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SURVEY CONCERNING THE CHALLENGES OF INDUSTRIAL DRYING OF QUERCUS LUMBER

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Abstract:
The paper presents the results of a survey performed in ten Romanian wood-processing companies which dry oak lumber (mainly Quercus petraea and Quercus robur, but also Quercus cerris). The purpose of this survey was to establish the current conditions applied for carrying out the drying process for these species, and to establish the aspects which need to be improved, according to the industrials' opinion. The results of this survey show the present level of applied knowledge concerning the drying of these species, but also some shortcomings that are prone to optimization. The information synthetized from the survey is to be used as starting point to set-up a plan for the scientific investigation of the conventional drying of oak lumber, especially of Quercus cerris, which has been less studied so far. Improving the drying uniformity, reducing the proportion of cracks, and drying time reduction are the main targets envisaged.

Key words: *survey; questionnaire; air drying; kiln drying; Quercus petraea; Quercus robur; Quercus cerris.*

INTRODUCTION

Oak wood represents one of Romania's most valuable natural resources, appreciated both in the furniture industry due to its special aesthetics, and in the construction industry, due to its high density, high mechanical strengths and very good natural durability.

Covering a surface of ca. 730000ha, the Romanian oak forests represent 15.9% of the hardwood forest area. They deliver annually 1894000m^3 of wood (out of which, ca. 71.8% is valorized as lumber). (https://insse.ro/cms/sites/default/files/field/publicatii/statistica_activitatilor_din_silvicultura_in_anul_2020.pdf).

The main represented *Quercus* species are:
• Pedunculate oak (*Quercus robur* L.);
• Sessile oak (*Quercus petraea* (Matt.Libl.);
• Turkey oak (*Quercus cerris* L.),
and in much lower quantities:
• Hungarian oak or Italian oak (*Quercus frainetto* Ten);
• Downy oak (*Quercus pubescens* Willd.);
• Red oak (*Quercus rubra* L.).

According to national statistics (https://silvanews.ro/silvicultura/silvotehnica/cata-padure-mai-avem-romania/), sessile oak has the highest share, with 10.8% of the Romanian hardwood forest fund; followed by Turkey oak, with 2.9%, and then by pedunculate oak, with 2.2%.

The drying of *Quercus* lumber always represented a challenge for industrials because, being a species with high density and an inhomogeneous, ring-porous structure, oak lumber develops high internal stresses during drying, and is prone to cracking. Even when applying air-drying or mild kiln-drying conditions, quality issues are frequent, especially with thick grades.

Only few scientific references were specifically dedicated to the drying behavior of oak lumber (*e.g.* Lamb and Wengert 1990, Campean and Lazarescu 2016), in order to assist industrials to deal with this challenge.

In order to establish the present level of applied knowledge concerning the drying of these species, a survey was conducted by the authors in 10 Romanian industries.

OBJECTIVE

The main outcome of this survey was to establish the current conditions applied for carrying out the drying process for these species, and also, to assess the main shortcomings, and to establish the aspects that need to be improved.

The results of this survey are meant to constitute a database to be used as a starting point for an optimization attempt through scientific research.

METHOD

The survey was based on a questionnaire, which was distributed in 10 Romanian wood-processing companies from different regions of the country (Fig. 1), which mainly dry and process *Quercus* lumber.

Fig. 1.
Positioning of the ten Romanian enterprises selected for the survey concerning the drying of Quercus lumber.

The questionnaire included a number of 10 questions, most of them having grid-type answer options, in order to be as suggestive, answer-friendly and time-effective as possible.

The questions envisaged:

- the processed *Quercus* species;
- the annually dried quantity, in m^3/year;
- the drying expertise of the company, in years;
- the drying method applied (exclusive kiln-drying, or air-drying followed by kiln drying); for the air-drying method: the moisture decrease interval, and the drying duration as function of the lumber thickness were also demanded;
- the kiln capacity (drying volume within one batch), in m^3;
- the control system used (manual or automatic);
- details regarding the kiln-drying conditions: temperature, humidity, drying gradient, as well as the total drying time for a specified moisture decrease interval;
- details regarding the most frequent drying defects;
- aspects desired to be optimized.

