Optimizing Lumber Drying Schedules For Oriental Beech and Sessile Oak Using Acoustic Emission

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The aim of this work was to detect sounds providing evidence of the creation of drying defects and to correlate such data with drying quality. A further goal was to establish sound wave thresholds of ideal drying through the drying process by using an acoustic emission (AE) monitoring method. Thus, it is projected to decrease long drying times and also drying costs by reaching to ideal drying schedules. In this study, commercially preferred sessile oak and oriental beech structural lumbers were dried with three different schedules in a conventional kiln. The lumbers were "listened to" with AE sensors while drying according to the first two schedules, which were called protective and severe, respectively. AE events of the drying experiments were compared with ambient conditions and drying classes according to the standard of European Drying Group. The third drying schedule was optimized based on the AE peaks and applied. The results showed that ideal drying times were reduced up to 19% relative to the protective drying schedule, while obtaining the same drying quality for both species.

Keywords: Acoustic emission; Drying time; Kiln drying; Oak; Beech

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INTRODUCTION

Freshly sawn wood has high moisture that needs to be removed before use. Many sawmills prefer technical drying, which means drying under controlled conditions such as relative humidity, temperature, and also air movement *etc.* instead of simple air drying. On the other hand, the control mechanism is a complex problem. There are multiple variables associated with the kiln, lumber, and atmospheric conditions. The large number of variables makes it difficult to determine optimum drying parameters for each operation. Because of this reality and lack of knowledge, many drying operators choose protective drying schedules to avoid defects. However, drying time becomes longer and also drying costs increase with the implementation of overly cautious schedules and drying operations. Ünsal (2007) indicated that the daily cost of 100 m^3 lumber capacity kiln can increase up to 140 € as a consequence of decisions about schedules of drying experiments.

Monitoring the condition of a kiln and lumber system based on automation allows the kiln operator to set manually the conditions or the control system to manage the process automatically based on time or some other inputs. However, such adjustments are more related to drying atmosphere conditions of a kiln than lumber parameters. Since moisture content (MC) is more determinable than stress, schedules have been constructed with MC as the controlling factor. But the ability to directly or indirectly measure drying stresses has been proposed as a method to control the drying process of wood species prone to checks and splits (Beall *et al.* 2005; Bond and Espinoza 2016). Although a few kiln automation software products have an option for measuring moisture gradients, they only give a choice to predict occurring defects, not to directly monitor them. For monitoring defects, nondestructive testing evaluation (NDE) can be used, which can be defined as the science on identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities and using this information to make decisions regarding appropriate applications (Ross *et al.* 1998). Compared to other nondestructive testing (NDT) methods, acoustic emission (AE) testing can be used for monitoring defects. Because of its measurement principle, AE tests can be performed during the course of drying.

AE testing can monitor changes in materials behavior over a long time and without moving one of its components *i.e.* sensors (Diakhate *et al.* 2017; Chai *et al.* 2018; Edwards *et al.* 2018). This makes the technique quite unique, along with the ability to detect crack propagations occurring not only on the surface but also deep inside a material. AE is produced in materials under stress and is usually sensed with piezoelectric transducers coupled physically to the surface of the material. Therefore, the AE method should be considered a “passive” non-destructive technique Fig. 1 (Grosse and Ohtsu 2008).

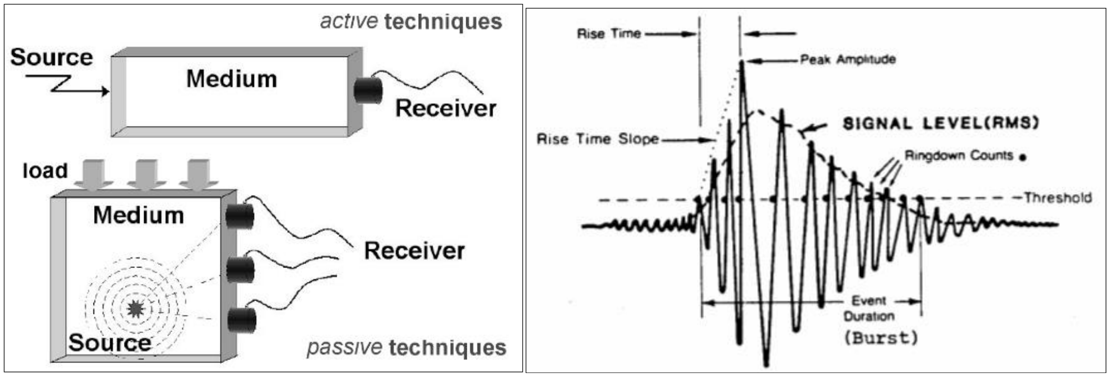


Fig. 1. (Left) Comparison of NDE principles using active or passive techniques (Grosse and Ohtsu 2008), (Right) Diagram of an acoustic emission event showing time domain characteristics that are often measured (Quarles 1990)

