed recorded during artificial drying (without forced air circulation) of 50mm thick lumber

Wood moisture reduction range	U_i, %	U_f, %	Drying time, days	Drying speed, %/day
Removal of free water	76.1	24.1	87	0.60
Removal of bound water	24.1	13.95	29	0.35
Throughout the entire range	76.1	13.95	116	0.54

Comparing the results presented in Table 5.24 with those obtained during natural drying of 50mm thick Turkey oak lumber, it was observed that in the water removal phase, the drying speed of Turkey oak wood is 8.6 times higher during artificial drying than during natural drying. For the bound-water phase, a comparison could not be made due to the absence of data for natural drying.

Comparing the results presented in Table 5.24 for 50mm-thick Turkey oak wood with those obtained for 28mm thick lumber, under the same conditions (without forced air circulation), it was observed that the drying rate is 39% lower in the free-water removal range and 24% lower in the bound water removal range. Over the entire moisture loss range, the drying rate at 50mm is 30% lower than at 28mm.

Upon visual examination after drying, the following is observed:

- two pieces cracked; one piece was narrow and one was wide, both had a high proportion of heartwood (over 70%);
- two pieces showed surface cracks; in both pieces the cracks were observed and marked before drying, but during the process they increased;
- no pieces showed end cracks after drying;
- one piece developed internal cracks; this piece had surface cracks in its initial state, so it cannot be clearly stated whether the internal cracks pre-existed in the wood or were generated during drying;
- no piece suffered deformation (bombing);
- it was found that, after drying, the cracks generated during steaming closed;

Six pieces were selected for the evaluation of post-drying stresses by the case-hardening test. The opening size, as determined by the case-hardening test, is between 2.0 to 3.0. This indicates the application of a correct drying schedule. The steamed pieces showed slightly less case-hardening (2.5mm) than the non-steamed artificially dried pieces (2.66mm). Overall, the drying quality of the steamed pieces was better, completely free of cracks. No significant effect of steaming on drying duration was observed.

Following the artificial drying test of edged lumber with a thickness of 50mm, the following findings can be formulated:

- based on practical experience gained when drying 28mm-thick lumber, the initial heating phase was carried out at a temperature of 30°C and a relative humidity of 87% (U_e =18%), but had a longer duration of 8 hours;
- by reducing the relative air humidity to 85%, the transition to the actual drying phase was made and indeed, in this case too, the wood humidity began to decrease;
- after the surface humidity reached U_{sf} =24%, the gradual increase in temperature by 5°C began, alternating with a decrease in relative humidity by 5%;
- around 34% wood moisture content, it was necessary to increase the temperature to 50...60°C combined with a relative humidity of 60...50% to avoid drying stagnation; it should be noted that the absence of forced air circulation is what leads to this stagnation;
- once the average humidity over the thickness of the test pieces reached the value U_{sf} =24%, the process was accelerated by reducing the air humidity, imposing a drying gradient of 2.2; in the bound water elimination area, drying took 29 days to reduce the humidity from 24.1% (average) to 13.95% (average), equivalent to a drying rate of 0.35%/day;
- no pieces showed cracks due to drying; pre-existing cracks widened; surface cracks that appeared during steaming closed after drying;
- no piece was deformed;
- the case-hardening test revealed that, at the limit, the applied schedule is correct, the pieces suffering case-hardening close to the maximum admissible limit for standard drying (≤3mm); the steamed pieces showed slightly less case-hardening than the non-steamed artificially dried pieces, but overall the drying quality of the steamed pieces was better, completely free of cracks.

These conclusions, together with those resulting from previous drying tests, allowed the formulation of recommendations regarding the optimal drying schedule for 50mm-thick ceiling lumber.

5.2.4 Interpretation of results and formulation of optimal drying schedules

28mm thick lumber. Given the results obtained, it is considered that only minor adjustments are needed, specifically limiting the maximum temperature to 55°C and reducing the drying gradient in the final phase of the actual drying. The proposed optimal schedule is found in Table 5.26.

The diagram in Fig. 5.35 represents the optimal schedule developed for 28mm oak lumber (curves with solid lines), compared to the drying schedule recommended by the SECAL company (Italy), for oak lumber of the same thickness (curves with dashed lines).