RESULTS AND DISCUSSION

The questionnaire analysis showed that:

- 70% of the respondent companies dry only sessile and pedunculate oak lumber, while 30% also dry Turkey oak lumber;
- 50% of the respondent companies dry over 1500m^3/year;
- 80% of the respondent companies have more than 10 years of drying experience, 10% between 5-10 years, and 10% less than 5 years.

Regarding the method used to reduce the moisture content of wood (MC) down to 30-40%, 30% of the respondent companies choose to kiln-dry the lumber from green state, while 60% air-dry the lumber before introducing it into the dryer. One company buys pre-dried lumber (MC=38%) and kiln-dries it from this point forward.

The average duration of the air-drying from green state to MC=30-40% (as given in Table 1) varies between 2 months for the thinner lumber (25mm) and 4 months for the thicker lumber (50mm). These values refer to early summer to autumn months (May-September), which in the temperate climate of Romania is the only one suitable for air-drying. In one single case, a duration of 9 months of the air-drying of 50mm thick Turkey oak was reported, probably due to the fact that the lumber was stacked in winter.

Based on these values, the drying rate was also calculated in each situation, as ratio between the moisture content decrease interval, and the afferent drying time:

$$\text{Drying rate} = \frac{\Delta\text{MC}}{\text{Time}} \quad [\%/\text{day}] \quad (1)$$

For the sessile/pedunculate oak lumber, its values ranged between 0.16%/day for 50mm thick lumber, and 0.5%/day for 25mm thick lumber (Fig. 2). The low number of responses for Turkey oak lumber does not allow any statement regarding this species at this point, but the value obtained from the single respondent who air-dries this species indicates a much longer air-drying time than for sessile/pedunculate oak. This behavior can be explained by the higher density (767…776kg/m^3) compared to 634…658kg/m^3 for *Quercus petraea/robur* originating from the same areal (Merela and Cufar 2013).

Table 1

Air-drying time for oak lumber

Species	Thickness, mm	Initial MC, %	Final MC, %	Drying time, days	Drying rate, %/day
Sessile oak, pedunculate oak	25 50	60 60	40 50	60 60	0.50 0.16
Sessile oak, pedunculate oak	50	60	40	100-120	0.16…0.20
Sessile oak, pedunculate oak	40	50	35	60	0.25
Sessile oak, pedunculate oak	35	50	30	60	0.33
Sessile oak, pedunculate oak	30	50	24	180	0.14
Turkey oak	44	45	35	270	0.04

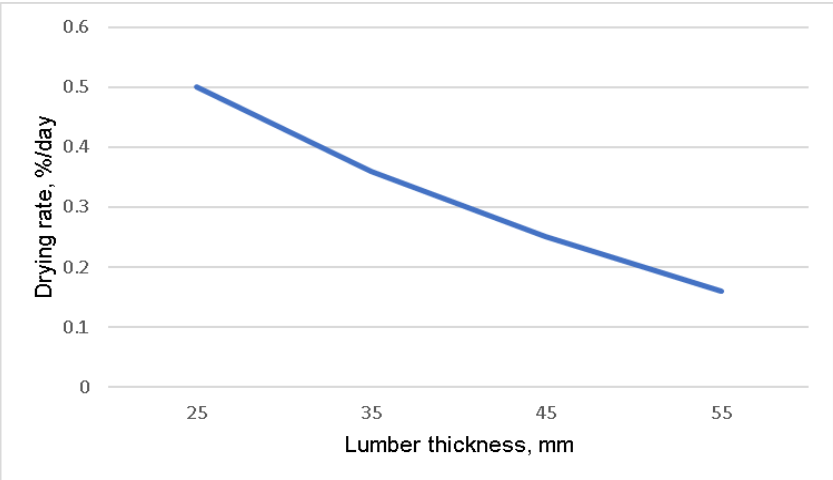


Fig. 2.
Average air-drying rate of Quercus petraea and Quercus robur lumber as function of wood thickness.