An AE ‘event’ is a burst of energy originating from drying stress release that exceeds a signal threshold. The threshold should be low enough to detect events of interest, but not so low to either sense continuous emissions and/or to overload the AE detection (Beall *et al.* 2005). If internal stresses could be monitored during lumber drying, they might warn that drying defects are about to occur. Checking caused by drying stresses can be regarded as the source of AEs that are premonitory symptoms of fracture (Noguchi *et al.* 1987). However, threshold crossings can be developed out of water movement or shrinkage, instead of defect occurrence in the course of drying.

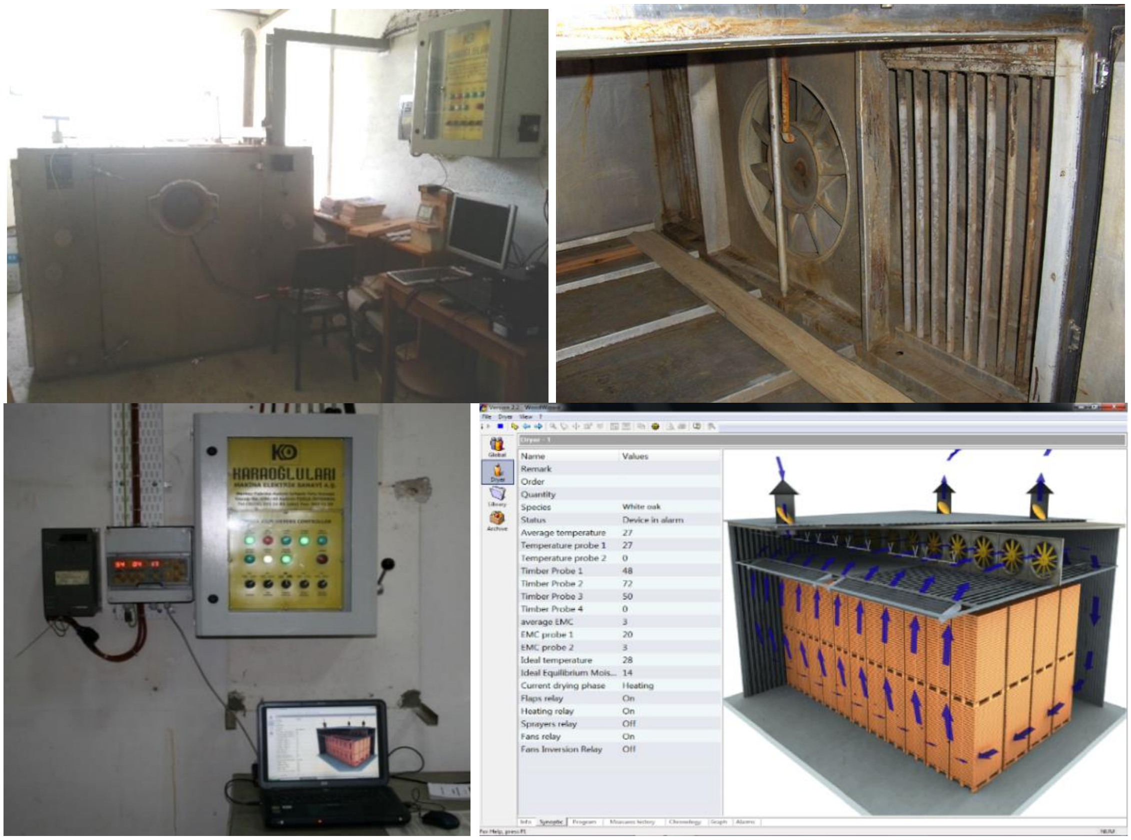
Still, as a possible strategy to minimize degrade from stresses and maximize the drying rate, the drying rate could be accelerated during the quiescent period until an acceptable rate of AE events is reached. At that point, the drying rate could be reduced until the peak has passed, and then it could be increased through the remainder of drying.

