European Hardwoods for the Building Sector (EU Hardwoods)

FINAL REPORT

Title of the research project	**European Hardwoods for the Building Sector**
Coordinator of the project	Peter Linsenmann

BASIC PROJECT DATA

Project period	01.03.2014 – 31.12.2016
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URL of the project	http://eu-hardwoods.eu

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<u>Finland</u> Tekes – the Finnish Funding Agency for Innovation Academy of Finland (AKA)	 [-] [-]
<u>France</u> Ministry of Agriculture, Fisheries and Forestry Resources (MAAF) French Environment and Energy Management Agency (ADEME)	 79 750 49 930

Germany Agency for Renewable Resources (FNR)	389 600
Ireland Department of Agriculture, Food and the Marine (DAFM - CoFoRD Programme)	[-]
Norway The Research Council of Norway (RCN)	[-]
Slovenia Ministry of Education, Science and Sport (MIZS)	129 000
Sweden Swedish Governmental Agency for Innovation Systems (VINNOVA)	[-]
Switzerland The Commission for Technology and Innovation (KTI; in the Federal Department of Economic Affairs FDEA)	[-]
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DEGREES (if relevant)
Degrees earned or to be earned within this project.

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PROJECT SUMMARY REPORT

A summary of the project, preferably one page only

EU Hardwoods presents industry oriented insight concerning the use of hardwoods in the building sector. Prior to in-depth analysis four species were chosen to be included in the project: beech (Fagus sylvatica), oak (Quercus robur, Qu. petraea), Sweet chestnut (Castanea sativa), and ash (Fraxinus excelsior).
The analysis of present standing stock and annual harvest as well as future prognosis formed the basis for a first estimate of an industry relevant hardwood resource. The national forest inventories showed that beech is the dominant species in Germany, Austria, and Slovenia whereas oak is dominant in France. Sweet chestnut is available on an economical level only in France although some German regions are also suitable for Sweet chestnut. The German and Austrian forest inventory were similar enough to be processed with the prognosis tool WEHAM. The French and Slovenian inventory differs significantly and thus cannot be analysed in that cause. The prognosis indicated that in the time period until 2052 a stable stock of beech and oak will be available.
Prior to the production of building products, the knowledge of sawn timber strength classes is mandatory. Visual grading is partially suited to address strength properties. Applying new machine grading techniques resulted in more promising results. Using microwave transmission has the potential to increase the prediction accuracy by approximately 25 %. Further analysis, especially regarding defining training and test data sets to eliminate statistical effects, are in preparation. Additionally, allocation reports for Austrian beech in the European strength class system, as a prerequisite for wide usability in building, are in preparation.
An extensive research on Slovenian beech was carried out where 210 beech logs were sampled from the eastern part of Slovenia and sawn into boards. Non-destructive measurements of logs and boards as well as tensile strength tests were performed. German, French, and UK visual grading standards were compared on the same boards. The results clearly show significantly higher values of mechanical properties of beech compared to those of oak and especially spruce.
Two well established building products are considered in EU Hardwoods. For glued laminated timber modelling software was prepared. Based on large data sets the distribution and autocorrelation of timber characteristics like knots and finger-jointed pieces were included in the simulation. A special Finite Element program which is capable of calculating crack initiation and crack propagation was implemented. This modelling software was verified by 80 bending test on French oak glulam beams. For cross laminated timber, a performance boost was possible by using beech in the middle layer of CLT plates increasing the rolling shear strength by approximately 100 %.

1.1 Introduction

1.1.1 Background

Describe the background of the project and the basic problem that it sought to address.

Hardwood is becoming an increasingly important material in Europe. Already existing stands throughout Europe as well as increased availability due to a change in forestry measures make it necessary to find and create new possibilities for hardwood usage.

Until now, hardwood is not used to a significant amount in the building sector. One reason is that European standardization is missing, i.e. no harmonized products can be produced and, subsequently, be put on the market. Today, the only possibility to use building products made of hardwoods is based on national technical approvals. Another reason for the lack of hardwood building products is that there are only very few products. Missing experience in usage, a more complicated handling during production, and considering that hardwood is not only more expensive than softwood but also exhibits completely different mechanical properties require a different approach for the utilization.
Different regions in the participating countries made it necessary to narrow down the species evaluated in this study. Those are beech (Fagus sylvatica; dominant in Germany, Austria, and Slovenia), oak (Quercus robur, Quercus petraea; dominant in Germany and France), Sweet chestnut (Castanea sativa; dominant in France), and ash (Fraxinus excelsior; common throughout Europe).

1.1.2 Objectives

Describe the project objectives.

Therefore, the proposal EU Hardwoods was prepared within the fourth joint call of WoodWisdom-Net which explicitly focuses on filling existing gaps of knowledge in using hardwood in the building sector and strives to assist the propagation of the new engineered products. In the future, the predominantly manufactured building products made of hardwoods will be hybrid glulam or hybrid cross laminated timber (CLT) consisting of lamellas with smaller cross-sections than solid wood products.
To approach the project in an as holistic way as possible the following objectives were evaluated:

- Definition of the raw material with respect to availability and log quality. The aim was to analyse the standing stock and prepare a prognosis for future stock based on different silvicultural scenarios, including the definition of the potential for different roundwood qualities and grades including sawing potential / patterns.
- Characterisation of the hardwood species of interest with respect to visual and machine strength grading as grading is the pre-requisite to widen the range of applications.
- Development of a FE model for the simulation of homogenous and inhomogeneous as well as hybrid glulam based on a FE model.
- Development of new high-tech products: cross laminated timber as a combination of hardwood and softwood lamellas. E.g. hardwood lamellas from beech can be placed in the inner zone to increase the (rolling) shear capacity in this zone which is often responsible for low strength values of the whole plate. This fact enables the usage of a broad variety of strength grades of hardwoods in high quantity.
- Derivation of strength models for glulam and cross laminated timber based on strength properties of lamellas and finger-joints, validation through testing.

So, the main objective of EU Hardwoods was to transfer and complete the knowledge along the whole production line of hardwoods to broaden the use of hardwoods in an efficient and economical way in practice.

1.2 Results and discussion

Main achievements of the project, quality, innovativeness, industrial relevance and contribution to competitiveness, environmental and societal impact.

Hardwood resources in Europe (WP 1)

Lorenz Breinig, Udo H. Sauter, Franka Brüchert

The establishment of a sustainable production chain for glued timber products such as gluelam and cross-laminated timber (CLT) from European hardwoods requires the knowledge of the current hardwood resource in Central Europe as well as its future development in terms of standing stocks and their availability.

- METHODS
- STANDING STOCK AND RESOURCE FORECASTS
- DETERMINATION OF CURRENT STANDING STOCK AND ANNUAL CUT

Information on the current standing stocks of the most important hardwood species in the participating countries Austria, France, Germany and Slovenia – beech, pedunculate and sessile oak, ash and sweet chestnut (in France) – were compiled from the latest available national forest inventories of these countries (3^{rd} German national forest inventory 2012, Austrian national forest Inventory 2007/09, French national forest inventory period 2009 - 2013 (inventory campaigns 2009, 2010, 2011, 2012, 2013)). Comparison of the inventory standards revealed differences in reporting and mensuration: while in Germany and Austria all trees > 7 cm dbh are reported, is a threshold of 7.5 cm defined in France. Additionally inventory data in France report a standing stock of “construction wood” (timber usable for sawing, *bois d’œuvre*) as “sufficiently straight” logs with a minimum top diameter of 20 cm and a minimum length of 2 m. Such stem form information is not available for the inventory data from Austria and Germany. All results related to the standing stock are reported in cubic meters solid *over* bark (m^3 sob), all figures of harvested volume are reported in cubic meters solid *under* bark (m^3 sub).

Forecast standing stock and annual cut

The WEHAM model — basic functionality

Predictions of the future development of the standing stock were performed for the case of Germany applying the *WEHAM* forest development simulation tool based on the latest forest inventory data. This tool is specifically adapted to data from the German forest inventory (BWI). It is a single-tree-based simulation of growth and harvest (including mortality). The input-database represents individual trees from a forest inventory point sampling and provides a projection to the whole forest area.

The simulation governed by a control database contains growth models, parameters of silvicultural treatment, and standard log bucking/sorting specifications (standard dimension and volume based on stem models (diameter/height), log quality not taken into account). There are restrictions to be noticed: the results are only valid on a large scale (e.g. the federal state is the smallest entity for analyses) and no change of species or change of site conditions can be implemented into the simulation model.

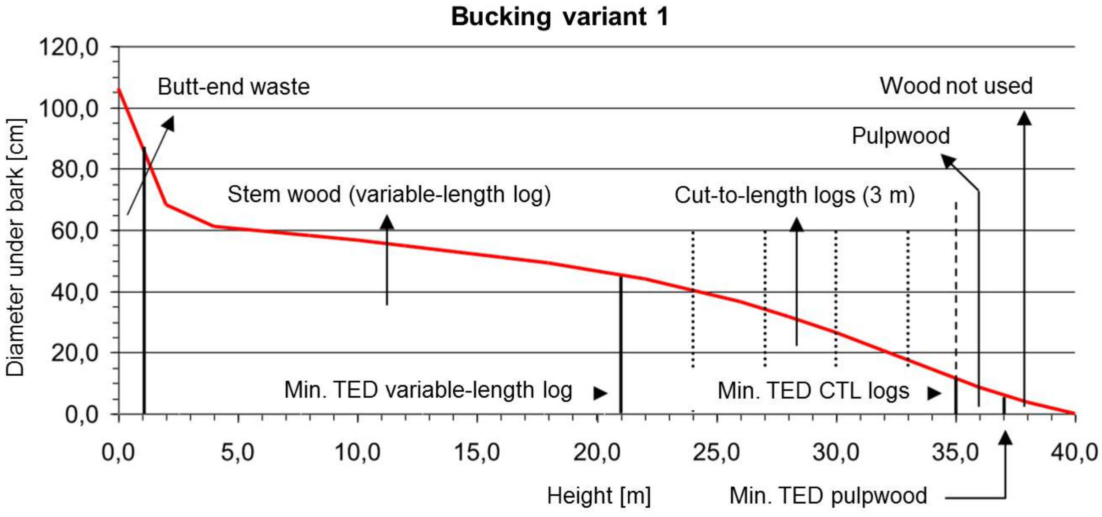


Figure 1: Approach bucking variant for estimation of assortments (TED Top-End-Diameter, CTL Cross Laminated Timber)

The bucking variant shown in Figure 1 is the most commonly used bucking principle for valuable hardwoods in Germany and most other countries in Central Europe. The length of the butt log varies in relation to the length of the high-grade stem section for the conversion in sawmills.
It was investigated whether this prognosis tool is also suitable for the forest inventory data available from the other participating countries. In cases where this approach is not feasible, existing predictions of forest resource development from the respective countries was compiled.

Technical characterisation of the hardwood resource
For the third part of the project, the acquired samples of the logs of the regarded species were characterized including measurement of roundwood features and grading according to EN 1316-1 and RVR, log MOE measurements (ViScan) and CT scans.
Sample logs were visually graded and examined by laser interferometry and computed tomography to obtain information on e.g. dynamic modulus of elasticity, variation of wood density and presence and size of knots in the logs. The logs were sawn into lamellas which in turn were examined and destructively tested in WP2. This step shall reveal possible relationships between roundwood characteristics and structural performance of the lamellas.

- RESULTS

Hardwood resources in Austria, France, Germany and Slovenia
The current resource, i.e. standing stocks, of the hardwood species considered is shown in Figure 2. For all four countries combined, the total standing stock of beech and oaks are on the same scale with about 1,100 M m³ each. For comparison, the total stock of fir and spruce amount to roughly 1,270 M m³ in Germany and slightly less than 400 M m³ in France.