When referring to the kiln-drying method, 100% of the respondent companies apply conventional drying. Half of them have kilns with a drying capacity of 50-80m^3/load, 20% of the respondents have smaller kilns, with a capacity lower than 50m^3/load, and the other 30% have large kilns, with a capacity higher than 100m^3/load.

Regarding the kiln-drying conditions applied, the following conclusions can be formulated from the filled-in questionnaires:

- 100% of the respondents use a temperature of 30...35°C at the beginning of the process; this temperature is correlated in 80% of the cases with an equilibrium moisture content (EMC) of 15…17%, while the other 20% choose an EMC<14%;
- 30% of the respondents use a maximum temperature (T_{max}) of 50°C after the fiber saturation moisture content is reached; the majority (50%) use T_{max}= 60°C, and 20% go up to T_{max}= 70°C;

• the drying gradient (DG) varies between 1.5 and 2.5: 40% of the respondents dry with the mild DG=1.5, 30% dry with DG=2, and 30% of the respondents dry with the quite severe DG=2.5, or even 3.

The kiln-drying time reported by the respondents as function of species, lumber thickness, initial and final moisture content is given in Tables 2 and 3. Based on these values, the drying rate was also calculated in each situation, using Eq. 1.

Table 2

Kiln-drying time for 25mm thick oak lumber

Species	Initial MC, %	Final MC, %	Drying time, days	Drying rate, %/day
Drying from green state				
Sessile oak, pedunculate oak	50	8	28	1.5
Sessile oak, pedunculate oak	50	10	30	1.3
Sessile oak, pedunculate oak	55	8	20	2.35
Turkey oak	60	8	90*	0.58*
Turkey oak	75	8	45*	1.49*
Drying from pre-dried state				
Sessile oak, pedunculate oak	40	10	40*	0.75*
Sessile oak, pedunculate oak	40	8	21	1.52
Sessile oak, pedunculate oak	38	8	21	1.42
Sessile oak, pedunculate oak	24	8	14	1.14
Turkey oak	35	8	45*	0.6*

**marked values are highly different from other values reported for similar grades and were excluded from the calculation of the averages.*

It can be noticed that the average drying time for 25mm thick sessile/pedunculate oak lumber is around 30 days, when drying from green state to 8-10%, and around 20 days when drying from 35-40% to the same final moisture content. The low number of responses, and quite contradictory results obtained for Turkey oak lumber do not allow any statement regarding this species at this point. However, it is confirmed that Turkey oak dries much slower than sessile/pedunculate oak, which can be attributed

Table 3

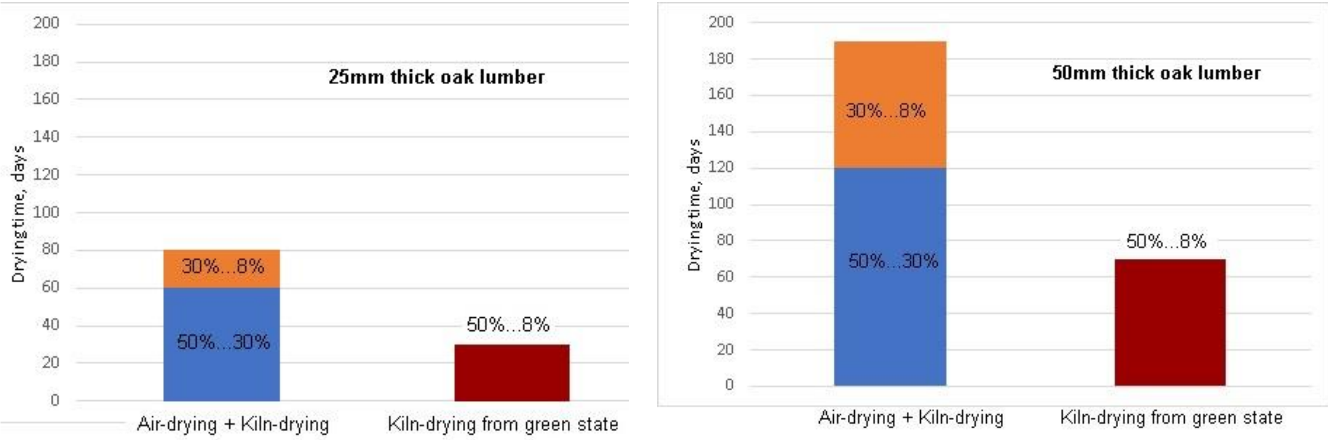
Kiln-drying time for 50mm thick oak lumber