Table 5.26

The optimal drying schedule proposed for 28mm thick lumber

Phase	Wood moisture, %	Temperature, °C	Relative humidity, %	Equilibrium humidity, %	Drying gradient
Initial heating	U_i	30	87	18	-
Actual drying	U_i...36	30	85...83	17.5...17.0	-
	36...24	50	83...75	15.5...12.6	-
	24...16	50	70...43	11.5... 7.0	2.3
	16...U_f	55	43...23	7.0....4.3	2.3
Cooling	U_f	30	-	-	-

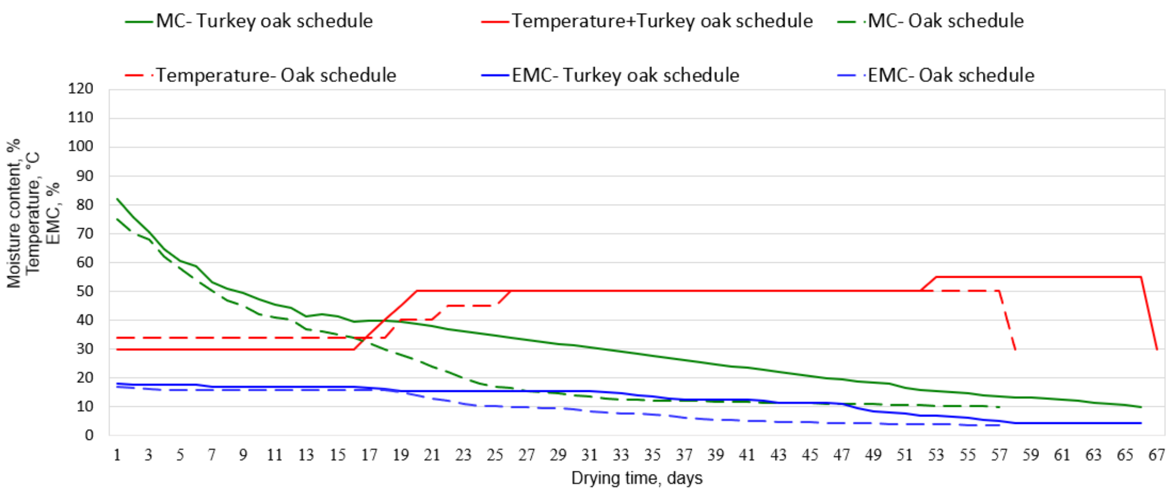


Fig.5.35 Graphic representation of the optimal schedule for 28mm Turkey oak lumber compared to the recommended schedule for 28mm oak lumber

It is observed that the drying time for the 28mm thick lumber is 15% (9 days) longer. The main features of the schedule developed in this research for the 28mm thick lumber can be summarized as follows:

- in the first stage of actual drying, the temperature must be 30°C lower than 34°C, and the equilibrium humidity must be higher (17.5% compared to 16.5%);
- the temperature can be raised from the moment the humidity reaches 40%, while for oak it is expected to reach 30% humidity;
- the maximum temperature supported by Turkey oak wood is 55 ° C. However, it is recommended to raise it to this value only after the wood reaches a fiber saturation moisture of 24%.

50mm thick lumber. The optimal schedule proposed based on the research results in this paper for 50mm thick lumber is presented in Table 5.27.

Table 5.27
The optimal drying schedule proposed for 50mm thick lumber

Phase	Wood moisture, %	Temperature, °C	Relative humidity, %	Equilibrium humidity, %	Drying gradient
Initial heating	Doors	30	87	18	-
Actual drying	U_{and}...40	30	85...80	17.5...16	
	40...24	35	80...70	16...12.5	
	24...16	40	60...50	10.2...8.7	2.2
	16...U_f	50	40...20	6.7...4.2	2.2
Conditioning	U_f	40	50	U_f	-
Cooling	U_f	30	-	-	-

The proposed schedule for 50mm-thick lumber is gentler not only due to lower temperatures in different stages of the process and the lower value of the drying gradient, but also in terms of the wood moisture at which it is recommended to raise the temperature (U=36% for 28mm thick lumber and U=24% for 50mm thick lumber).

And compared to the schedule applied to the industrial batch presented in the exploratory research, the proposed schedule is milder by:

- an initial temperature that is lower than 30°C compared to 36-38°C;
- a maximum temperature 15°C lower;
- the wood moisture at which the temperature is raised being 24% compared to 30% in the experimental batch;
- a higher equilibrium humidity in the last phase of the actual drying: 4.2-6.7% in the proposed schedule compared to 2-3% in the experimental batch.