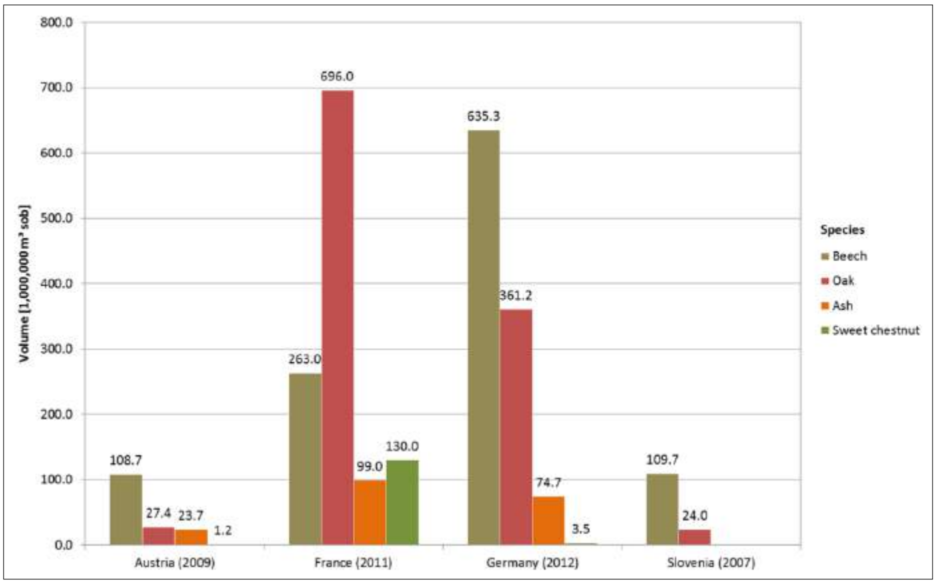


Figure 2: Total standing stocks according to the latest national forest inventories in the EU Hardwoods partner countries

Hardwood resources in Germany

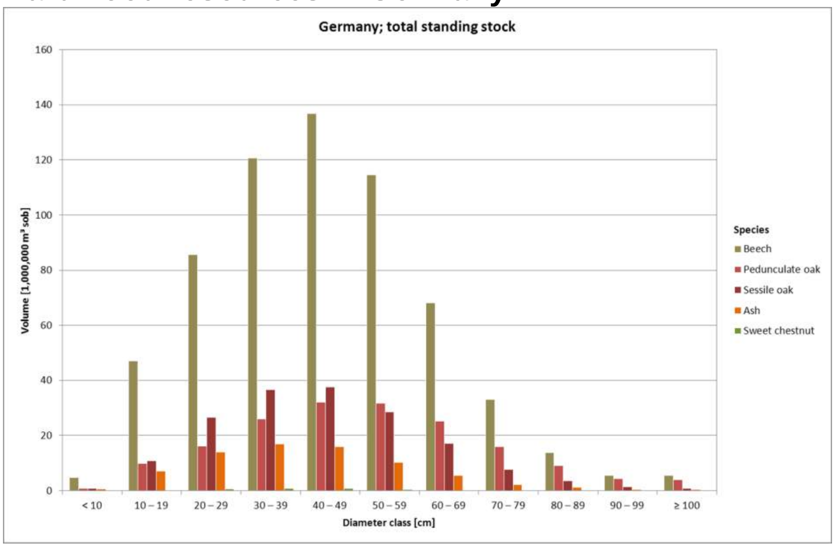


Figure 3: Total standing stocks of main hardwood species in Germany

Figure 3 visualises the ascendence of beech of the standing hardwood resource of German forests. The two oak species (*Q. petreae* and *Q. robur*) are well represented, but represent only one third of the beech resource. Ash plays still a certain role. The biggest portion of the total resource is found in the dimension classes 40 to 60 cm at breast height.

Annual hardwood harvest in Germany

The current annual cut of the two main hardwood species beech and oak reaches a total of about 14 M m³ sub, but only about 3.2 M m³ sub are converted to sawn products (Figure 4). A far too large percentage is used as energy wood, which underlines the necessity for research on options to use European hardwoods as basis for valuable construction wood such as laminated timber.

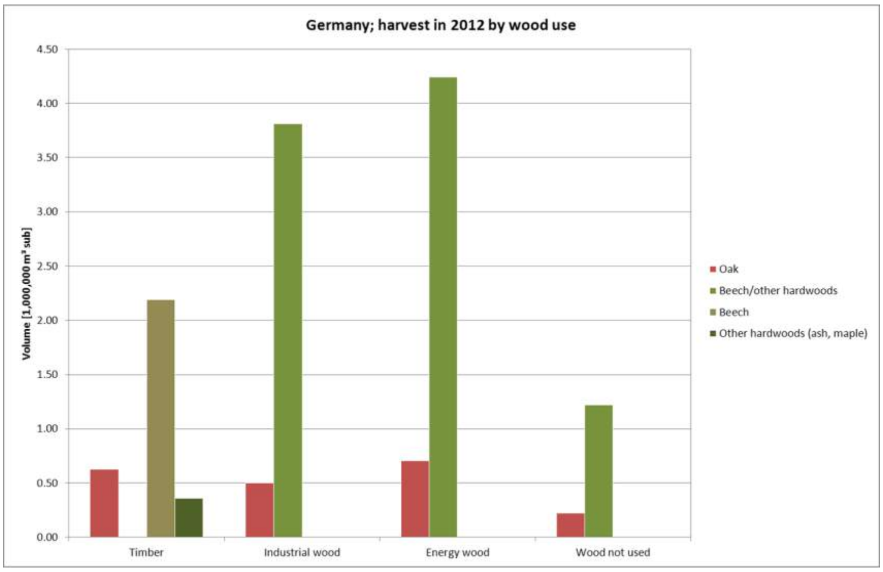


Figure 4: Main uses of hardwoods in Germany

Hardwood resources in Austria

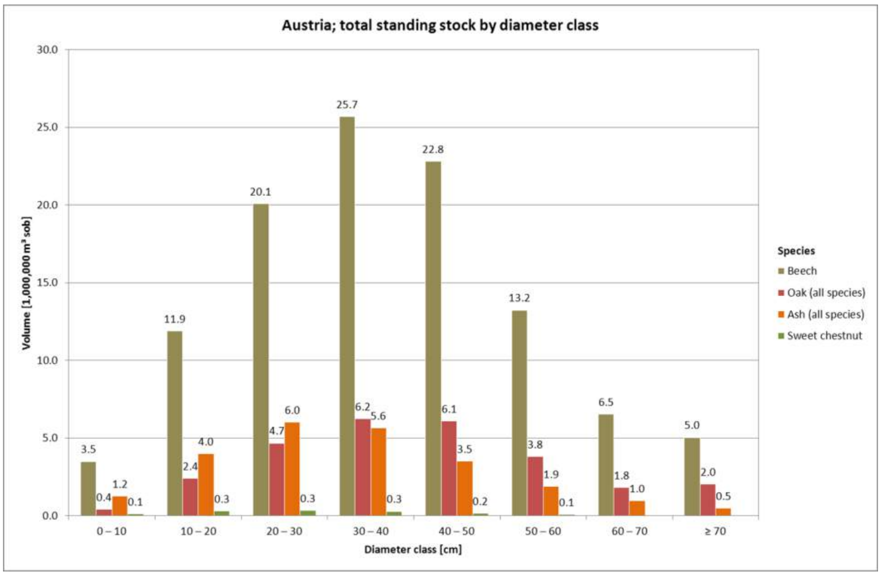


Figure 5: Total standing stocks of main hardwood species in Austria

The hardwood resources in Austria are also dominated by beech (Figure 5). The stem dimensions are dominated by the diameter classes from 20 to 50 cm at breast height, which is smaller than in Germany. The dominating use is also energy wood. Only a small portion of annually 300,000 m³ sub is currently allocated for the high valuetimber production in sawmills.

Hardwood resources in France

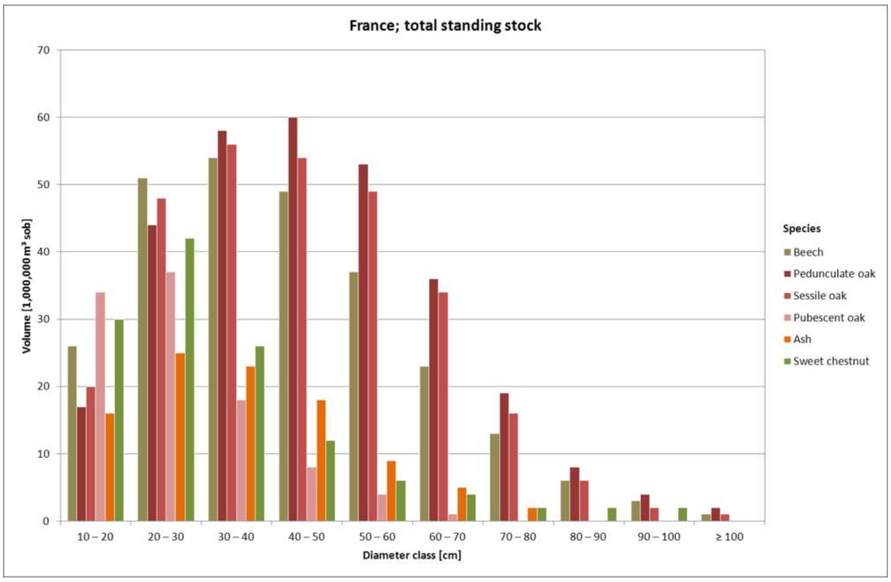


Figure 6: Total standing stocks of main hardwood species in France

In contrast to the German and Austrian hardwood resource, oak species are dominating the forests in France. Additionally to pedunculate and sessile oak a third oak species pubescent oak (*Q. pubenscens*) in south western parts of France contributes a reasonable portions to the total hardwood standing stock. Especially the oak resource reaches the largest average stem dimensions of all hardwoods in Europe (Figure 6). Besides oak and beech, ash and sweet chestnut contribute reasonable shares the hardwood resource in France.

Current hardwood resources in Europe – Summary

The hardwood stock for all four partner countries Austria, France, Germany and Slovenia total to 1,116.7 M m³ for beech, 1,108.7 M m³ for oak, 197.4 M m³ for ash and 134.7 M m³ for sweet chestnut. For comparison, the softwood stock in France and Germany amount to 1,617.6 M m³ for Norway spruce, whereas from silver fir standing volume reaches 290.4 M m³. Currently Douglas fir resource is still growing and accounts for 184.7 M m³, while the standing stock of the two dominating pine species Scots pine and Maritime pine total to 1,048.8 M m³. In Germany, the stock of spruce has decreased by 48.6 M m³ since the previous forest inventory (in 2002), while the stock of beech and oaks has grown by 57.8 and 50.1 M m³, respectively.
Oak has by far the highest share of hardwood standing stock in France (59%), the second highest share in Germany (33%) but only 17% and 18% in Austria and Slovenia. Beech has the highest share of the hardwood resource in Slovenia (82%), Austria (68%) and Germany (60%) and accounts for 22% in France. Ash represents shares between 7% (Germany) to 15% (Austria) which means considerably lower importance to the market than beech and oak.

A high uncertainty in the prediction of its future availability is caused by the rapidly spreading ash dieback disease which could cause up to 90% loss of ash standing stock in some regions within the next decade. Sweet chestnut shows a considerable standing stock in France (11%), but only very small stock in Austria (1%) and Germany (0.3%).

The figures for reported harvests show that energy wood has a very high share of the annual hardwood harvest in Austria (62–72%) with beech contributing the highest portion of the annual timber harvest (48–54%), however the total amount is small in comparison. For Germany beech has the largest share of timber harvest (2012: 69%) and the relative share of energy wood is much lower than in Austria (2012: 36%). However the absolute total volume of beech as energy wood is very high. The reported figures on annual harvest must be seen as a rather coarse estimate; especially harvested volumes from small private forest owners are often estimated.

Forecast to future resource availability

Forecast of hardwood resources and harvest in Germany

The prediction of the annual roundwood harvest in Germany sums up to 14.8 M m³ for the period 2023–2027 (year of reference is 2025) (Figure 8), while the volume of beech stem wood (total of volume of long logs, CTL logs and stem wood) only accounts for 6.63 M m³ (45%)

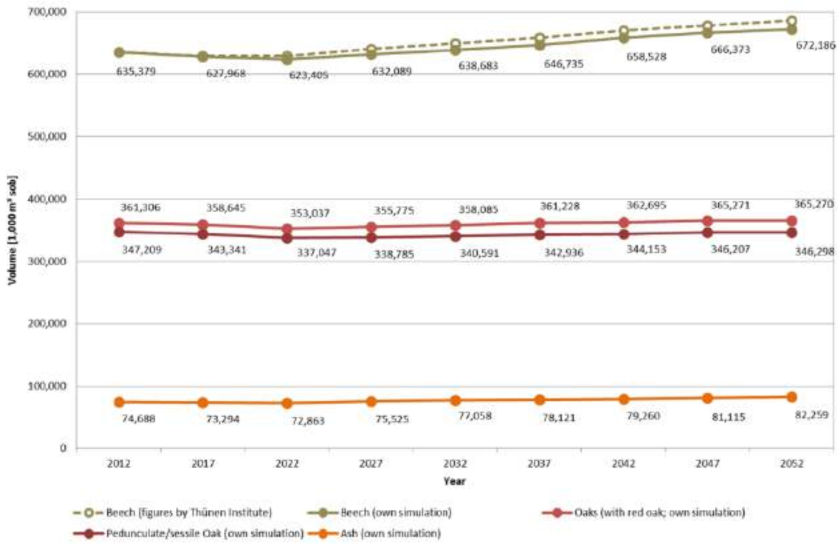


Figure 7: WEHAM prediction of standing stocks according to the official scenario (Germany)

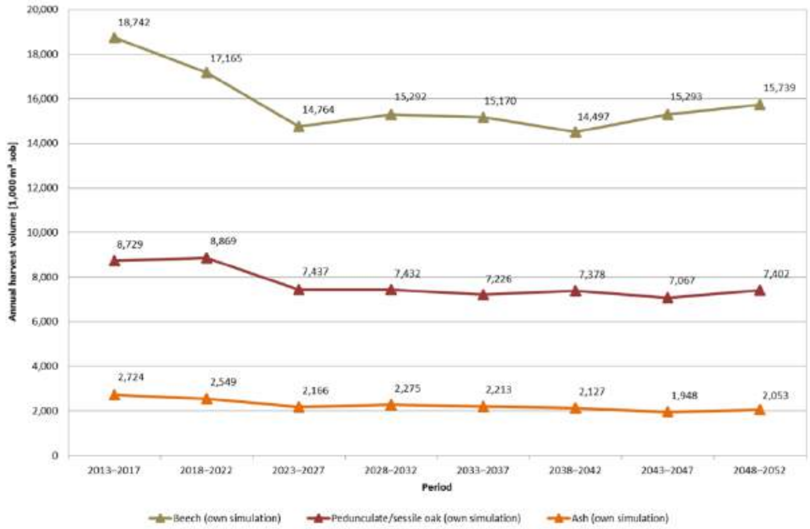


Figure 8: WEHAM prediction of annual harvest volumes according to the official scenario (Germany)