Species	Initial MC, %	Final MC, %	Drying time, days	Drying rate, %/day
Drying from green state				
Sessile oak, pedunculate oak	50	8	50	0.84
Sessile oak, pedunculate oak	50	8	90	0.47
Sessile oak, pedunculate oak	55	8	45	1.04
Sessile oak, pedunculate oak, Turkey oak	60	8	90	0.58
Turkey oak	75	8	75	0.89
Drying from pre-dried state				
Sessile oak, pedunculate oak	40	10	60	0.5
Sessile oak, pedunculate oak	40	8	90*	0.35*
Sessile oak, pedunculate oak	38	8	50	0.6
Sessile oak, pedunculate oak	24	8	42	0.38
Turkey oak	35	8	45	0.6

**marked values are highly different from other values reported for similar grades and were excluded from the calculation of the averages*

The average drying time for 50mm thick sessile/pedunculate oak lumber is around 70 days, when drying from green state to 8-10%, and around 50 days when drying from 35-40% to the same final moisture content. With 50mm thick Turkey oak lumber, the kiln-drying time from 35-40% to 8% is similar (45 days).

Thus, the survey results show that the drying time from green state down to a moisture content of 8% is ca. 2.5 times lower when applying kiln-drying from the beginning (Fig. 3).



a. ***b.***

Fig. 3.
Reduction of drying time when kiln-drying oak lumber directly from green state:
a – 25mm thickness; b – 50mm thickness.

As far as the drying defects are concerned, most of the respondents indicated the end cracks as the most frequent defect, followed by the deformations. All other usual drying defects (like uneven moisture, high moisture gradient over the lumber thickness, surface checks, discolorations) were reported by less than half of the respondents. Just 10% of the respondents indicated inner cracks as a frequent defect (Fig. 4) in drying Turkey oak.

This result lets us conclude that the obtained qulaity is quite good, better than expected. One may suspect that this result is due to a lack of measurements performed at the end of the process, in order to assess the drying quality according to all criteria proposed by reference literature (Cividini 2000), but the question concerning the percentage of compliant pieces confirms that the interviewed companies are satisfied with the drying quality obtained (Fig. 5). This is also due that most of the respondents (60%) are furniture manufacturers and their fabrication programme allows valorizing even lumber pieces with defects by smart cuts. Moreover, in many cases (especially for Turkey oak), the end product are rustic tables, where cracks are often desired to create the „aged" impression.

As far as the envisaged optimization directions are concerned, most of the respondents (70%) required solutions for reducing the drying time and the cracking tendency (Fig. 6).

Following-up the demands expressed by the interviewed industrials, a correlation of their answers concerning the most frequent drying defects with the drying method, the drying conditions applied, and with the drying time was performed (Table 4).