The diagram in Fig. 5.36 represents the optimal schedule developed for 50mm-thick oak lumber (solid line curves) compared to the drying schedule recommended by SECAL (Italy) for oak lumber of the same thickness (dashed line curves).

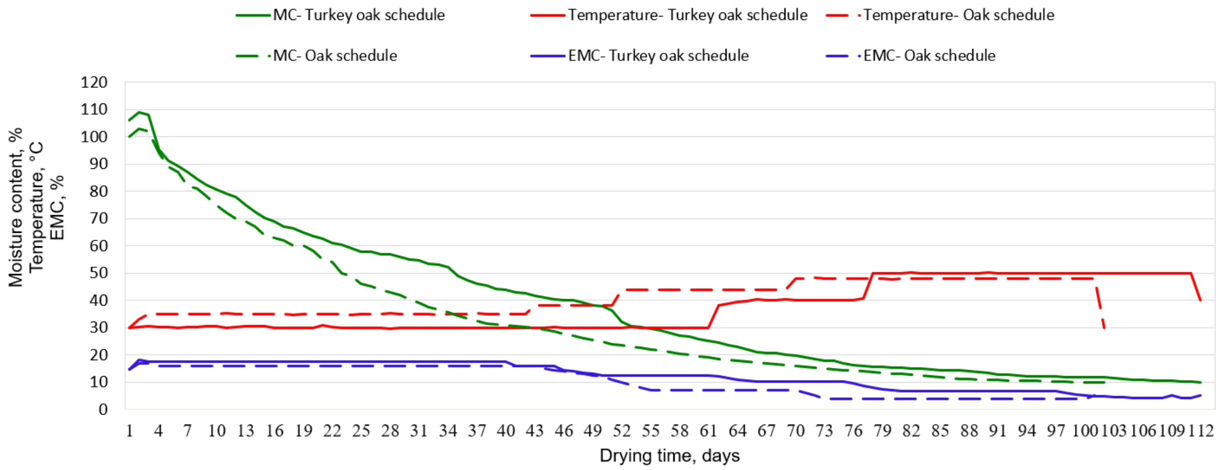


Fig. 5.36 Graphic representation of the optimal schedule for 50mm Turkey oak lumber compared to the recommended schedule for 50mm oak lumber

It is observed that the drying time for the 50mm thick lumber is 10.7% (11 days) longer. The main features of the schedule developed in the thesis for the 50mm thick lumber can be summarized as follows:

- in the first stage of actual drying, the temperature must be 30°C lower than 35°C, and the equilibrium humidity must be higher (17.5% compared to 15.8%);
- the temperature can be raised from the moment the humidity reaches 24%, while for oak it is expected to reach 30% humidity;
- the maximum temperature supported by 50mm Turkey oak wood is 50° C. However, it is recommended to raise it to this value only after the wood reaches a fiber saturation moisture of 16%.

To validate the proposed schedule, a batch of 50mm thick lumber was dried in an industrial facility of the SECAL company, applying the schedule in Table 5.27.

5.3 Industrial drying of a batch of Turkey oak and oak lumber to validate the proposed schedule

5.3.1 Material, method, apparatus

The material used for this research consisted of Turkey oak and oak lumber boards, with lengths ranging from 2m to 3.5m, widths of 10-30cm and a thickness of 50mm.

The boards were introduced into a SECAL-type dryer (Italy) with a capacity of 100 m^3: 32 stacks, of which 8 stacks of Turkey oak lumber and 24 of oak. The average initial humidity was 66.2±7% for Turkey oak lumber and 66.9±2% for oak.

Wood moisture was monitored using eight resistive sensors inserted halfway into the test boards. Four of the sensors were placed in Turkey oak boards and the other half in oak boards.

At the end of the process, the drying record sheet and drying diagram were saved, automatically recorded by the process computer.

The final quality control was carried out in accordance with the SR EN 14298:2005 standard, according to which the quality of drying is expressed by the uniformity of the final moisture content in a batch. Optionally (for lumber thicker than 40mm) it is also recommended to evaluate the degree of case-hardening according to the SR EN 14298:2005 standard.