With experience, the AE outputs could be correlated with moisture content (MC) to assist in the prediction of the desired end-point (Beall *et al.* 2005). Villalobos (2016) investigated AE signals resulting from the drying-induced fractures of *Phyllostachys* *pubescens* bamboo for evidence of scale-free phenomena. Kowalski and Smoczkiewicz (2004) indicated that the drying process was optimized for the purpose of shortening of the drying time and avoiding the destruction of the material with this approach. In another study, Beall *et al.* (2005) demonstrated that acoustic emission (AE) monitoring could reduce drying times by 40% when drying above the fiber saturation point, compared with conventionally controlled loads (Bond and Espinoza 2016).

The aim of this study was to obtain optimum drying schedules using the acoustic emission technique to minimize drying duration while obtaining the same drying class according to standard of European Drying Group (1994) for commercially preferred Sessile oak and oriental beech structural lumbers.

MATERIALS AND METHODS

Commercially procured structural lumber with green dimensions of 6 x 15-20 x 200 cm for sessile oak (*Quercus petraea*, totally 0.48 m^3 volume) and 8 x 15-20 x 200 cm for oriental beech (*Fagus orientalis*, totally 0.64 m^3 volume) were used. Similar quality lumber pieces were chosen and stacked with 2 x 4 cm sticks in 1 m^3 lumber capacity conventional kiln. Some softwood lumber pieces were used for top loading. Air velocity was fixed at 3 m/s and an electrical resistance heater was used. Drying automation hardware of Logica co. with Holzmeister licensed were used with Wood Wizard software (Fig. 2).



Name	Values
Remark	
Order	
Quantity	
Species	White oak
Status	Device in alarm
Average temperature	27
Temperature probe 1	27
Temperature probe 2	0
Timber Probe 1	48
Timber Probe 2	72
Timber Probe 3	50
Timber Probe 4	0
average EMC	3
EMC probe 1	20
EMC probe 2	3
Ideal temperature	28
Ideal Equilibrium Mois...	14
Current drying phase	Heating
Flaps relay	On
Heating rolay	On
Sprayers relay	Off
Fans relay	On
Fans Inversion Relay	Off

Fig. 2. (Upper) 1 m^3 lumber capacity kiln and its equipment, (Lower) Drying automation system and WoodWizard software

The software library has drying schedules for all species with different thickness groups. Moreover, it allows changes in parameters, especially with respect to atmospheric conditions. In this study, schedules from the library were used for protective drying schedules based on older experiences. Drying quality of each schedule was determined according to the standard of European Drying Group (EDG) (1994). According to standard of EDG the drying quality of lumbers were evaluated according to moisture homogeneity and drying defects. In particular, case hardening, collapse, surface – internal – end checks were considered. Three quality classes, Standard (S), Quality dried (Q), Exclusive (E) (best quality) were considered, and minimum "Quality" class was aimed for ideal drying quality. Older experiments with kiln and software were referenced in order to aim for the desired quality. Temperature and drying gradient values were increased to obtain severe drying conditions and to decrease drying duration. Third (final - optimum) drying schedules of each species were determined according to AE event data and quality results, especially in severe dryings. Atmospheric conditions were changed with correlating AE events to obtain optimum drying schedules with better quality results and shorter drying durations for each species. At least two drying operations were done for an optimized schedule to be sure for each species. Conditions in schedules for protective and severe dryings according to species are shown in Table 1.

Table 1. Drying Schedules for Protective and Severe Drying Experiments

	Phase	**Variable**		**Oriental Beech**	**Sessile Oak**
Both Drying	Heating	Degrees / Hour		7	7
		EMC** (%)		17	17
	Core Heating	Time (hour)		17	17
	Conditioning	Time (hour)		17	17
		EMC (%)		12	13
1st Drying (Protective)	Drying	Above FSP	Drying Gradient	2.3	2.3
			Temperature	46 ºC	44 ºC
		Below FSP	Drying Gradient	2.9	2.9
			Temperature	64 ºC	67 ºC
2nd Drying (Severe)		Above FSP	Drying Gradient	2.6	2.6
			Temperature	55 ºC	49 ºC
		Below FSP	Drying Gradient	3.1	3.4
			Temperature	66 ºC	63 ºC

* EMC: Equilibrium Moisture Content, FSP: Fiber Saturation Point, **The software consider 30% MC for above FSP.