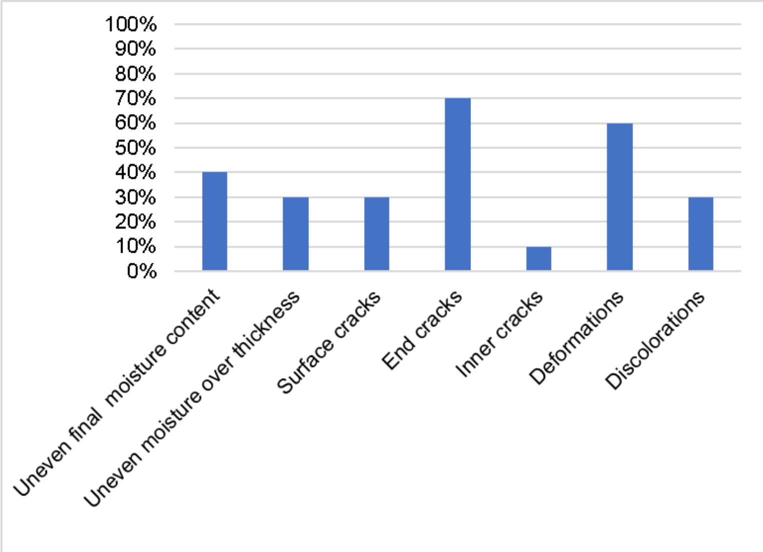


Fig. 4.
The most frequent drying defects, as resulted from the survey.

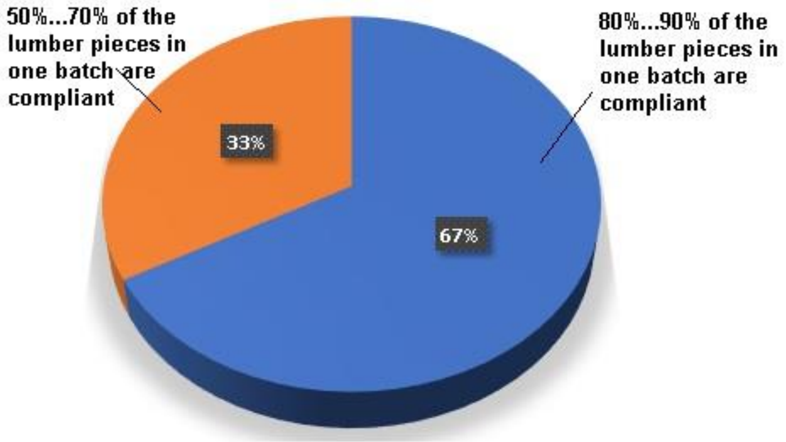


Fig. 5.
Degree of satisfaction concerning the percentage of compliant pieces from one batch, after drying.

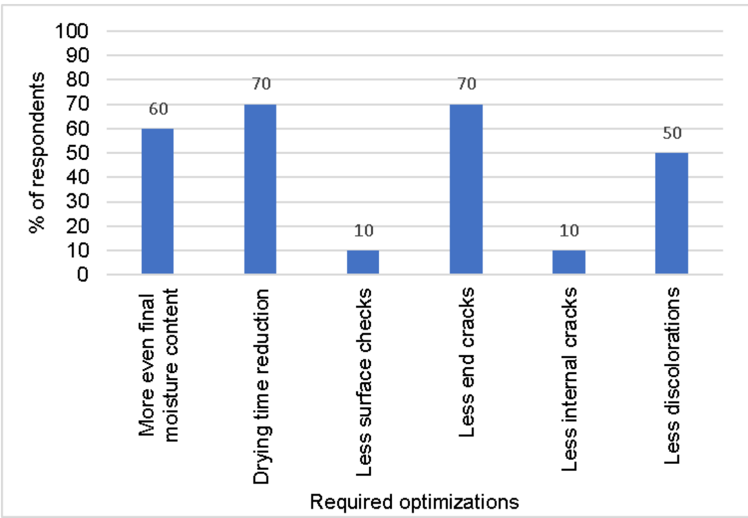


Fig. 6.
Necessary optimization directions according to the respondents.