Depending on the batch size, the number of packages to be randomly selected and opened is determined (according to the SR EN 12169:2000 standard). In the present research, the batch had a total of 32 packages (stacks), so four were opened, two of each species.

In the case of the industrial batch, it is included a total of 1205 pieces of lumber, for which the standard requires 125 pieces to be measured. A total of 126 pieces were selected, 63 for each species.

According to the SR EN 14298:2005 standard, for the batch to be compliant, two criteria must be met:

- the average moisture content of the 63 boards should fall within the range of ω_{tar} ±1.5% (when ω_{tar} =10…12%) and ω_{tar} ±1% (when ω_{tar} =7…9%), where ω_{tar} is the targeted moisture content (in the present research ω_{tar} for Turkey oak was 10%, and for oak 8%) (Table 5.30);
- 93.5% of the pieces must have an individual moisture content between 0.7 ω_{tar} and 1.3 ω_{tar}.

If one of these requirements is not met, then the batch cannot be considered compliant with regard to moisture content uniformity.

Given the thickness of the dried lumber (50mm), a case-hardening test was also considered necessary to assess the quality of drying. The case-hardening test was performed on 16 boards of each species.

To assess the number and severity of cracks, visual analysis was performed after drying of the 63 pieces selected for each species.

5.3.2 Results and discussions

Drying time and speed. The drying diagram of the industrial batch is shown in Fig. 5.41. As can be seen, the process started with an initial heating phase during which the temperature reached 30°C. and the equilibrium humidity increased to 18%.

During this phase, the moisture content of the Turkey oak wood increased by 3.5% and that of the oak wood by 1.8%. The duration of the initial heating phase was 24 hours.

Subsequently, the equilibrium humidity was reduced to 17.5% to begin the actual drying. The temperature was then kept constant at 30°C and the equilibrium humidity gradually decreased from 17.5% to 16% over the 51 days of actual drying until the average moisture content measured by the eight sensors reached 40%. At this point, the temperature gradually increased to a maximum value of 50°C towards the end of the process. Simultaneously, the equilibrium humidity was continuously reduced from 16% to 4%.

The actual drying period lasted 111 days. During this time, the Turkey oak planks reduced their moisture content from 66.2% to 10.8%, while the oak planks dried from 66.9% to 8%, which equates to a drying rate of 0.5%/day for Turkey oak and 0.53%/day for oak.

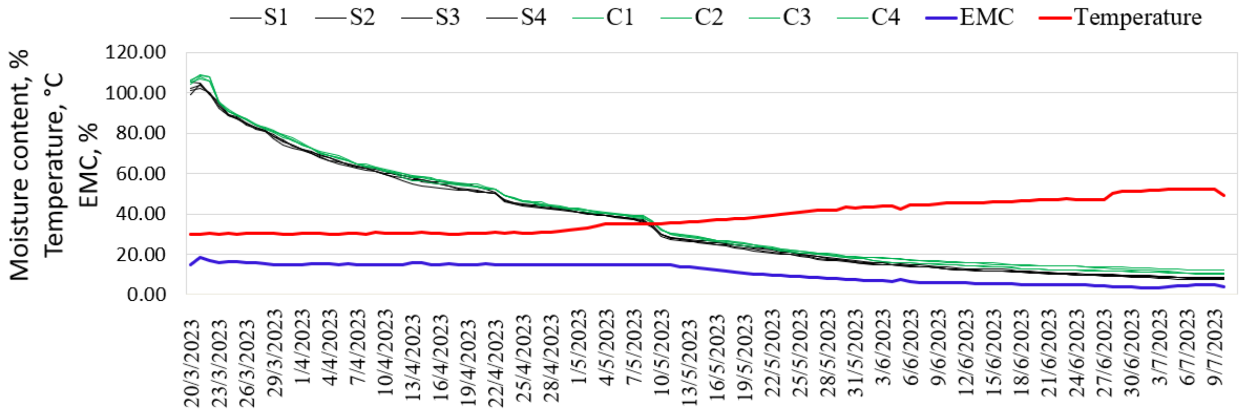


Fig. 5.41 Drying diagram for the Turkey oak lumber and oak in a industrial dryer : S- Oak ; C- Turkey oak

Comparing the drying rate values obtained during kiln-drying with and without forced air circulation (Fig. 5. 42), it is observed that air speed has a decisive influence on drying only in the free water range.