For acoustic emission (AE) testing, similar studies were based for experimental design (Kowalski and Smoczkiewicz 2004; Li *et al.* 2020). A piezoelectric transducer (R15a - from Physical Acoustic Corporation (PAC)) with an operating frequency from 50 to 200 kHz and a 2/4/6 preamplifier with gain of 40 dB threshold for not detecting noise were used to pick up the AE signals. Silicon grease was used as a means of coupling the transducers to the lumber, which was then bonded with a band resistant to heat and moisture. The four-channel AE transducers system were placed 20 cm away from the cross-section of four lumbers pieces, which were chosen as having potential risk of experiencing the occurrence of drying defects in each stack. Moisture electrodes based on the electrical resistance method were connected to the same lumber pieces to measure moisture content (MC). At one lumber sample in each stack, two electrodes were connected to surface and center in thickness for following the moisture gradient. AE events from each transducer were detected. AE events, whose amplitude exceeds the threshold value at any stage of the AE test, were considered. The number of AE events (event count) was used for emissions in the form of bursts. Remarkable, in other words, significantly higher number of AE events were considered for correlating kiln conditions with drying quality. AEWIN software was used to control the system (Fig. 3).

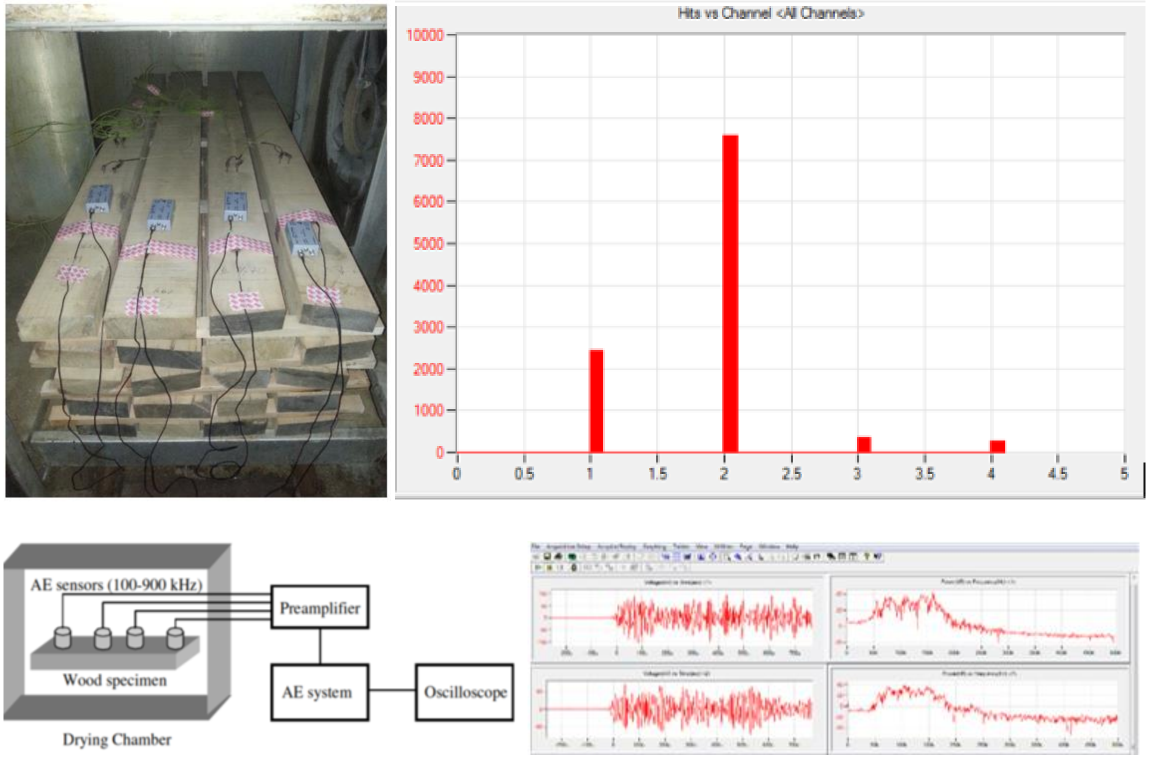


Fig. 3. (Left) Acoustic emission test setup, (Right) AE events in AEWIN software (Top-down) Two AE event samples, AE events of cumulative and each transducer