Resource forecasts for Austria

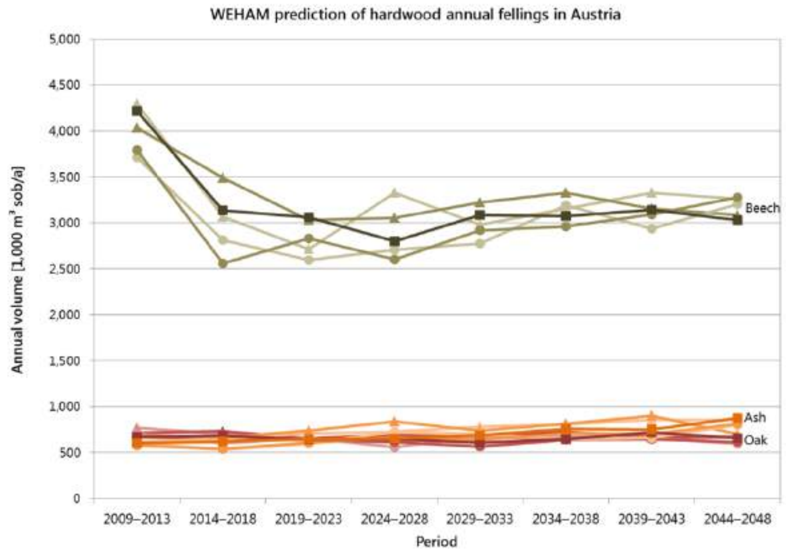


Figure 9: WEHAM prediction of annual harvest volumes according to the official scenario (Austria); the beech parametrization reflects the growth model of beech in Bavaria which obviously leads to overestimating growth and annual harvest volume

The WEHAM forecast simulation for Austria applied the German official scenario and the parametrization according to growth of beech in Bavaria. The results show an overestimation of harvested volume for beech (2.8 M m³/a (2025)), whereas the Austrian national inventory (ÖWI) estimates 1.8 M m³/a (+ 60%) (Figure 9). The figures for oak are 0.64 M m³/a (WEHAM) and 0.56 M m³/ a (ÖWI) with still a deviation of +14%. Therefor it was recommended to re-parameterize the growth models in WEHAM with repeated inventory data for beech and oak (data from ÖWI 2007–09 and preceding inventory provided by BFW) and to repeat the simulations.

Resource forecasts for France (study by IGN/FCBA)

The following reflects the study on potential roundwood availability covering the entire forest area in France (*Disponibilités forestières pour l'energie et les matériaux à l'horizon 2035*; on request by the French environment agency). The data basis includes inventories 2009–2013. The models contain growth, mortality and silviculture yield gross annual availability (comparable to the annual fellings in WEHAM). Applying volume reductions due to technical/economical restrictions lead to the usable annual availability. Two scenarios are simulated: 1. constant management: maintaining mean felling rates observed between the last two inventories for the distinguished forest type units (strata) and 2. "dynamic management": progressively applying the highest observed felling rate to the entire stratum. The usable annual availability of hardwood timber (all species combined) increases from 9.7 to 11.9 M m³/a in the constant management scenario or increases from 9.7 to 15.2 M m³/a in the "dynamic management" scenario (Figure 10).

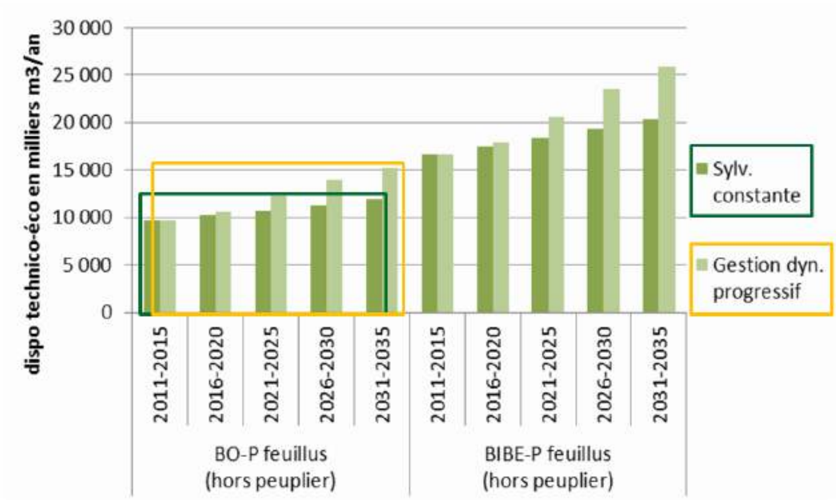


Figure 10: Usable annual availability of hardwood timber (all species combined) in France

Forecast of hardwood resources in Europe – Summary

All species show an increasing or at least constant development of the standing stock for the involved countries. An exception is ash which may show instable growth and stock volume because of the dieback disease.

Despite some methodical uncertainties related to the WEHAM forecast software approach, which was developed for German growth conditions, constant or even increasing annual cuts for main hardwood species beech and oak throughout the next decades can be expected.

Technical characterisation of the hardwood resource

The distribution of MOE_{dyn} and green density of sample logs of all four species from Baden-Württemberg is shown in Figure 11. Mean MOE_{dyn} varied between 10.2 (oak) and 11.7 kN/mm² (chestnut). Beech logs showed the largest spread of MOE with 11.2±17% (CV).

Average ash log MOE was found as high as 10.7 kN/mm² with CV=16%. Mean density varied between 774 (ash) and 963 kg/m³ (beech) (878 kg/m³ for oak, 864 kg/m³ for sweet chestnut).

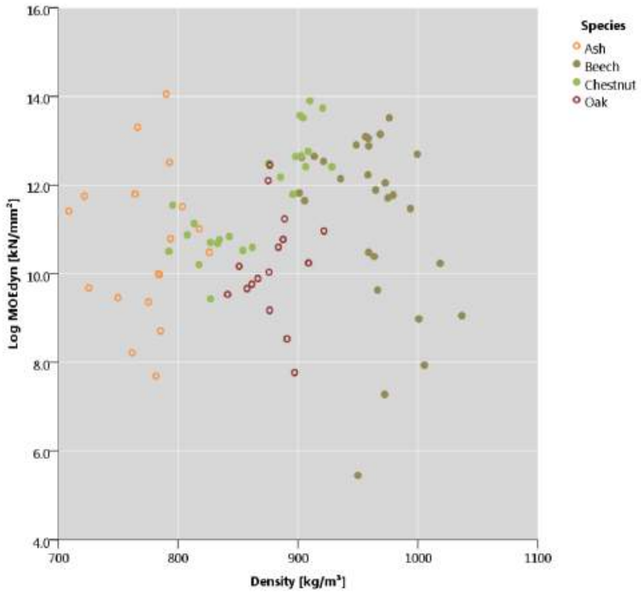


Figure 11: MOE_{dyn} plotted against green density of the sample logs

The frequency distribution of MOE_{dyn} for the 116 ash and 86 beech boards is presented in Figure 12. A lower mean MOE_{dyn} was observed for the ash boards with 13.0 kN/mm² versus 14.3 kN/mm² for the beech boards. Standard deviation was 2.2 kN/mm² for ash and 2.3 kN/mm² for the beech boards which corresponding CV of 15% and 18%, respectively.

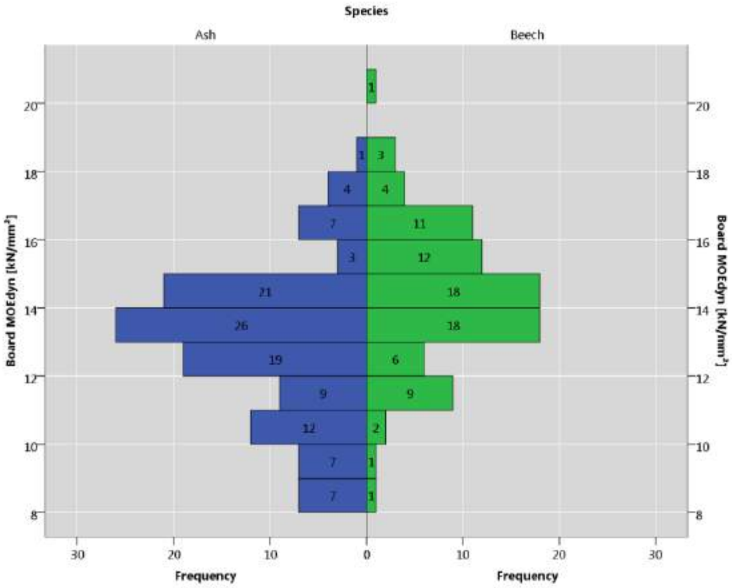


Figure 12: Frequency distribution of MOE_{dyn} of the ash and beech boards

Figure 13 shows the relation between MOE_{dyn} of the boards and MOE_{dyn} of the corresponding log. For ash, the plot suggests a slight relationship between both measurements. Likewise, for a linear regression of the mean MOE_{dyn} of the boards of one log against the MOE_{dyn} of the corresponding log, a coefficient of determination of $R^2 = 0.70$ was observed. For beech, a much weaker relationship is indicated by the plot, and for the same type of regression, the coefficient of determination was only $R^2 = 0.47$.

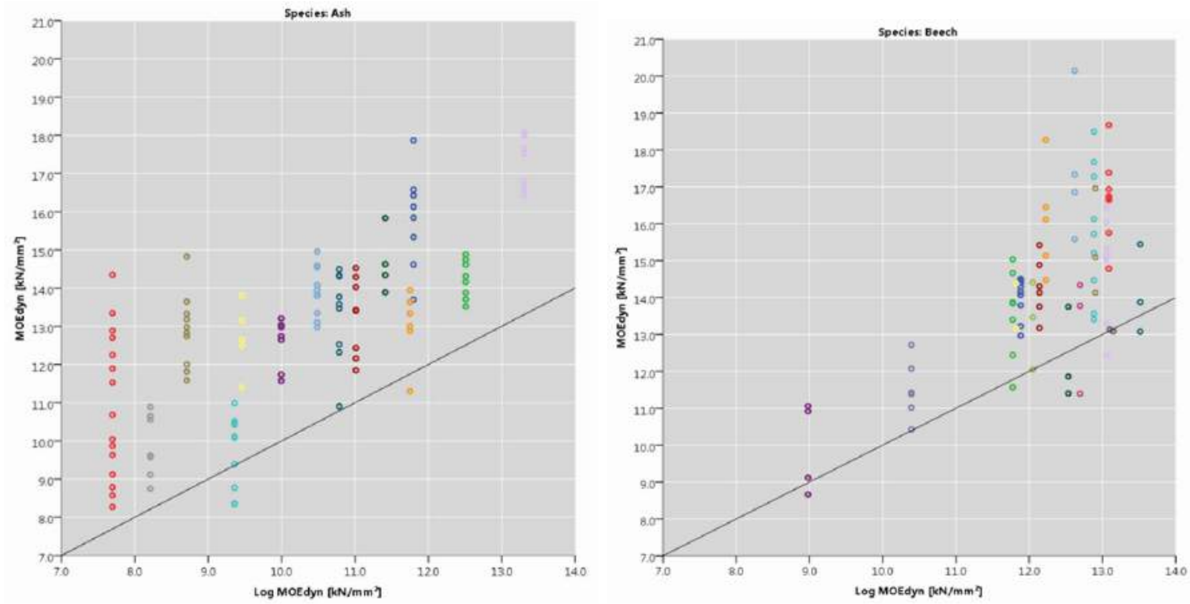


Figure 13: Board MOE_{dyn} plotted against MOE_{dyn} of the corresponding log for the ash and beech boards. A 1:1 reference line is indicated in each plot

The analysis is supposed to be complemented with the data from testing at HFA before conclusions about the relationships between roundwood characteristics and strength properties of the lamellas can be drawn.

Basic hardwood strength data and grading tools (WP2)

The knowledge of strength classes is mandatory if hardwoods are to be utilized in building products. A strength class can be obtained based either on visual grading (national visual grading standards) or by machine grading and subsequent destructive testing. EU Hardwoods focusses on lamellas which are the primary raw material for glued laminated timber and cross laminated timber. These lamellas are tested in tension i.e. other test setups are neglected for this evaluation.

To avoid unnecessary new testing, an evaluation and possibly collection of existing data among the participating partners and affiliated institutions was done. New tests were only planned in case the modelling required additional strength information on lamella or finger-joint characteristics. This general data evaluation revealed that the increasing amount of research initiatives related to hardwoods will lead to a vast stock of data in the future.
At present, the availability of data sets based on single values, i.e. that strength, stiffness, and density information as well as information on visual grading is given for each specimen, is limited by intellectual property rights of data holders and / or funding bodies. In the end, the available and suitable data of the partners was collected (

Tab. 1).

Tab. 1 available data within the consortium and affiliated institutions

loading mode	origin	species	number
tension	DE / CZ / FR	European oak	300
	US	White oak	100
	ES	Sweet chestnut	249
	N.N.	birch	40
	DE	beech	21
bending edgewise	AT	European oak	345
finger-joints (bending flatwise)	DE / CZ / FR	European oak	260
	US	White oak	140
	ES	Sweet chestnut	212
	N.N.	birch	20
finger-joints (tension)	DE / CZ / FR	European oak	296
	US	White oak	100
	ES	Sweet chestnut	109
	N.N.	birch	20
	DE	beech	21

This data proved to be sufficient for the modelling in EU Hardwoods. It became also obvious that a dedicated data collection throughout Europe will be beneficial for future research related to influence of origin and grading.