Table 4

Correlation between the drying defects and the drying conditions applied

Ref. N°	Species	Drying method	Kiln capacity, m^3/batch	Observations regarding the drying schedule*	Drying time	Frequent defects	Optimization demands
1	Sessile oak, pedunculate oak	Air-drying (75%...50%) +Kiln-drying (50%...8%)	80	Mild heating; Mild drying	Average	End cracks Discoloration	Time reduction Less end cracks and discoloration
2	Sessile oak, pedunculate oak and Turkey oak	Kiln-drying from green (75%...8%)	75	Mild heating; Severe drying	High	Uneven MC Surface checks End cracks	Time reduction More even final MC Less cracks and discoloration
3	Sessile oak, pedunculate oak	Air-drying + Kiln-drying (40%...10%)	65	Mild heating; Mild drying	Slightly above average	Deformations	Time reduction More even final MC
4	Turkey oak	Air-drying + Kiln-drying (35%...8%)	62	Severe heating; Mild drying	High	Uneven MC Surface checks End cracks Deformations Discolorations	More even final MC Less end cracks
5	Sessile oak, pedunculate oak	Kiln-drying from green (55%...8%)	45	Mild heating; Mild drying	Average	Deformations	More even final MC Less discolorations
6	Turkey oak	Kiln-drying from green (60%...8%)	100	Severe heating; Severe drying	High	Uneven MC Surface checks End cracks Deformations	Time reduction More even final MC Less cracks and discolorations
7	Sessile oak, pedunculate oak	Air-drying + Kiln-drying (40%...8%)	70	Mild heating; A little bit forced drying conditions	Low for 25mm, very high for 50mm	End cracks	Time reduction More even final MC Less cracks
8	Sessile oak, pedunculate oak	Kiln-drying (38%..8%)	100	Mild heating; Mild drying	Average	Uneven MC High moisture gradient across thickness Deformations	More even final MC
9	Sessile oak, pedunculate oak	Air-drying (80%...50%) +Kiln-drying (50%...10%	100	Mild heating; A little bit forced drying conditions	Below the average	End cracks Discolorations	Time reduction Better drying quality
10	Sessile oak, pedunculate oak	Air-drying + Kiln-drying (24%...8%)	45	Mild heating; Mild drying	Below the average	End cracks Deformations	Time reduction Less cracks

* *Mild heating means T=30…35%, combined with EMC=15…17%; Severe heating means EMC<14%; Mild drying means T_{max}≤60°C and DG<2; Severe drying means T_{max}>60°C and DG>2.*

It can be noticed that the time reduction was requested both by companies which apply air-drying to pre-dry the lumber, and by those which kiln-dry from green state, in equal shares. The same measure was requested both by companies which use a mild drying schedule (which is expected to last longer), but also by companies which already use more severe drying conditions (see companies N° 2 and 6). However, it has to be mentioned that these two companies dry Turkey oak and the time reduction requirement refers to this species. So basically, for the companies which dry only sessile and pedunculate oak, with mild conditions (*e.g.* companies N° 1, 3, 7, and 9) a schedule optimization should be undertaken. For the companies which dry Turkey oak as well, a special drying schedule, milder than the one applied for the white oak species, should be developed.

The requirement concerning the uniformity of the final moisture content may be achieved through a longer initial heating, and/or through a longer conditioning period at the end of the process. Both measures are meant to reduce the moisture gradient across the lumber thickness. A longer heating period with abundant spraying is necessary when the lumber is kept in the yard for a longer period of time, like in the case of performing air-drying prior to kiln drying. A longer conditioning period is required with thick grades (>40mm). However, both measures involve longer drying time. This is why companies which require both optimization measures (*e.g.* companies N° 2, 3, 6, 7). Simultaneous monitoring of drying time and drying gradient across the lumber is envisaged within future research in order to find optimum kiln schedules, capable of reducing both parameters at the same time.

The requirement concerning less cracks is complex and delicate. End cracks are caused by the too rapid elimination of water through the lumber ends. They are practically unavoidable during air-drying, and during conventional drying, especially in the case of wood species with rays of two sizes (some wide, and others very narrow), such as *Quercus* species. Their occurrence can only be minimized by applying a paraffin-based sealer on the lumber ends, or by applying a different drying method, using superheated steam as drying agent.