RESULTS AND DISCUSSION

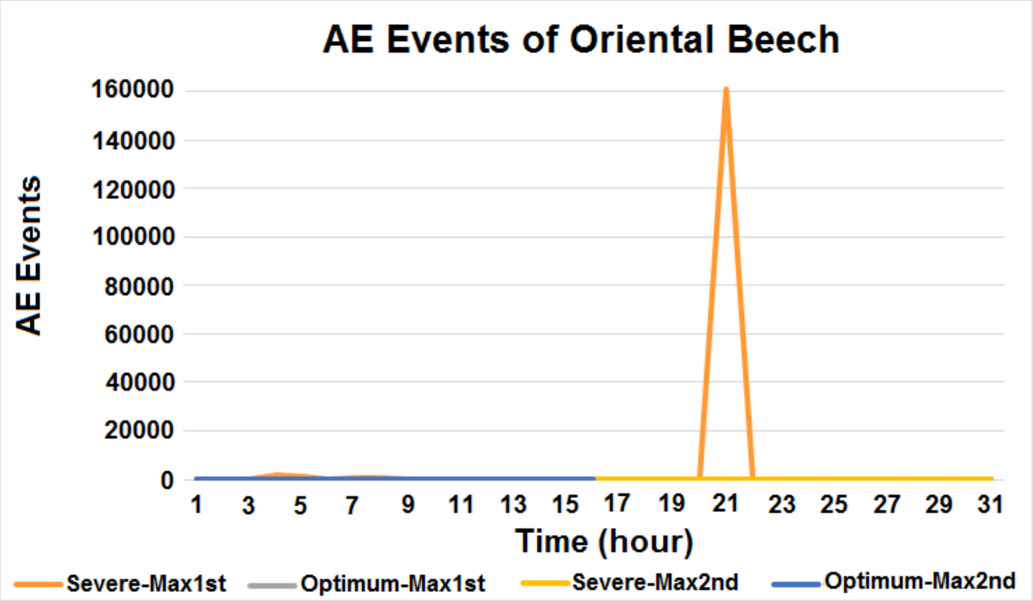
In the first step, the "protective" schedules from the software library were applied to each species. The results were obtained as expected; Q class was obtained in Oriental beech while E class was obtained in sessile oak drying operation. In the second step, "severe" drying operations, lower quality classes (S for oriental beech and Q for sessile oak) were obtained due to drier atmospheric conditions. Drying defects were determined in severe drying operations, especially on sessile oak lumber pieces, as can be seen in Figs. 4, 5, and 6, respectively.

Fig. 4. Drying results for oriental beech: (Left) protective; (Right) severe drying

Fig. 5. Drying results for sessile oak: (Left) protective; (Right) severe drying

Fig. 6. Quality problems (distortion, case hardening, and honeycombing) in severe drying of sessile oak

After protective and severe drying operations AE events, atmospheric conditions, and quality results were compared. Significant peaks in AE events were obtained at the beginning of drying for each operation.



*Max1st was the most event obtained sensor, where Max2nd was the second most event obtained sensor of each schedule.