At HFA, together with partner FVA questions related to machine strength grading were investigated. Since a CT scanner was available at FVA, all roundwood as well as all lamellas were scanned. This technology possesses great potential concerning the detailed analysis of a whole piece of roundwood to obtain characteristics on sawn timber. The main drawback of this technology is the very high costs limiting the actual usability and distribution. Analysing this CT data requires sophisticated image processing and will be done at a later point of time.
A set of beech (n = 83), oak (n = 83), ash (n = 109), and Sweet chestnut (n = 94) lamellas with German origin was analysed. As a relatively new strength grading technology microwave radiation can be used to detect fibre deviations, e.g. locally around knots or globally due to warp or twist.

In combination with other – easily obtainable – grading parameters like dynamic modulus of elasticity (MOE) a very convincing grading result, i.e. a prediction for strength, can be obtained. All lamellas were used for the determination of dynamic modulus of elasticity and tensile strength whereas the microwave measurement was based on a sub-sample of 40 specimens – 20 with high and 20 with low fibre deviations – of each species. Although this sub-sample is limited due to the small number of specimens, a training and test setup was adopted. This helps in detecting possible issues with model overfitting. The assessment of the potential of microwave scanning for the examined hardwood species is based on the independent test sample and thus more objective. The division in training and test was based on the log data and it was taken care not to split lamellas of one log between the samples but to assign all lamellas of one log completely to training or test. Additionally, the tensile strength and density distributions within the samples are as evenly distributed as possible (Tab. 2).

Tab. 2 number of specimens in training and test sample

	training	test	total
beech	21	20	41
ash	23	14	37
oak	18	27	45
Sweet chestnut	26	17	43
total	**88**	**78**	**166**

Based on a linear regression, indicating properties (IP), i.e. regression models for tensile strength, were derived separately for each species. The derivation was done using the linear multivariate stepwise regression procedure from SPSS 20 and was solely based on the training sample. The models were subsequently applied to the test sample to obtain an estimate of how well the models would work on new data. Based on the results on the test data, some variables were manually removed from or added to some of the models, and the new models were again trained solely on the training sample to obtain the final models.

Figure 14 shows the results of this process for linear and exponential models and the model classes eρk (based on the laboratory values of MOE, small sample density ρ and total knot area ratio tKAR), m (based solely on the microwave variables) and me (based on microwave variables and MOE). We will discuss the results species by species. The coefficients of determination (or r^2 values) mentioned in the following always refer to the values obtained on the independent test sample.

The ash models all show a rather high amount of variance in tension strength (f_t) that cannot be explained by the models Figure 14. Since this is also true for the reference model, the conclusion is that either ash strength is particularly difficult to predict or that a larger sample is required for more stable results. The r^2 of 38% (reference model eρk) is low in comparison to r^2 values achievable for softwood. The microwave variables alone (model m) are not sufficient for ash strength prediction, as the r^2 is only 17%.

However, combining microwave and MOE leads to a very promising model. While an r^2 of 47% is still not very high, it could be high enough for use in machine strength grading. Moving from linear to exponential models leads to some improvement for the reference model (eρk), but not for the ash microwave models, so we recommend using a linear model for ash.
For beech, the reference model has an r^2 of 70%, which can even be increased to 75% by using an exponential model (Figure 14). These lab-data beech models only include the variables MOE and ρ, which can be accurately measured by current high-end grading machines for softwood. The pure microwave models in Figure 14 only reach an r^2 of 45% (linear) and 51% (exponential). Combining microwave and MOE measurement leads to r^2 values of 56% (linear) and 64% (exponential). While these latter values are still lower than the test sample r^2 values from the reference models, they are quite high enough for use in machine strength grading. As microwave scanners are expected to be much cheaper than x-ray scanners, the present results suggest that for beech, the decision between one or the other involves a trade-off between grading performance and investment cost, where a microwave scanner would be competitive.
With the sweet chestnut reference models, we encounter the curious situation that the test sample r^2 (89% for the linear, 93% for the exponential model) is much higher than the training sample r^2 (60% respectively 70%). This is probably an effect of the low sample size and highlights that the present research was a preliminary study to assess the potential of microwave strength grading of hardwood. In this case (and also for the oak reference models, where a similar effect can be observed), we assumed that the test sample r^2 is overly optimistic and stuck to the training sample r^2 for comparison with the other models. So, the reference models have acceptable r^2 values; the pure microwave model, on the other hand, with test sample r^2 of 28% (linear) and 31% (exponential) is not suitable for machine strength grading. The ideal solution for sweet chestnut seems to be a combination of microwaves and MOE, where the r^2 values (61% for the linear, 67% for the exponential model) are nearly as high as the training sample r^2 values of the reference models.
The oak reference model r^2 values for the test sample also exceed the r^2 values for the training sample, so we again assumed the training sample r^2 values (33% for the linear, 31% for the exponential model) to be the more realistic assessment. The linear pure microwave model then has a considerably better performance with a test sample r^2 of 45% and might be sufficient for machine strength grading. Neither the addition of MOE to the model nor the transition to an exponential model form can substantially improve on this.
Comparing the performance of the linear models with the exponential models, the exponential approach seems particularly beneficial with beech and sweet chestnut. For these two species, clear increases in test sample r^2 can be observed for all models. For ash, only the reference model shows such an increase; for oak, no increase can be observed from any linear to the corresponding exponential model.
On the whole, microwave scanning showed potential for all four hardwood species tested. For oak, the linear pure microwave model showed most promise and was considerably better than the reference model. For ash, beech and sweet chestnut, combined microwave+MOE models were found to be competitive. This preliminary study therefore forms an excellent basis for further studies with a greater number of boards to prepare the way for industrial hardwood strength grading based on microwave scanning.

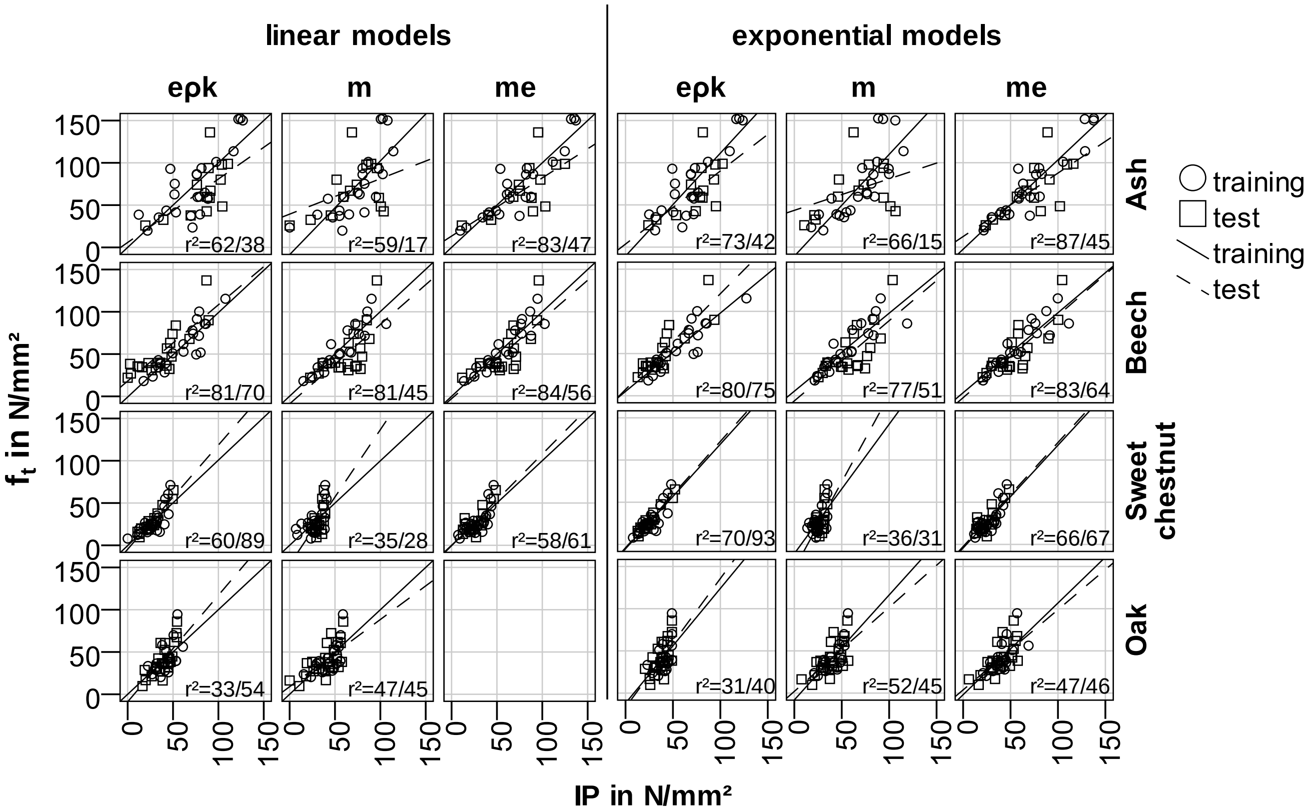


Figure 14: Calculated IP values (linear and exponential models) versus tension strength, separated by species, model class and training/test, including regression lines and coefficients of determination both for training and test sample. Model classes: eρk = lab data of MOE, density and total KAR; m = microwave data; me = microwave data and lab MOE

Additionally, in Austria allocations for hardwoods to the European strength class system are missing. Within EU Hardwoods it was possible to close this gap and to gather a suitable sample of Austrian beech for this allocation via a collaboration with the Austrian hardwood industry. The sample comprises five sub-samples and four cross-sections, in total 466 specimens (Tab. 3).

Tab. 3 sub-samples of Austrian beech

cross-section	sub-sample: Lower Austria	Vienna Woods t = 30mm	Vienna Woods t = 40mm	Upper Austria	Styria	**total**
30x100	45	--	--	36	17	**98**
40x100	--	--	30	--	--	**30**
30x150	51	94		49	85	**279**
40x150	5	--	52	2	--	**59**
total	**101**	**94**	**82**	**87**	**102**	**466**

The lamellas were visually graded acc. to DIN 4074-5 and tested afterwards. The data was evaluated based on EN 384 and EN 14358, which define for example the required correction factors for moisture content or parametric calculation of characteristic values, a preliminary allocation can be made: The visual grade LS7 can be allocated to strength class T12 and the visual grade LS10+ to T22. Tab. 4 shows the achieved characteristic values and relates them to the requirements of EN 338 defining the strength classes. The necessary allocation report will be prepared for submission to the responsible European Committee (TC 124 WG 2 TG 1), enabling the use of visually strength graded beech timber in building products.

Tab. 4 achieved characteristic values; in brackets: requirements acc.to EN 338

LS7 → T12	LS10+ → T22
$f_{t,0,k}$ = **12,8** (12,0) N/mm²	$f_{t,0,k}$ = **23,6** (22,0) N/mm²
$E_{t,mean}$ = **11,8** (9,5) kN/mm²	$E_{t,mean}$ = **15,5** (13,0) kN/mm²
ρ_k = **647** (330) kg/m³	ρ_k = **641** (390) kg/m³

In order to expand knowledge of strength properties and evaluate the suitability of existing standards for visual grading of Slovenian beech logs and boards, additional 210 beech logs were collected at UL FGG with lengths from 3,85 m to 4,65 m and with average middle diameter from 33 to 64 cm. Logs were visually graded according to EN 1316-1 standard for visual grading of round timber. For each of the 17 parameters, the quality grade was determined. The most influential parameter is the red heart, which in many cases is not taken into consideration as it is mostly a cosmetic defect. The second most important parameter are the occluded knots. Before cutting, longitudinal vibrational frequency was measured using a laser vibrometer. From those measurements, the dynamic modulus of elasticity was calculated. Logs were then sawn into boards with a cross-section of 32 x 130 mm². For the purpose of the research, only one board from each log was taken.

Tab. 5: A representative sample of the beech logs.

Quality grade	*Frequency*	*Frequency [%]*	*Log E_{dyn} median [N/mm^2]*	*Log E_{dyn} average [N/mm^2]*
A	16	7.7	12158	12522
B	31	14.9	12588	11637
C	81	38.9	11824	11805
D	80	38.5	11531	11353
Total	208			

The longitudinal vibrational frequency was measured on the boards before and after the drying process. After drying, the boards were planed and sawn to their final (nominal) dimensions of 24 x 120 x 3900 mm and further non-destructive tests were made:

- Moisture content of boards using a resistance moisture meter and a capacity moisture meter.
- The ultrasonic time of flight through the length of the boards.
- The longitudinal vibrational frequency measured with a regular and a shotgun microphone.
- Measurements of dynamic MOE with a strength grading machine for spruce MTG Timber Grader.

From each measurement of the frequency the dynamic modulus of elasticity was calculated. The relationship of the dynamic moduli of elasticity with the tension modulus of elasticity and tension strength was observed. The correlations were fairly good, but much weaker than those observed for spruce wood.

The dynamic modulus of elasticity of the logs from grade A have a slightly lower median than logs from grade B, followed by grades C and D respectively. Visual grades and dynamic MOE have a relatively good relationship. Dynamic moduli of elasticity of dry boards in grade A have lower values than in grade B. Otherwise the dynamic MOE decreases with grade quality. However, the differences are not significant. Additional sampling is needed and will be performed in future.