The surface checks are generally caused by a too harsh drying schedule in the heating-up phase and during the first phase of actual drying, when the relative air-humidity (RH) should be around 85-90% and the EMC≅18%. As the survey also demonstrated, such high air humidity is rarely applied in practice, because it increases the drying time. So, same as in the case of the final moisture uniformity, the user has to decide if he prefers a longer time, in order to get more uniform drying and less cracks, or if the time criterion is a stronger priority.

The above-mentioned recommendations refer to the conventional drying of oak lumber. Vacuum drying in superheated steam (Brunner 1997, Joyet and Meunier 1996, Tremblay *et al*. 2001), or radio-frequency vacuum (RFV) drying (Resch and Gautsch 2001, Rosza 1996) have already proven their efficiency to simultaneously solve all issues raised by the respondents to this survey.

With Turkey oak, which raises even more problems than sessile/pedunculate oak during drying (higher drying time, higher cracking tendency), steaming prior to drying seems to be an effective solution (Todaro *et al.* 2012, Ferrari *et al.* 2013).

CONCLUSIONS AND FUTURE RESEARCH

According to the results of the survey performed in ten Romanian wood-processing enterprises that dry oak lumber conventionally, the following conclusions can be formulated:

- air-drying prior to kiln drying is still applied: 60% of the respondents air-dry the lumber before introducing it into the kiln; most of them air-dry the lumber until a moisture content of 30-40% is reached;
- the average air-drying time of sessile/pedunculate oak lumber from green state to MC=30-40% varies between 2 months for the thinner lumber (25mm) and 4 months for the thicker grades (50mm); the graph in Fig. 2 drawn based on the values obtained from the questionnaires, can be used to approximate the necessary duration of yard storage of these pieces of lumber, as function of their thickness;
- kiln-drying from green state reduces the drying time by 63% compared to air-drying down to MC=30…40% followed by kiln-drying; however, the drying quality reported is better in the case of the companies which air-dry prior to kiln drying (see Table 4, companies N°3, 4, 5);
- the kiln-drying begins in all cases with an initial heating at 30…35°C. In 80% of the cases, spraying is also present, leading to an equilibrium moisture content of 15…17%; in 20% of the cases, the EMC is kept lower (<14%) during this initial stage of the process – in these cases, the respondent companies indicated uneven final MC, surface checks, and end cracks as main defects;
- the maximum drying temperature applied in case of sessile/pedunculate oak varies between 50°C and 70°C, but most of the respondents (60%) opt for T_{max}=60°C; the total absence of reported internal cracks for these species is probably due to this low but safe temperature, which has to be considered an optimum for sessile/pedunculate oak;

• for Turkey oak, further investigation concerning the optimum T_{max} is necessary; applying 60°C or 70°C generates many drying defects (see companies N°2, 4, 6 in Table 4), so the reduction of T_{max}, also combined with a reduction of DG has to be taken into consideration when drying this species;

• the average drying rate during kiln-drying from 30% to 8% (mainly bound water removal) is around 1.3%/day for 25mm, and 0.5%/day for 50mm thick sessile/pedunculate oak lumber. Future research envisages a more detailed assessment of the drying rate over precise moisture decrease intervals (*e.g.* 40…30%, 30…20%; 20…10%), both for common/sessile oak and Turkey oak (separate approach of Turkey oak is necessary because, unlike common and sessile oak which are "white oaks", Turkey oak belongs to the group of "red oaks" and its density is higher); adapting the drying schedule to the lumber thickness is also necessary, in order to get a better control of the moisture gradient across the wood section during the process;

• even if the conventional drying is a challenge, industrials clearly showed in this survey that they reached a maturity and a good expertise in controlling this process, so as to obtain satisfactory results. The fact that more than half of the respondents valorize up to 90% of the dried lumber pieces (which means less than 10% waste) proofs that the drying of oak with air as drying agent is still a sustainable method, which deserves further investigation, in order to refining the drying schedules for common/sessile oak, and also for a better understanding of the peculiarities of drying Turkey oak.

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