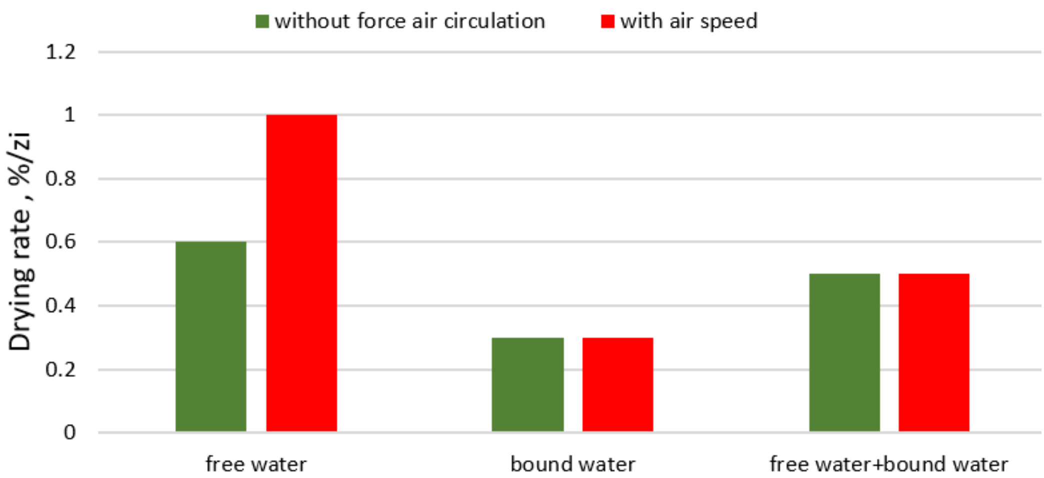


Fig. 5.42 Drying speed of 50mm thick lumber

Quality drying - Uniformity final humidity. Measurement The final moisture content was measured on the 63 boards of each species, chosen randomly from the 4 opened stacks. The results obtained were grouped into four intervals (Fig.5.43) .

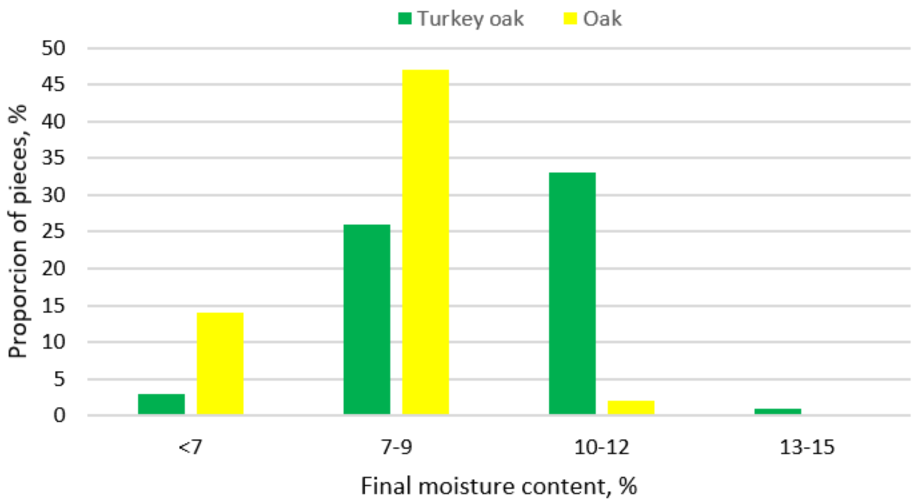


Fig.5.43 Final moiture content of the Turkey oak lumber and oak with a thickness of 50mm dried in an industrial dryer

It is observed that, Turkey oak lumber the majority of the pieces (52.38%) were within the humidity final in the range of 10-12%, the majority of oak pieces (74.60%) were included in the range of 7-9%, which looks once again the difference in drying dynamics between the two species.

Both species had average final humidity values located in the given allowed interval, depending on the targeted environmental humidity content:

- for oak : $\omega_{final, average}$ =8.06%± 1%$\in$ [ω_{target} ±1%], i.e. 7...9%;
- for Turkey oak : $\omega_{final, average}$ =10.17% ±1.5%$\in$ [ω_{tar} ±1.5%], i.e. 8.5...11.5%.