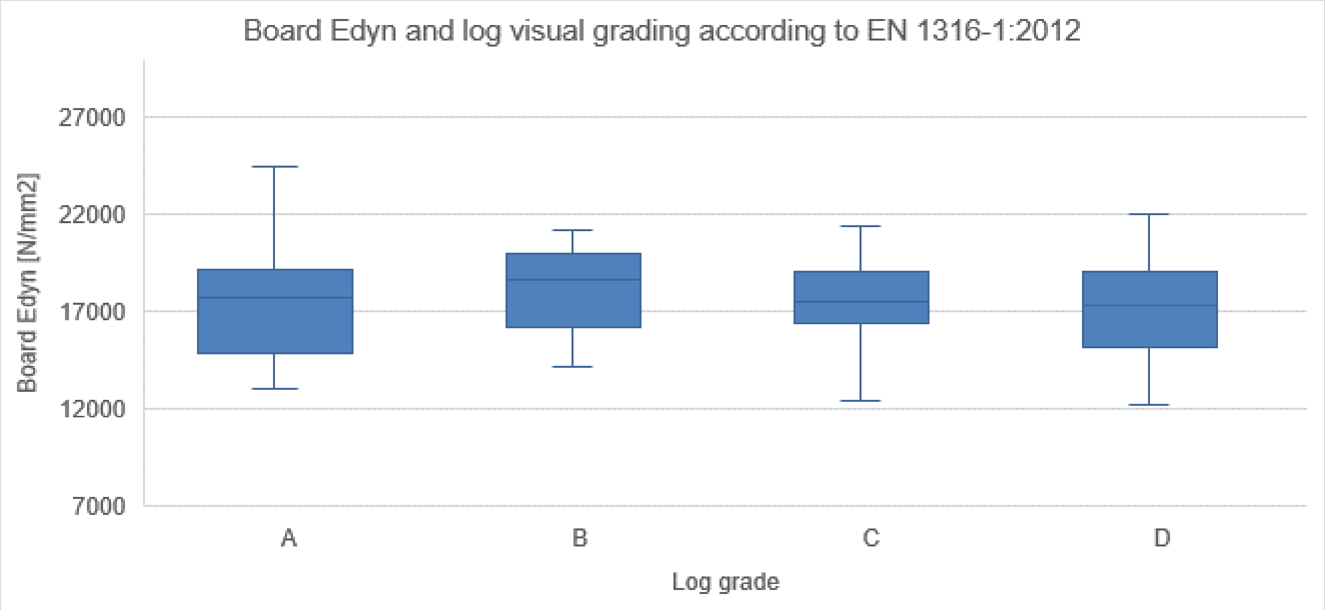


Figure 15: Board Edyn and visual grade of the logs

- VISUAL GRADING

All the boards were visually graded edgewise. For 113 boards, we measured all the required visual parameters for the visual assessment of the boards by the DIN 4074-5:2009 (Germany), by the French NF B 52-001-1:2016 and the British BS 5756:2007 standard for visual grading of hardwoods. The boards were then classified to the proper grades according to standards requirements. The French standard offers two grade combinations for visual grading. It can be observed, that in both cases the two standards gave comparable results. In terms of D grades, combination 1 (grade combination H1/D40, H3/D24) is closer to the German combination and has been used for comparison between the two standards. Below is a comparison between the German and combination 1 of the French visual grading standard. The German standard is somewhat more conservative. More boards are assigned to higher grades by the French standard.

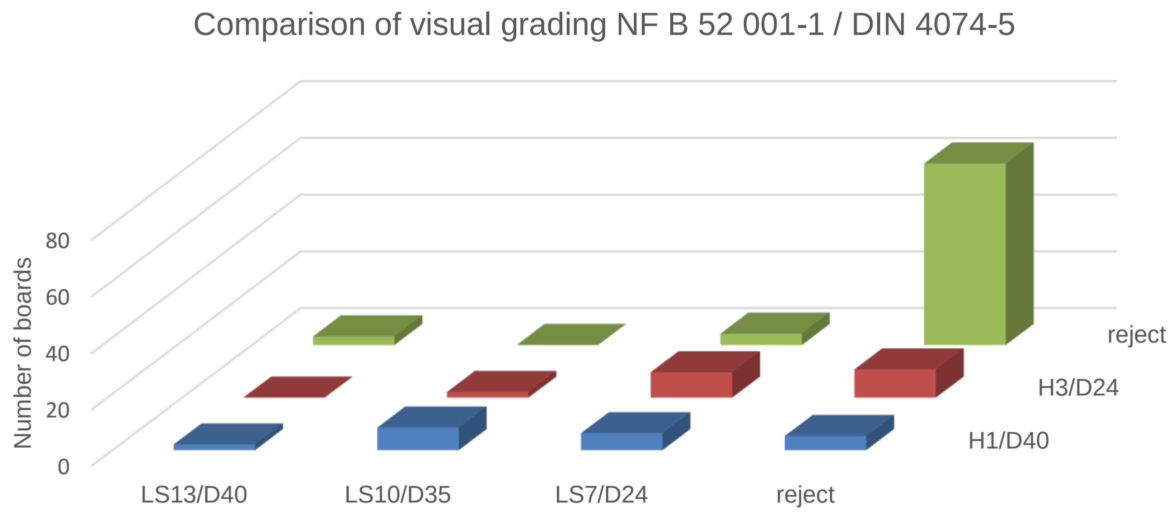


Figure 16: Visual grading according to NF B 52 001-1:2016 and DIN 4074-5:2009

To see how important is the influence of some of the parameters (warping and slope of grain) we graded boards disregarding these parameters. As expected the parameters have biggest impact on lowest grades, especially on the reject. When warping was omitted, the frequency of the grades LS13 and LS10 increased, while omitting slope of grain influenced only on the lowest grade LS7 and the reject.

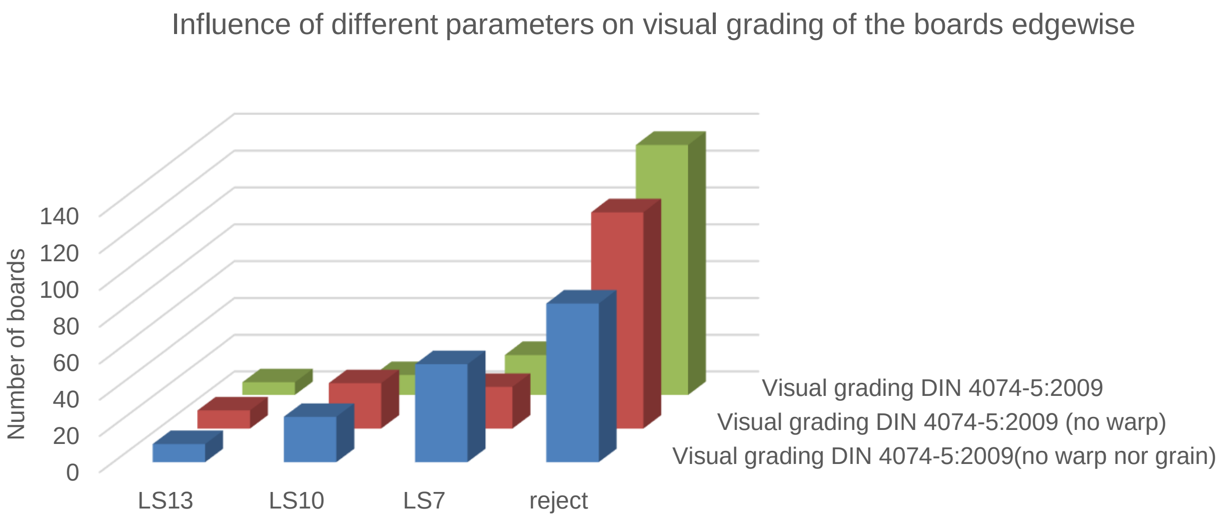


Figure 17: Influence of slope of grain and warping on the visual grading according to DIN 4074-5:2009

- TENSION TESTS

After visual grading and other non-destructive testing, the tension strength of the boards was tested according to the standard EN 408:2003. Before the boards were loaded to failure, the static modulus of elasticity in flatwise bending was measured according to EN 408:2003.

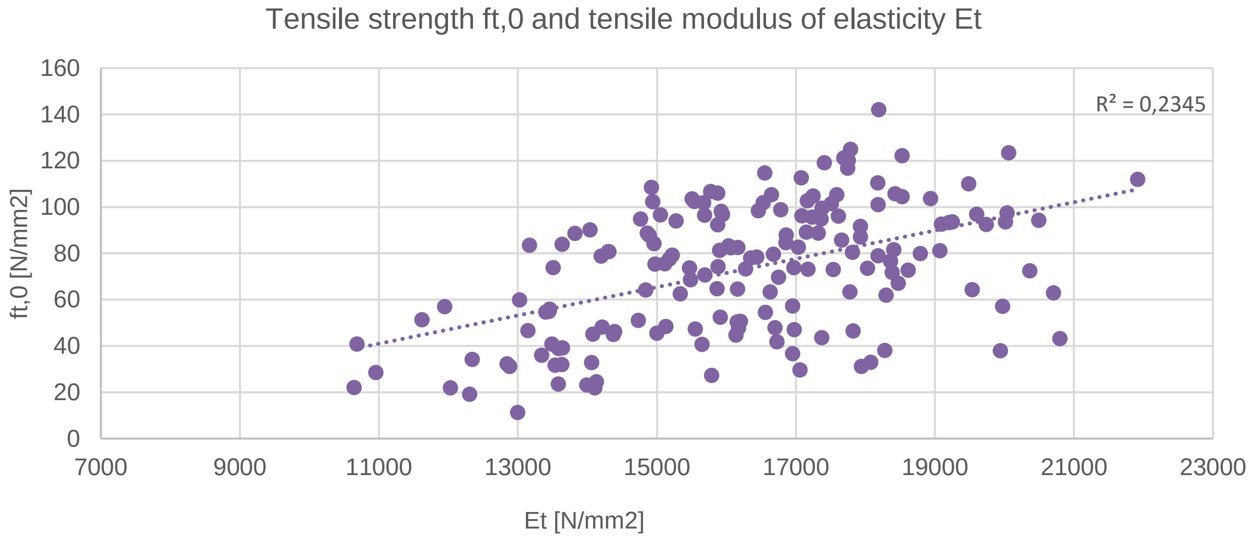


Figure 18: Tensile strength and tension modulus of elasticity of boards

The correlation between the tension strength and the MOE seems to be relatively low. Since these are tension strength properties and in majority the rupture occurred due to local defects like knots, slope of grain etc. such results were expected. By obtaining the tension strengths of the boards, we can assess the quality and reliability of non-destructive testing and visual grading of both logs and boards.
No significant relationship between the log grades and the tensile strength of the boards was observed. In the case of static MOE, the results are somewhat better.
The comparison of strength properties and visual grading of boards according to German and French standards for visual grading DIN 4074-5:2009 and NF B 52-001-1:2016 was made. In the case of the German standard, a poor correlation of visual grades and both tensile MOE and MOR was observed. The moduli of elasticity of the highest grade LS13 have the lowest value. Similar are the results in the case of tension strength, where grade LS13 has lower strengths than grades LS10 and LS7. These results are not conclusive. The sample of boards is small (the LS13 grade has only 5 specimens). Additional sampling is needed and will be performed in the future.
The French standard for visual grading gives a better correlation between the tensile strength properties and the visual grades than the DIN standard, but the moduli of elasticity are still not entirely consistent with the visual grades, since the second grade H3/D24 has the highest moduli of elasticity.

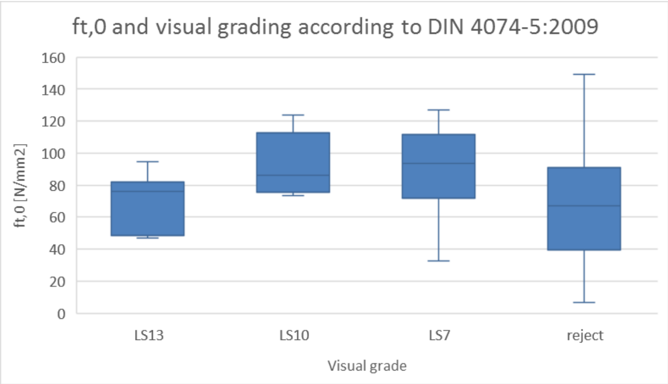


Figure 19: Tension strength ft,0 and visual grading according to DIN 4074-5:2009 grades

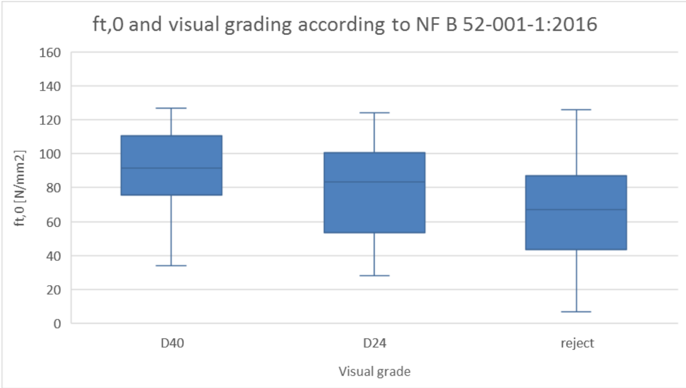


Figure 20: Tension strength ft,0 and visual grading according to NF B 52-001-1:2016

The correlation between the tensile strength and the dynamic MOE of the boards with a correlation coefficient R^2= 0,29 is slightly better than the one with static MOE measured during the tension strength. Due to the test setup the result was expected. The static MOE is measured only on half (5h) of the tension span (10h) and not all the defects are included. Meanwhile the large knots and bark pockets on the boards outside the static MOE measurement did influenced on the longitudinal vibrational frequency.