Fig. 7. AE peaks comparison in severe and optimum schedules for oriental beech

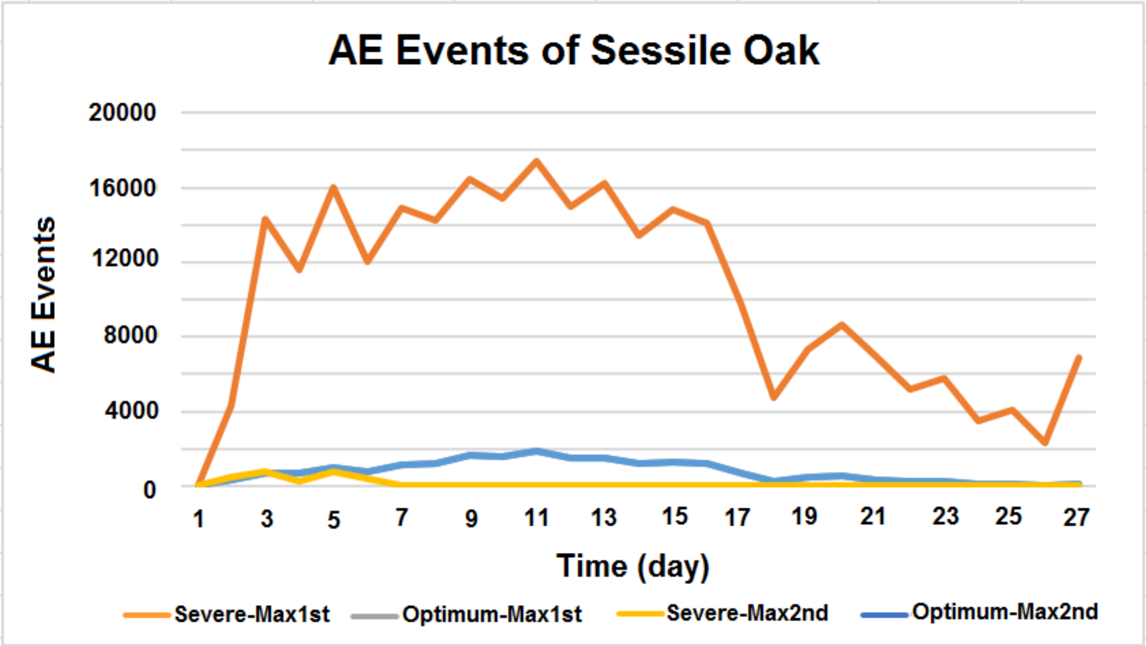


Fig. 8. AE peaks comparison in severe and optimum schedules for sessile oak

As can be seen in Figs. 7 and 8, AE peaks reached up to 150000 events for oriental beech and 18000 events for sessile oak. The events and also AE peaks were concentrated in the first 30 h for Oriental beech and in first 15 days for sessile oak. In other words, the events mainly occurred while taking free water from the lumber. Only atmospheric conditions at above fiber saturation point (FSP) in severe drying operations were changed to more protective conditions (lower temperature and higher relative humidity) in the third (optimum) drying schedule. The optimized conditions can be seen in Table 2 and the results can be seen in Table 3.

AE peak change both severe and optimum drying schedules can be seen in Fig. 7. As can be seen in Figs. 7 and 8, AE peaks significantly decreased for each species (max. 20 events for Oriental beech and max. 750 events for sessile oak). Although drying times were decreased, drying quality was increased in comparison to the severe operation (Fig. 9).