Following the count, it was found that 59 Turkey oak (93.5%) and 62 oak (98.41%) boards had a final moisture content content within the range 0.7 ω_{tar} - 1.3 ω_{tar}. According to SR EN 14298:2005, the Turkey oak lumber was thus close to the lower limit of meeting this compliance criterion, while the oak wood also met this second compliance criterion without any problems.

Quality drying - Case-hardening test . A total of 16 samples of each species were tested and their degree of case-hardening was assessed by measuring the opening after conditioning in a climatic chamber. The values were grouped into three intervals to highlight the frequency of different sizes of opening (severity of case-hardening) (Fig.5.44). It is observed that the Turkey oak planks had a higher value of sag value (Fig.5.45).

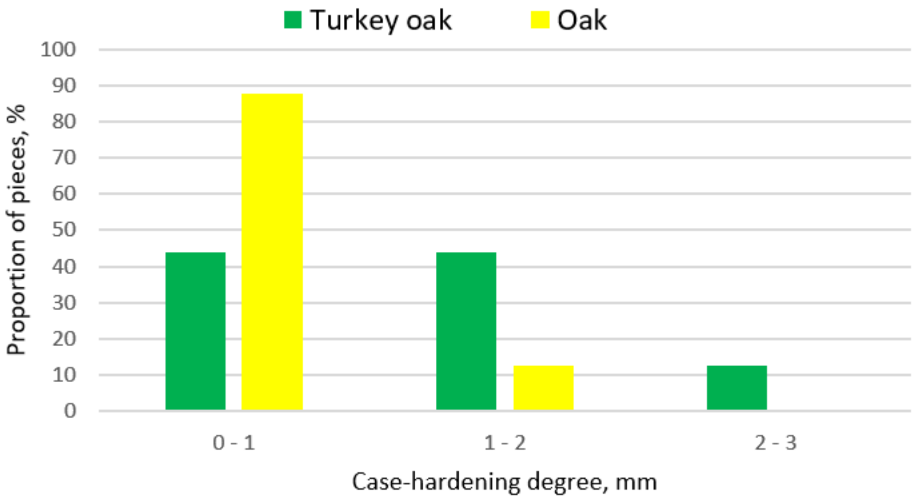


Fig. 5.44 Opening size obtained from the case-hardening test for industrially dried 50mm thick oak and Turkey oak lumber

a. ***b.***

Fig. 5.45 Case-hardening measurement: a – Turkey oak; b – Oak

Quality drying – Cracks . Visual examination of the boards showed that:

● In the case of Turkey oak wood: 6 (9.5%) of the boards analyzed showed severe surface cracks , and 14 (22.22%) showed end cracks despite paraffin protection . Only 2 of the boards analyzed (3.17%) also showed internal cracks as well;

● In the case of oak wood: 37 (58.7%) of the analyzed planks showed severe surface cracks , and 55 (87.3%) showed end-to-end cracks. Addittionally, 35 pieces (55.55%) showed surface cracks ; however, none exhibited internal cracks.

5.3.3 Conclusions

This research led to the following conclusions:

1. In the field of free water removal, drying occurs at a similar drying rate, with an average of 1%/day.

2. In terms of bound water removal, the drying speed is lower for alder than for oak. This is why when drying both species within the same batch, a difference of at least 2-3% in the final moisture content occurs (for example, 10-11% for alder, while oak reaches 8%).

3. Oak wood dries more evenly. The final moisture values are less variable than in the case of Turkey oak wood.

4. Turkey oak wood develops higher internal stresses during drying than oak wood.

5. Oak wood developed a higher proportion of surface and end cracks, but internal cracks only appeared in alder wood, in a very low proportion (3%).

6. Comparing the industrial batch, dried with the schedule developed in this research, with the reference batch from the preliminary research, carried out at another enterprise (with the existing software schedule on that installation), a number of differences were found. These are summarized in Table 5.35.