- BOARD TENSILE STRENGTH AND LOG DYNAMIC MODULUS OF ELASTICITY

For the sake of analysis, the logs were classified into three virtual grades based on the measured dynamic modulus of elasticity. The correlation between the two parameters was poor (R^2 = 0,02), but when we grouped logs to three grades we saw that the average values of board strengths are increasing with the dynamic modulus of elasticity.

Tab. 6

	to 10 000 [N/mm^2]	from 10 000 to 13 000 [N/mm^2]	from 13 000 do 17 000 [N/mm^2]
Average	36,61	63,26	66,27
Standard Deviation	27,03	28,65	28,32

We compared the tensile MOEs and strengths for spruce (2001 specimens), oak (533 specimens) and beech (278 specimens). Although beech wood is known as a strong wood species, the strength characteristics are higher than expected. Tension strength and tension MOE are both almost is twice as high as spruce wood and also significantly higher than oak.

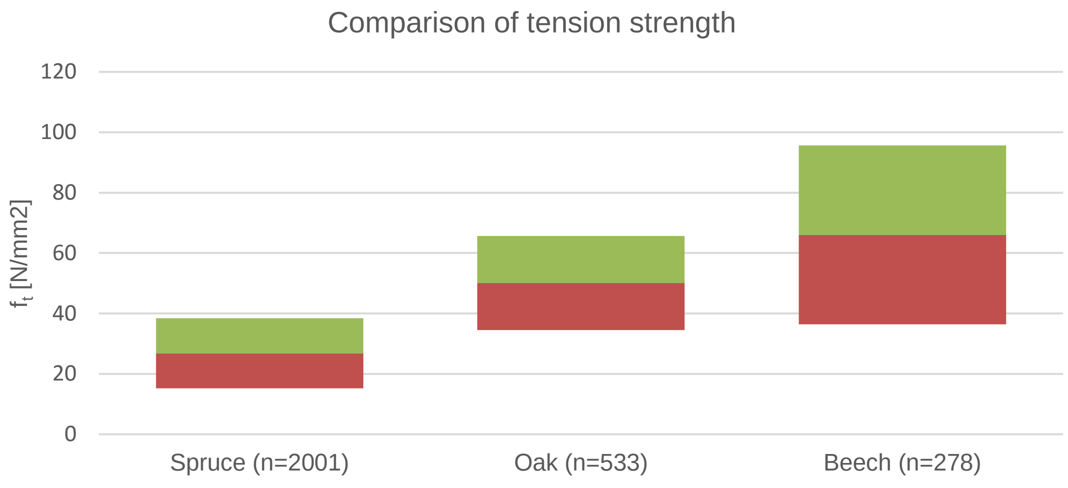


Figure 21

Adhesives for structural hardwood bonding (WP 3)

Due to limited personnel resources MPA Stuttgart was not able to send Input for this section in the final report.

Glulam made of hardwoods or hardwoods and softwoods (WP4)

Valorization of the hardwood resource in the form of glued laminated timber (GLT) (WP 4)

Objectives and issues

In order to enhance the aesthetic and mechanical advantages of hardwood species on the construction market and to face higher supplying and processing costs compared to softwood species, it is essential to create products with high added value such as Glued Laminated Timber (GLT) or Cross Laminated Timber (CLT).

It is important to point out at this level the importance of preparing the normative and / or regulatory framework that will allow these new products to enter the market. In this way, the EU-Hardwood project aims to enhance the information collected and / or acquired to the relevant standardization groups in order to bring them into "traditionality". In the meantime, the National Technical Approval or the European Technical Assessment procedure remains the only possible ways of recognition.

Homogeneous and combined hardwood GLT

The harmonized EN 14080 standard for the CE marking of GLT is limited to the softwood species mentioned in the standard and poplar. However, it provides the possibility of making GLT from hardwood species based on the same requirements. On the other hand, Annex ZA, that is to say the CE marking of the product, is not applicable. The development of new reconstituted products from hardwood species remains possible and the inventory of National

Technical Approvals and European Technical Assessments that have already been issued across Europe has been produced. An overview of the mechanical potential of GLT covered by these assessments is also given hereafter. It highlights the interest of enhancing the mechanical potential of hardwood species in the form of glued laminated products.

Tab. 7: National Technical Approvals and European Technical Assessments of hardwood GLT issued across Europe since 2004 *(Simon Aicher - MPA, Glulam made of hardwoods State of the art – species, adhesives and national / European approvals, EU Hardwood workshop, Bordeaux, 2017)*

First year of approval	Approval		Species of laminations (origin)	Service Class for use acc. to EN 1995-1-1	Holder of Approval
	German Technical Approval Z - 9.1 - …	European Technical Approval ETA			
2004	577	--	Dark Red Meranti (Indonesia)	1, 2	Enno Roggemann, Bremen, Germany
2008 - 2012	Approvals in single cases (Germany)		Oak (Germany, Czech Rep.)	1	Different holders, Germany
2009	679	--	Beech (Germany)	1	Studiengemeinschaft Holzleimbau, Wuppertal, Germany
2012 2013	704 --	-- 13/0642	Oak (France)	1, 2	Elaborados y Fabricados Gamiz S.A., Spain
2013	821	--	Oak (Germany, Czech Rep.)	1, 2	Holz Schiller GmbH, Regen, Germany
2013	--	13/0644	Sweet Chestnut (Spain)	1, 2	SIEROLAM SA., Spain
2013 2015	837 --	-- 14/0354	Beech LVL (Germany)	1, 2	Pollmeier Furnierwerkstoffe GmbH, Creuzburg; Germany

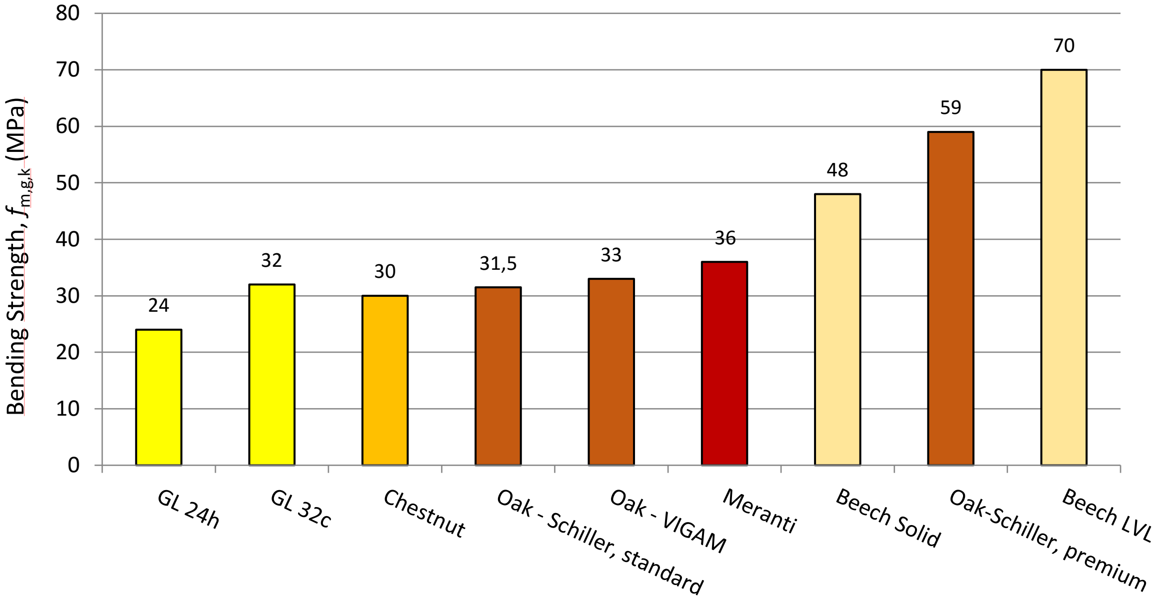


Figure 22: Overview of the mechanical potential of hardwood GLT based on National Technical Approvals and European Technical Assessments issued throughout Europe - characteristic bending strength (MPa) *(Simon Aicher - MPA, Glulam made of hardwoods State of the art – species, adhesives and national / European approvals, EU Hardwood workshop, Bordeaux, 2017)*

NB : GL24h and GL32c grades acc. to EN 14080 for softwood GLT given as reference

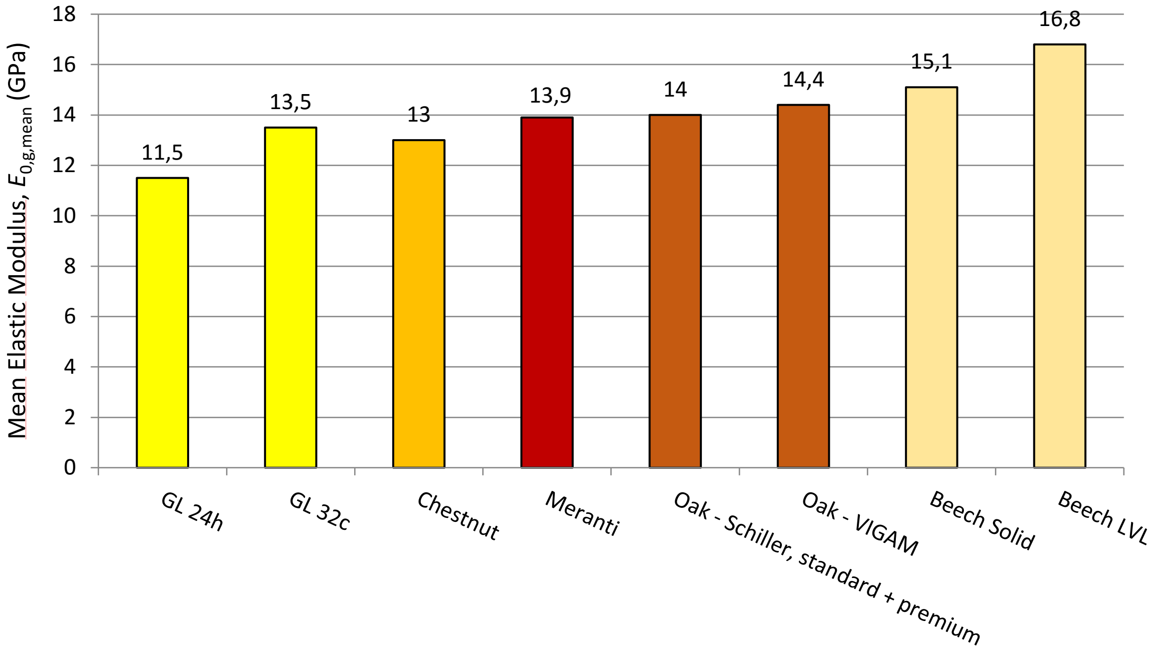


Figure 23: Overview of the mechanical potential of hardwood GLT based on National Technical Approvals and European Technical Assessments issued throughout Europe – mean modulus of elasticity in bending (MPa) *(Simon Aicher - MPA, Glulam made of hardwoods State of the art – species, adhesives and national / European approvals, EU Hardwood workshop, Bordeaux, 2017)*

NB : GL24h and GL32c grades acc. to EN 14080 for softwood GLT given as reference

At the same time, FCBA has put a technical, organizational and economical perspective on the creative ambitions of such new products, in particular homogeneous and combined Oak GLT from the French resource which is the biggest in Europe and needs to be valorized. This, from the raw material supply, then the first processing, to the second processing. In such an integrated approach with industrial partners, the results can not only facilitate the recognition of these products by markets subject to strong regulatory requirements, but also inform technical and economic adjustments to be made in the medium term to ensure their emergence on competitive markets already occupied by softwood products.

Methodology

FCBA has relied on several industrial partners with which two prototype productions have been carried out: glulam manufacturer SIMONIN SAS (Montlebon - FR), partner of the EU-Hardwood project, its glue supplier AKZO NOBEL (SE), Oak sawmills MUTELET (Rahon - FR) and TRENDEL (Haguenau - FR) and the National Forestry Office (ONF). A first enquiry was conducted to establish the specifications of the target lamellae for GLT production. On this basis, and gradually capitalizing on feedback, FCBA proposed **2 scenarii of value chains to be tested, involving a low degree of change for the first scenario and a strong degree of change for the second scenario**.

Scenario 1: production and evaluation of Oak GLT from traditional square edged timber - low degree of change

The objective of the first prototype production was to investigate the feasibility of producing Oak GLT at least equivalent to strength grade GL24h according to EN 14080 standard for softwood GLT, from square edged timber traditionally proposed by Oak sawmills (usually sawn from large diameter logs, excluding butt logs). It was assumed that this type of GLT can be produced from strength grade D24 square edged timber (after visual grading for strength according to NF B 51002-1 and allocation to a strength grade of EN 338 according to EN 1912) and that these quality can be obtained from aesthetic class QF2 and QF3 square edged timber (after visual grading for aesthetic according to EN 975-1). Such a scenario implies a **low degree of change** on the whole value chain compared to the existing one.

On the basis of this assumption, SIMONIN SAS ordered 20 m^3 of aesthetic grades QF2 and QF3 square edged timber to MUTELET sawmill. To meet this demand on time, MUTELET sawmill was forced to use square edged timber from different production methods and to supplement the volume ordered by over-quality (QF1-b aesthetic class).

At reception, a visual grading for strength according to NF B 52001-1 was carried out by FCBA on behalf of the GLT manufacturer and allowed the allocation of the boards to various EN 338 strength grades.