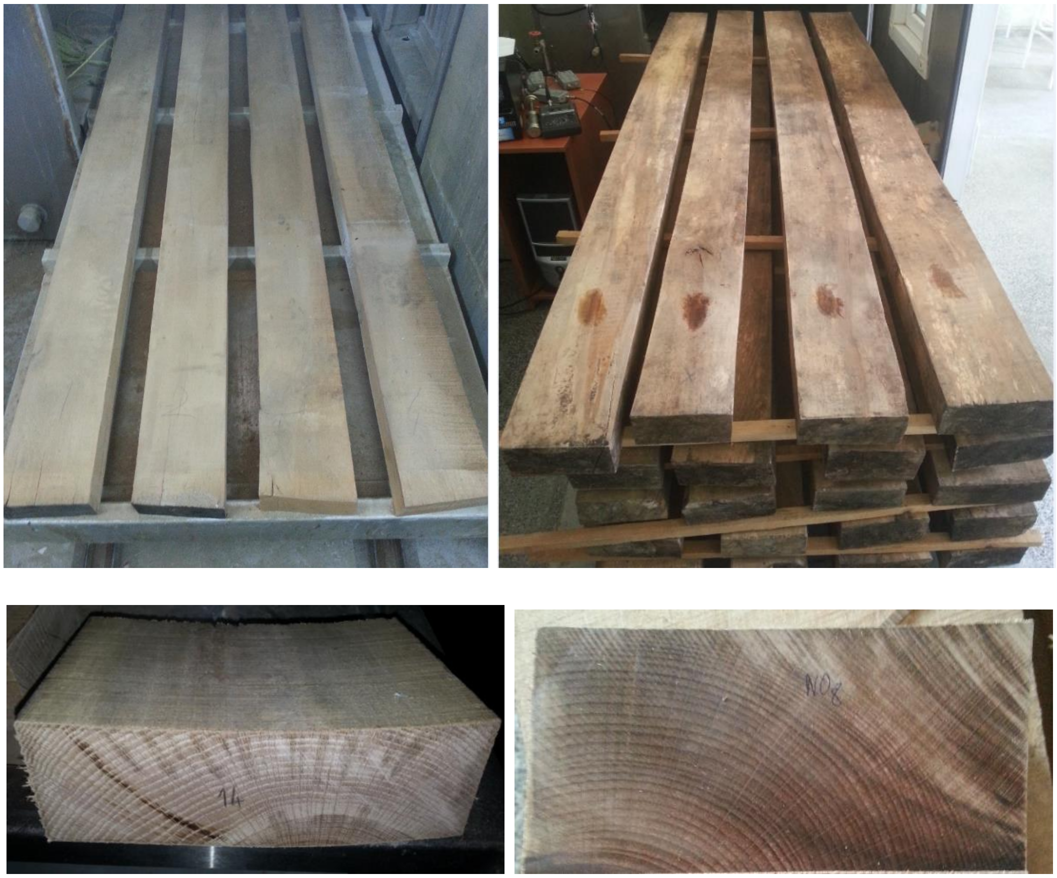


Fig. 9. Drying quality results after optimized schedules (Left: sessile oak, Right: Oriental beech)

Table 2. Optimized Drying Phase Conditions

Tree Species	Moisture Steps		Drying gradient	Temperature (ºC)
Oriental Beech	Above FSP		1.9	43
	Below FSP		1.9	60
Sessile Oak	Above FSP	70% - 60%	2	40
		60% - 50%	2.1	40
		50% - 40%	2.3	45
		40% - 30%	2.5	52
	Below FSP	30% - 20%	2.7	58
		20% - 15%	3.0	61

Table 3. Results of Different Drying Schedules

Tree Species	**Drying Condition**	**Initial Moisture (%)**	**Final Moisture (%)**	**Drying Time (day)**	**EDG* Quality Class**
Oriental Beech	Protective	69.5	11.5	39	Q
	Severe	76.6	11.4	26	S
	Optimum	67.5	13.1	33	Q
Sessile Oak	Protective	61.3	10.4	71	E
	Severe	69.3	17.0	48	Q
	Optimum	62.3	10.7	58	E
EDG: European Drying Group (1994)					

CONCLUSIONS

1. The behavior of acoustic emission (AE) events showed that the prediction of the beginning of lumber checking while drying is feasible by the AE technique. As a suggestion from Skaar *et al.* (1980), kiln control could be maintained through a feedback loop from AE data. A similar suggestion from Kowalski and Smoczkiewicz (2004) was helpful in this regard, to use the AE method for “online” monitoring of the material destruction, and thus provide a basis for drying control. However, Beall *et al.* (2005) indicate that detection of collapse would be very difficult using AE technology since this type of failure plastic. Similarly, sound from the water movement or microcracks (or friction) due to shrinkage can be misleading, they can produce AE events that falsely appear to represent the development of checks.
2. In this study, significant AE events were obtained at the beginning phases of drying. This situation could be realized due to capillary activity and water behavior at the cellular scale. Otherwise, Beall *et al.* (2005) indicate that there is disagreement on the contribution of surface *vs.* internal effects on AE. Several researchers suggested that AE was caused by cell wall shrinkage for AE event and drying stress correlation (Ogino *et al.* 1986; Noguchi *et al.* 1987). *Ogino et al.* (1986) featured that checking can be predicted by means of AE events caused by shrinkage of wood which takes place after the free water movement is completed at and near the drying surface. Quarles (1990) found similar results that an initial event rate peak occurred at similar phases into the run, and it was thought to be caused by the cavitation of water in the surface region.
3. The stresses can occur due to larger moisture gradients especially in thick lumber pieces on aggressively-dried wood species at the beginning of the drying. In this phase, the surface of lumbers can dry to under fiber saturation point (FSP) and can start shrinkage, while the core is above FSP. Quality results of in this study can provide evidence of check occurrence arising from surface stresses. However, it is suggested that studies should continue determining thresholds carefully to separate surface and internal checks while avoiding noise.

4. Crack prediction and obtaining optimum drying schedule with AE event system can be realized in industrial kilns. This should be tested for current and possible bottlenecks before using such as thresholds due to industrial type fan movement noise.

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