Table 5. 35
Comparative analysis of drying indicators for the experimental batch compared to the reference batch

Criterion	**Reference batch**	**Experimental batch**	**Percentage change recorded in the experimental batch**
Drying time, days	102	113	Increase by 10.8%
Initial temperature, °C	36-38	30	-
Maximum temperature, °C	65	50	-
Average final moisture, %	8	10	-
Uniformity of final moisture content within the batch (percentage of conforming parts)	56.5	93.5	Increase by 65.5%
Case-hardening degree, mm	1.85 ± 0.33	1.44±0.68	22.16% decrease
Surface cracks, %	28.5	22.22	22.03% decrease
End cracks, %	57.5	9.5	83.5% decrease
Internal cracks, %	13.3	3.17	76.17% decrease
Coloration	Yes	Not	

Compared to the reference batch, the proposed schedule allowed for improving the drying quality by achieving a more uniform drying, reducing the proportion of cracks in all categories and the size of the case-hardening. It is true that the duration was extended by 10.8% (11 days) which was due to the application of a milder schedule. The consequences of this extension of the duration are the proportional decrease in the annual drying capacity (by approx. 30m^3 /year) and the increase in energy consumption (by approx. 1.62euro/m^3). Under these conditions, it is considered that the advantages obtained from a qualitative point of view compensate for the disadvantage of the extended duration. In conclusion, it can be stated that the proposed schedule has demonstrated its efficiency.

Chapter 6. GENERAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS. DISSEMINATION OF RESULTS. FUTURE RESEARCH DIRECTIONS

6.1 General conclusions

Following the research carried out, the following conclusions can be drawn:

1. Although conventional drying of oak wood is a challenge, Romanian industry companies demonstrate good expertise in controlling the drying process and achieving satisfactory results. According to the survey conducted in 10 specialized companies in Romania that dry oak lumber, the main aspects that require optimization are: reducing the duration, improving the uniformity of the final moisture content, reducing the proportion of cracks, especially the end ones, and avoiding discoloration.

2. Macroscopic analysis of the Turkey oak wood showed that it has a lower heartwood proportion than that characteristic of oak and alder wood (P_d =50%). This means that when cutting, either very narrow pieces are obtained (containing only sapwood or only heartwood), or pieces that include both sapwood and heartwood areas. Drying these wide pieces proved difficult, being accompanied by the appearance of numerous cracks, both surface and internal. Drying in the form of narrow planks is recommended.

3. The colour tests used to indirectly determine the content of tanning substances showed that the content of tannin in the Turkey oak wood is lower than in the Sessile oak wood, both in the sapwood and in the heartwood. Thus, the risk of drying discolorations when drying the Turkey oak wood can be considered lower than when drying the pedunculate/sessile oak wood. The drying tests confirmed this conclusion: in none of the drying tests carried out, the dried pieces showed this type of defect.

4. Tests on the determination of secondary chemical compounds revealed that the pine sapwood contains an appreciable amount of extractable substances, the percentage obtained, for example, by the extraction method with NaOH solution being 26.5% higher than in the pine heartwood and only 19.8% lower than in the pine heartwood. This result correlates very well with the result regarding the density of the Turkey oak wood, which proved to be 1.27% higher in the sapwood than in the heartwood - an unexpected result, but also noted by other researchers (*e.g.,* Merela and Cufar 2012).

5. With a value of approx. 730 kg/m^3, the dry density of alder wood is significantly higher than that of oak and alder wood. This result explains the approx. 6% longer drying time required for this species.

6. The literature does not indicate values for the fiber saturation moisture content of Turkey oak wood. According to the results of this research, it is 24%, which is higher than that of oak heartwood (22%).

7. Natural drying proved effective only in the case of 28mm thick lumber, where, within a period of 7 months, it was possible to eliminate both free and bound water (up to 16%). For 50mm thick lumber, in the same period of time, the moisture reduction occurred only in the free water range (up to 37%). Regarding the quality of drying, the main problem of the windage was represented by end and surface cracks in both lumber thicknesses.

8. Both in terms of process duration and drying quality, the results were better in the case of artificial drying from the green state than in the case of artificial drying preceded by an outdoor fan.

9. Following the drying tests carried out in the laboratory, the following conclusions were drawn regarding the optimal artificial drying conditions:

- in the first stage of the actual drying the temperature must be 30°C and the equilibrium humidity must be 17.5%. This combination extends the time required to eliminate free water, but ensures the gradual adaptation of the wood to the drying environment so that it does not accumulate tensions;
- The temperature can be raised from the moment the humidity reaches
- The maximum temperature supported by the Turkey oak wood is 55 ° C for 28mm lumber and 50°C for 50mm thick lumber. However, it is recommended to raise this value only after the wood reaches 40% for 28mm lumber and 24% for 50mm thick lumber.