Tab. 8: Allocation of the square edged timber supplied by MUTELET sawmill to EN 338 strength grades after visual grading for strength according to NF B 52001-1

Strength grade acc. to EN 338	D30	D24	D18	Reject
Percentage of the whole batch	24%	70%	4%	2%
Comment	Extra material coming from QF1-b aesthetic grade (over-quality)	Requested material coming from QF2 – QF3 aesthetic grades		

In order to enhance the total volume available, 70 Oak GLT were manufactured by SIMONIN SAS in various qualities and quantities.

Tab. 9: Composition of Oak GLT produced by SIMONIN SAS from traditional square edged timber supplied by MUTELET sawmill (requested D24 equivalent strength grade)

Composition	Lamellae			GLT		
	Strength grade acc. to EN 338	Length (mm)	Quantity	Cross section (mm²)	Quantity	Volume (m^3)
Homogeneous	D24	4 500	8	160 x 150	20	2.2
Homogeneous	D24	7 000	15	300 x 150	20	6.3
Total	--	--	--	--	40	8.5

Tab. 10: Composition of Oak GLT produced by SIMONIN SAS from traditional square edged timber supplied by MUTELET sawmill (extra D30 + reject D18 equivalent strength grades)

Composition	Lamellae			GLT		
	Strength grade acc. to EN 338	Length (mm)	Quantity	Cross section (mm²)	Quantity	Volume (m^3)
Homogeneous	D30	3 500	9	180 x 150	20	1.9
Combined	D30 / D18 / D30	3 500	3 / 3 / 3	180 x 150	10	0.9
Total	--	--	--	--	30	2.8

In order to evaluate the GLT, the test method according to EN 14080 was used. It is based on 4-points bending tests on solid lamellae, finger jointed lamellae and beams. The bonding quality (inter-lamellae bonding) was also checked by means of delamination and shear tests of the glue joints.

The test results for the verification of the bonding quality, all satisfactory, make it possible to conclude that the company is in control of Oak bonding by means of suitable adhesive and bonding parameters.

The results of the mechanical tests on the homogeneous GLT produced from D24 strength grades lamellae are presented hereafter. The properties of the Oak GLT are compared with the minimum requirements of strength grade GL24h according to EN 14080 for softwood GLT of similar composition taken as reference. For the characteristic bending strength, these minimum requirements take into account coefficients related to scaling effect of GLT and thickness of the lamellae.

Integrating these coefficients makes it possible to compare configurations with each other when the constituent lamellae and the final GLT do not have the reference dimensions given in EN 14080.

The results show the satisfactory behavior of the manufactured GLT whose mechanical properties correspond to the requirements of the GL24h strength grade. This is the case for each of the mechanical properties taken into account for the strength grading of GLT: mean modulus of elasticity in bending, characteristic bending strength and characteristic density.

It is underlined that this comparison is established with respect to the only existing standardized grades for GLT, namely the softwood GLT, from which the various mechanical properties that can be used for the design of structures are derived. One of the objectives of the EU Hardwood project is to propose optimized grades, or even new grades, for hardwood GLT whose mechanical properties may differ from those of softwood GLT. This, on the basis of the bibliographic survey and the experiments carried out within the framework of the project that shall also make it possible to propose a model for predicting the mechanical properties of hardwood GLT.

Tab. 11: Mechanical properties of Oak GLT produced by SIMONIN SAS from D24 strength grade lamellae (traditional square edged timber sawn from large diameter logs, excluding butt logs) and softwood GLT reference

Properties	Beams composition	
	Homogeneous D24 Traditional sawn timber visually graded for strength acc. to NF B 52001-1	
	Results Correction to h = 300 mm n = 40	Requirements GL24h acc. to EN 14080:2013 for softwood GLT C24 → GL24h Correction to h = 300 mm

Beams	Mean modulus of elasticity $E_{0,g,mean}$ (N/mm²)	11 700	11 500
	Mean bending strength $f_{m,g,mean}$ (N/mm²)	42,8	--
	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	32,4	27,0
	Mean density $\rho_{g,mean}$ (kg/m^3)	653	--
	Characteristic density $\rho_{g,k}$ (kg/m^3)	627	385
Finger jointed lamellae n = 30	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	30,1	30,0

The results of the mechanical tests on the homogeneous (h) and combined (c) GLT produced from the D30 and D18 strength grades lamellae are shown hereafter. In the present case, the mechanical property limiting the grading is the modulus of elasticity in bending.

Tab. 12: Mechanical properties of Oak GLT produced by SIMONIN SAS from D30 and D18 strength grades lamellae (traditional square edged timber sawn from large diameter logs, excluding butt logs) and softwood GLT reference

Properties		Beams composition			
		Homogeneous D30 Traditional sawn timber visually graded for strength acc. to NF B 52001-1		Combined D30 / D18 / D30 Traditional sawn timber visually graded for strength acc. to NF B 52001-1	
		Results h = 180 mm n = 20	Requirements GL28h acc. to EN 14080:2013 For softwood GLT C30 → GL28h Correction to h = 180 mm	Results h = 180 mm n = 10	Requirements GL28c acc. to EN 14080:2013 for softwood GLT C30 / C18 / C30 → GL28c Correction to h = 180 mm
Beams	Mean modulus of elasticity $E_{0,g,mean}$ (N/mm²)	11 400	12 600	11 200	12 500
	Mean bending strength $f_{m,g,mean}$ (N/mm²)	46,3	--	52,6	--
	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	35,7	32,3	34,2	32,3
	Mean density $\rho_{g,mean}$ (kg/m^3)	655	--	662	--
	Characteristic density $\rho_{g,k}$ (kg/m^3)	622	425	638	390
Finger jointed lamellae n = 30	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	29,6	36	29,6 36,0	37 28

This can be explained by the heterogeneity of the supply from multiple origins. Above all, for equivalent strength grade D30 (hardwood) / C30 (softwood) the modulus of elasticity of traditional sawn Oak timber is lower than that of softwood. This has led to an adjustment of the threshold for the modulus of elasticity in EN 338 when revising the characteristics of D30 grade (EN 338 : 2009). This is reflected in the glue laminated beams and justifies the approach to establish optimized grades for hardwood GLT as it has been done for hardwood sawn timber.
We consider, for example, an optimization with respect to modulus of elasticity which is estimated at 12 GPa for softwood sawn timber graded as C30 whereas it is 11 GPa for hardwood sawn timber graded as D30. In this case, we could imagine the creation of a GL28h grade for hardwood GLT in which the threshold for the modulus of elasticity would be revised downward and those for strength and density revised upwards.

As far as the economic and organizational aspects are concerned, this prototype production points out areas for improvement in the progressive introduction of a supply chain for oak lamellae dedicated to the production of GLT, between the sawmill and the glulam manufacturer:

- It is possible to find, in the existing products range, available D24 equivalent square edged timber provided that the sawmill is given a minimum time to fulfill orders (3 to 4 months) and that the raw material is not directly competing with traditional high-demand and remunerative markets. Otherwise, to position sawmills on such market, it is expected contractualized one-year rather than one-shot orders;
- With regards to lengths and dimensional tolerances, confidence has to be built between clients and suppliers by understanding the production constraints lived on both sides;
- The adoption of the visual grading for strength at sawmill place and the acceptance of different lengths and grades by the GLT manufacturer will facilitate the dialogue.

Scenario 2: production and evaluation of oak GLT from a selected supply - high degree of change
The objective of the second prototype production was twofold:

- Implementing a value chain for selected logs from young trees of average diameter D_{130} = 25 - 40 cm most often from thinning cuts, deemed particularly interesting because of their high mechanical properties (JD Lanvin, D Reuling , Mechanical characterization of the French oak resource for structural use, Revue Forestière Française, 2012) and whose outlets are less obvious than those of large trees already well valued in other markets;
- Producing combined GLT in order to enhance all the qualities resulting from such logs, in particular boards with singularities, to echo the expectations of sawmills that wish to value the lower qualities.

Such a scenario implies a **high degree of change** in relation to the existing value chain.

Based on this assumption, FCBA identified on the ONF catalog a batch of logs from a thinning cut of requested age and diameter class, considered relatively homogeneous by ONF and without second logs. In this way, the operator has taken the maximum quality out of the length from the foot and the products above the cut have been upgraded in industrial wood or wood energy. The logs were taken over by TRENDEL sawmill, sawn, dried and calibrated on behalf of the company SIMONIN SAS, which received a volume of 10 m^3 of sawn timber after a period of 3 months.

At reception, a visual grading for strength according to the methodology of NF B 52001-1 was carried out by FCBA on behalf of the glulam manufacturer after modification of several grading criteria in order to bring out boards likely to correspond to a D40 grade currently not provided in the standard. This grading allowed the allocation of the boards to various EN 338 strength grades.

Tab. 13: Allocation of the sawn timber proposed by TRENDEL sawmill to EN 338 strength grades after visual grading for strength according to modified NF B 52001-1

Strength grade acc. to EN 338	D40	D30	D24	D18	Reject
Percentage of the whole batch	37%	44%	13%	5%	1%

In order to enhance the total volume available, 60 Oak GLT were manufactured by SIMONIN SAS in various qualities and quantities.

Tab. 14: Composition of Oak GLT produced by SIMONIN SAS from square edge timber sawn by TRENDEL sawmill from a selected supply (average diameter logs, coming from a thinning cut)

Composition	Lamellae			GLT		
	Strength grade acc. to EN 338	Length (mm)	Quantity	Cross section (mm^2)	Quantity	Volume (m^3)
Homogeneous	D30	3500	9	180 x 150	25	2.4
Combined	D30 / D18 / D30	3500	3 / 3 / 3	180 x 150	5	0.5
Homogeneous	D40	3500	9	180 x 150	15	1.4
Combined	D40 / D24 / D40	3500	3 / 3 / 3	180 x 150	15	1.4
Total	--	3500	--	--	60	5.7

The GLT were tested according to the test procedure described above. The properties of the homogeneous (h) and combined (c) GLT are compared with the minimum requirements of strength grades GL28h,c or GL32h,c according to EN 14080 for softwood GLT of similar composition taken as reference.

The results show the very satisfactory behavior of the Oak GLT, whose mechanical properties are higher than the requirements of the softwood GLT grades taken as reference. This is the case for each of the mechanical properties taken into account for the strength grading: modulus of elasticity in bending, characteristic bending strength and characteristic density. In this case, **the bending strength and especially the modulus of elasticity in bending are much higher than the value indicated for a softwood GLT**, which was expected due to the choice of a selected supply.

This is valid whatever the strength grading of the lamellae (D30, D40) and the composition of the GLT (homogeneous, combined). The whole supply was therefore perfectly valorized without compromising the mechanical properties of the beams. The introduction of lamellae of lower strength grades in combined compositions only slightly penalize the bending strength.

Tab. 15: Mechanical properties of Oak GLT produced by SIMONIN SAS from D30 and D18 strength grades lamellae (square edged timber sawn from specified average diameter logs) and softwood GLT reference

Properties	Beams composition			
	Homogeneous D30 Specified sawn timber visually graded for strength acc. to the methodology of NF B 52001-1		Combined D30 / D18 / D30 Specified sawn timber visually graded for strength acc. to the methodology of NF B 52001-1	
	Results h = 180 mm n = 25	Requirements GL28h acc. to EN 14080:2013 For softwood GLT C30 → GL28h Correction to h = 180 mm	Results h = 180 mm n = 5	Requirements GL28c acc. to EN 14080:2013 for softwood GLT C30 / C18 / C30 → GL28c Correction to h = 180 mm

Beams	Mean modulus of elasticity $E_{0,g,mean}$ (N/mm²)	15 800	12 600	15 000	12 500
	Mean bending strength $f_{m,g,mean}$ (N/mm²)	63,8	--	56,3	--
	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	46,5	32,3	*	32,3
	Mean density $\rho_{g,mean}$ (kg/m^3)	725	--	729	--
	Characteristic density $\rho_{g,k}$ (kg/m^3)	703	425	*	390
Finger jointed lamellae n = 30	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	54,5	36	54,5 57,7	37 28

* The quantity of beams is too small for a characteristic value to be announced. However, the mean values are shown here.

Tab. 16: Mechanical properties of Oak GLT produced by SIMONIN SAS from D40 and D24 strength grades lamellae (square edge timber sawn from specified from specified average diameter logs) and softwood GLT reference

Properties	Beams composition			
	Homogeneous D40 Specified sawn timber visually graded for strength acc. to the methodology of NF B 52001-1		Combined D40 / D24 / D40 Specified sawn timber visually graded for strength acc. to the methodology of NF B 52001-1	
	Results h = 180 mm n = 15	Requirements GL32h acc. to EN 14080:2013 For softwood GLT C40 → GL32h Correction to h = 180 mm	Results h = 180 mm n = 15	Requirements GL32c acc. to EN 14080:2013 for softwood GLT C40 / C24 / C40 → GL32c Correction to h = 180 mm

Beams	Mean modulus of elasticity $E_{0,g,mean}$ (N/mm²)	16 300	14 200	17 100	13 500
	Mean bending strength $f_{m,g,mean}$ (N/mm²)	81,2	--	71	--
	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	61,7	37	55,1	37
	Mean density $\rho_{g,mean}$ (kg/m^3)	726	--	732	--
	Characteristic density $\rho_{g,k}$ (kg/m^3)	709	440	712	400
Finger jointed lamellae n = 30	Characteristic bending strength $f_{m,g,k}$ (N/mm²)	59,8	41	59,8 52,5	44 31

This demonstration opens new doors of valorization for the GLT manufacturers. Indeed:

- From homogeneous batches in the forest in terms of origin and age, it is possible to generate a mix of sawn timber qualities which can be transformed using the entire mechanical pallet (from D18 to D40) to generate homogeneous and, above all, combined beams, mobilizing only a partial volume of high performance lamellae (D30 or even D40) and using, in addition, the lamellae with lower properties (D24 or even D18);
- The use of sawn timber issued from a selected supply (average diameter logs from young trees) made it possible to overcome the limiting character of the modulus of elasticity of the traditional sawn timber coming from large logs. The obstacle to a classification of the beams at least comparable to that of softwood GLT of similar composition would then be overcome. Interesting prospects for the creation of new grades of higher characteristics are even conceivable.