10. Based on observations from the various drying tests carried out in the laboratory with Turkey oak lumber, two schedules considered optimal for Turkey oak lumber of 28mm (Table 5.26) and 50mm (Table 5.27) were established.

11. The industrial-scale implementation of the schedule for 50mm thick Turkey oak lumber has shown that it is possible to improve the drying quality of this species without significantly affecting the duration (Table 5.35).

6.2 Original contributions

The original contributions are found in all stages of the thesis development and can be summarized as follows:

- Creating a synthesis of information regarding the particularities, properties and drying behavior of Turkey oak wood;
- Establishing the research methodology adopted within the present doctoral thesis;
- Designing a questionnaire to conduct a survey in ten companies in Romania that dry oak lumber;
- Analysis and interpretation of survey responses, establishing correlations between drying conditions applied by different companies and declared drying defects (Table

3.5). These correlations revealed aspects that can be improved in the industrial drying of Turkey oak;

- Characterization of the Turkey oak wood, originating from the Getic Subcarpathian area, which has an important share of the Turkey oak wood resource in Romania, in terms of structure, secondary chemical components and relevant physical properties in the drying process;
- Carrying out two exploratory researches on the drying of oak lumber with other oak species: one in laboratory conditions and one in industrial conditions;
- Development of the experimental drying plan under different conditions (natural drying vs. artificial drying, without and with forced air circulation) for 28mm and 50mm thick lumber;
- Creation of an experimental stand for continuous monitoring of wood moisture during drying in a climatic chamber;
- Development of a guideline on drying schedules for lumber, useful for production specialists;
- Development of optimal drying schedules for 28mm and 50mm thick lumber;
- Managing the drying of an industrial batch of Turkey oak lumber and performing final quality control according to the developed methodology.

6.3 Dissemination of results

The results of the research conducted were published in 6 ISI and BDI indexed articles, all as first author.

1. Deaconu, I., Campean, M. (2022). "Survey concerning the challenges of industrial drying of Quercus cerris wood," *PRO LIGNO* 18(4), 36-44, ONLINE ISSN 2069-7430, ISSN-L 1841-4737.

2. Deaconu, I., Georgescu, SV, Campean, M. (2022). "Evaluating a drying schedule for oak lumber through drying rate calculation and quality assessment," *PRO LIGNO* 18(2), 42-47, ONLINE ISSN 2069-7430, ISSN-l 1841-4737.

3. Deaconu, I., Porojan, M., Timar, M. C., Bedelean, B., Câmpean, M. (2023). "Comparative research on the structure, chemistry, and physical properties of Turkey oak and sessile oak wood," *BioResources* 18(3), 5724-5749. DOI: 10.15376/biores.18.3.5724-5749.

4. Deaconu, I.T., Georgescu, S.V., Câmpean, M. (2023). "Drying Behaviour of 50mm Thick Turkey Oak Lumber," *Appl. Sci* 13(9), 10676 https://doi.org/10.3390/app131910676.

5. Deaconu I., Timar, M.C., Bedelean, B., Câmpean, M. (2023). "Comparative research regarding the hydrophilic extractives content in Turkey oak and sessile oak wood and their related staining susceptibility by reaction with iron," *Bulletin of the Transilvania University of Brasov* , Series II: Forestry Wood Industry Agricultural Food Engineering, Vol. 16 (65), No.2, DOI: https://doi.org/10.31926/but.fwiafe.2023.16.65.3.4.

6. Deaconu, I., Bedelean, B., Georgescu, SV, Zeleniuc , O., Câmpean , M. (2024). "Quantitative and qualitative aspects of industrial drying of Turkey oak lumber," *11 th Hardwood Conference*

Proceedings , 30-31 May 2024, Sopron, Hungary, pp.508-517, ISBN 978-963-334-518-4 (pdf) DOI https://doi.org/10.35511/978-963-334-518-4 ; ISSN 2631-004 X.

6.4 Future research directions

Based on the results and conclusions from the thesis, the following future research directions can be formulated:

1. Conduct a broader national survey on the application of different drying processes for other species.

2. Using the methodologies developed in this research to study the drying of other species.

3. Conducting research on the finishing of Turkey oak wood, with a view to the larger-scale exploitation of Turkey oak wood in the production of furniture, finished wood products, and interior and exterior design.

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