From an economic and organizational point of view, as in the case of the first scenario, constrained production conditions had an impact on sawmill yield. This experiment does nevertheless reveal interesting perspectives to be taken into account at each of the steps of the value chain:

- In forest: for roundwood supplies selected on specified dimensional, qualitative and age criteria;
- At sawmills: for a first transformation integrating an expanded products range including GLT lamellae and incompressible time constraints to minimize deformations and downgrades;
- For the glulam manufacturer: for the adoption of organization adapted to production of combined GLT.

Comparison of valuation chains and associated courses

During the two prototype productions, FCBA was able to raise the manufacturing costs from the various stakeholders. These data, collected in special circumstances, should be taken into consideration with caution. They still offer a first level of comparison between the prototype productions themselves, and with respect to spruce GLT production more conventionally conducted by SIMONIN SAS, taken as reference. The equivalent overall costs for scenario 1 and 2 are shown to be approximately 2.7 times higher than for spruce BLC.

Tab. 17: Comparison of the 2 production scenarii of Oak GLT studied with the usual production of spruce GLT by the company SIMONIN SA *(M. Vuillermoz, G. Legrand, P. Fenart, JD Lanvin, D. Reuling and C. Faye – FCBA, Productions de bois lamellé collé en chêne français : enseignements technico - économiques des campagnes EU Hardwood, 2017)*

	Scenario 1	Scenario 2
Degrees of change	Low Only the sawmill / glulam producer interface is concerned	High Changes at all stages: • Specified roundwood • Sawing services • Homogeneous and combined GLT
Roundwood supply	Large diameter logs, excluding butt logs	Average diameter logs, coming from thinning cuts
Products from 1st processing in sawmill	Traditional dry square edged timber taken from the sawmill stock; cross section 27 x 160 mm² Delivery 850 €/m³ Estimated material yield ~ 35%	Dry sawn timber according to the requirements of the glulam producer cross section 27 x 175 mm² Delivery 647 €/m³ Estimated material yield ~ 40% NB : Cost and yield excluding final calibration

Calibration		Final calibration at the glulam factory: 24 x 160 mm^2	Final calibration at the sawmill: 23 x 160 mm^2
Cross section yield from dry sawn timber to calibrated lamella		71%	60%
Transport		Cost function of the quantity	
Visual grading for strength acc. to NF B 52001-1		D24 and D18 NB : Although valued elsewhere, the D30 grade was excluded from this comparison	D40, D30, D24 and D18
GLT production		Traditional production of straight homogeneous GLT from D24 lamellae	Specific production of straight homogeneous and combined GLT from D40, D30, D24 and D18 lamellae
Production cost (raw material + GLT production)	Index 100 Spruce	277	283
GLT strength grade	Spruce GLT	D24 → GLxxh > GL24h NB : According to EN 14080 for softwood GLT of similar composition; GLxxh remains to be specified when creating grades specific to hardwood GLT	D30 → GLxxh > GL28h D30 / D18 → GLxxc > GL28c D40 → GLxxc > GL32h D40 / D24 → GLxxh > GL32c NB : According to EN 14080 for softwood GLT of similar composition; GLxxh remains to be specified when creating grades specific to hardwood GLT

This comparison demonstrates the need for Oak GLT to find its own place on the construction market. Even if the theoretical gap between Spruce and Oak GLT could be reduced by various improvements at each step of the production, Oak GLT would have to find a valuation on its own market segment (s) in line with its mechanical, aesthetic and social assets. More market and cost studies are still needed, but first and second transformation companies will be better suited to find this balance than hardwood species will have obtained their right place in the standardization framework.

Finite element model to assess the bending strength of hardwood glulam beams
Currently, the European glulam standard EN 14080 covers exclusively specifications, requirements and evaluation of conformity procedures for glulam made of softwoods. The standard includes a bending strength model for homogeneous glulam based on the characteristic values of the mechanical properties – tension strength of the boards and bending or tension strength of finger joints. Inhomogeneous build-ups with different strength classes of the boards are then captured by beam theory and transformed sections. However, since the mechanical properties of boards and finger joints for hardwood can significantly differ from those of typical softwoods, a direct application of this model to hardwood glulams is not possible in generalized manner.

One of the tasks of the MPA, University of Stuttgart, was to develop a finite element (FE) model, capable of predicting the bending strength of glulam beams made of hardwoods. For this, an intensive literature study of previous work done by Ehlbeck and Colling (1987), Blaß et al. (2005) and Frese and Blaß (2009) on the modelling of glulam beams was done. Similar as the mentioned existing models, the present model was designed to account for the variation of the mechanical properties – tensile strength and modulus of elasticity (MOE) – of each board of the glulam build-up, the respective finger joints, as well as the variation of these properties within each board. In addition, the model is capable of modelling inhomogeneous build-ups as well as hybrid configurations.

Homogeneous, inhomogeneous and hybrid build-ups
The manufacture and use of inhomogeneous glulam beams, i.e. build-ups from same wood species but different lamination grades and hence strength classes at distinct cross-sectional positions is a very common practice as hereby the wood resource can be utilized far more efficiently as in case of homogenous build-ups without significant draw backs in technical performance. Hence the newly developed model was designed to handle such build-ups with no problem. Hereby homogeneous build-ups are automatically covered as they are a special case of the inhomogeneous arrangement, where only one zone within the cross-section of the glulam is defined. Figure 24 shows an example of an inhomogeneous glulam beam, where boards of the higher strength grade LS13 (DIN 4074-5) are used in the outer zones (green and blue) whereas the inner region is filled with boards of the lower strength grade LS10.
The modelling of hybrid beams, i.e. build-ups from laminations of different wood species and strength classes is possible as well, as this represents just a special case of inhomogeneous beam build-ups.

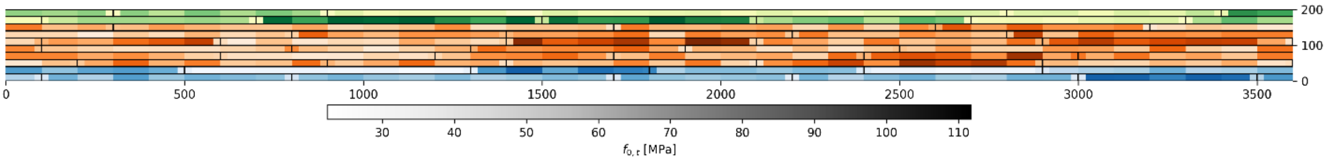


Figure 24: Example of the distribution of the tensile strengths and position of finger joints in an inhomogeneous glulam build-up. The outer zones (colors blue and green) correspond to boards of the strength class LS13, while the inner boards (red) correspond to the strength class LS10

Input parameters

A major task in this work package was to develop a procedure to generate the needed input data for the model, in such a manner that the statistical fingerprint of each property could be accurately reproduced. Roughly speaking, the method used to generate the data consists of three steps:

- the experimental data are analyzed in order to obtain: a) statistical distributions of each property and b) the correlation coefficients between them (when possible)
- the properties (MOE, tensile and compressive strengths, and board lengths are generated for a number *N* of boards, where special care is taken in reproducing the observed correlations between the different properties
- the properties for the different segments within each board are generated and used as input parameters for the model

Mechanical properties of boards and finger joints

The properties used to describe the boards were the length of the boards (distance between adjacent finger joints), MOE, tensile strength and compressive strength, as well as the correlations between tensile strength and MOE and compressive strength and MOE. For all of these variables a lognormal distribution was fitted and used to generate the simulated input data for the model. Figure 25 shows an example of the generated data for MOE and tensile strength and the correlation between them, based on experimental data for a set of oak boards, investigated in the context of a technical approval campaign (ETA-13/0642:2013).

Similarly, the finger joints were described based on results of tensile strengths and MOE values of the corresponding boards connected. In this manner it is also possible to extract a correlation between the MOEs of the boards at each side of the finger joint and the tensile strength, which is used later to generate the simulation data. Since it is expected that a relatively high percentage of the failures will initiate at the finger joints, due to their often rather low strength values in comparison to the boards in case of hardwoods, it is very important to capture and reproduce their properties in a good manner.

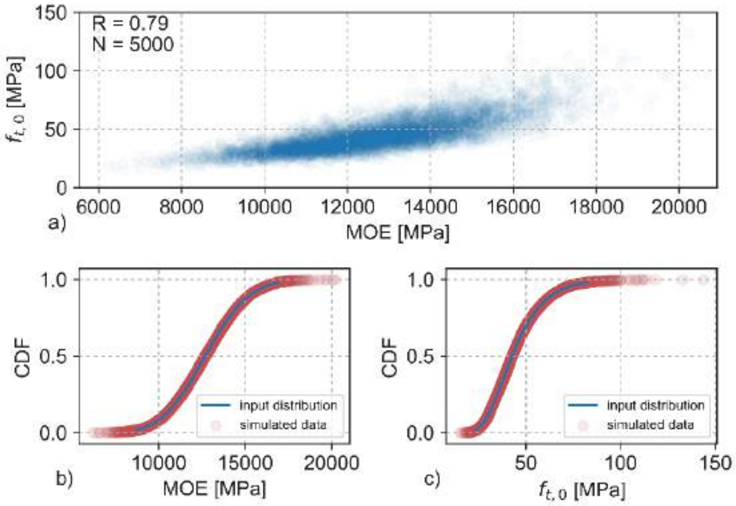


Figure 25: Example of the correlated MOE – $f_{t,0}$ data generation; a) MOE–$f_{t,0}$; b, c) input distributions and simulations of individual properties MOE and $f_{t,0}$

Variation of properties within board

The variation of the MOE along each board was experimentally studied for a specific set of oak laminations from France with cross-sectional dimensions (thickness t x width b) of 27mm x 155 mm and a length of 3m. The moisture content conformed in average to 12.7 ± 1.5%. The material obtained from company Mutelet was pre-graded to non-structural grades QF2 and QF3 according to EN 975-1 and then regraded acc. to DIN 4074-5 to structural hardwood grades LS10 and LS13. The MOE variation along board length was performed in tension tests as shown in Figure 26, whereby a specially modified extensometer with a base measurement length of 100 mm was used to measure the MOE in evenly spaced sections of the board. In total 40 boards were tested, giving an insight into the variation of the mechanical properties and providing the basis to establish the intra-board MOE variation for the simulations

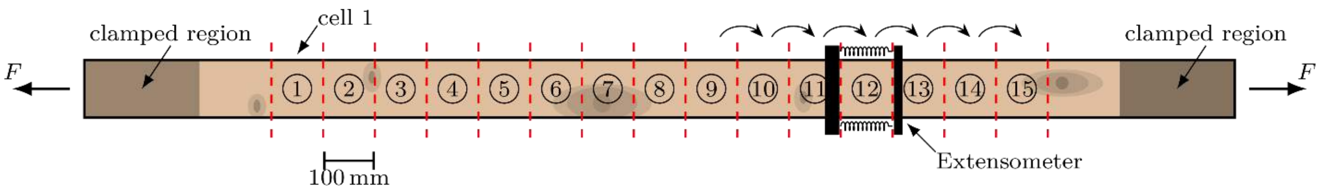


Figure 26: Test set-up used to investigate the variation of the MOE within a single board of French oak

Finite element model

Description

The developed two-dimensional model applies many of the concepts specified in the above cited literature, however comprises new relevant parameters and modelling techniques, such as the extended finite element method (XFEM). The latter addition has a strong potential of increasing the accuracy of the simulation model, since it describes the failure as a process, where several cracks may start independently, stop and continue before global failure is reached.

Two-dimensional, linear plain stress elements with reduced integration (CPS4R) were used for the beam modelling and rigid line elements (R2D2) were applied in the support and loading zones. The modelling was performed with Abaqus 2016. Figure 27 shows a sketch of the created FE model, where the loading and support points, as well as the position of the element enriched zone (XFEM) is visible.

The essential global mechanical properties used for the model are those obtained from the experimental tests, combined with the mechanical properties given in EN 338 for the MOE perpendicular to the fiber (E_{90}) and the shear modulus (G). These latter two values are modified according to the MOE parallel to fiber attributed to the boards based on the proportionality assumption $E_{90,i} = E_{90,\mathrm{ref}} \cdot E_{0,i}/E_{0,\mathrm{ref}}$.

Different fracture energies were assigned to finger joints and boards to account for the difference in the materials that are involved in the failure process – wood in the boards and some combination of adhesive and wood in the finger joints. The failure criterion chosen corresponds to the *maximum stress criterion*, where damage initiation is related to the tensile strength of either the finger joint or the wooden board. The fracture energies used in the finger joints are based on values obtained by Serrano (1997), while the one used for the wood is based on a recent model by Blank et al. (2017). These values are $G_f = 10$ N/mm and $G_f = 20$ N/mm for finger joints and wood, respectively.

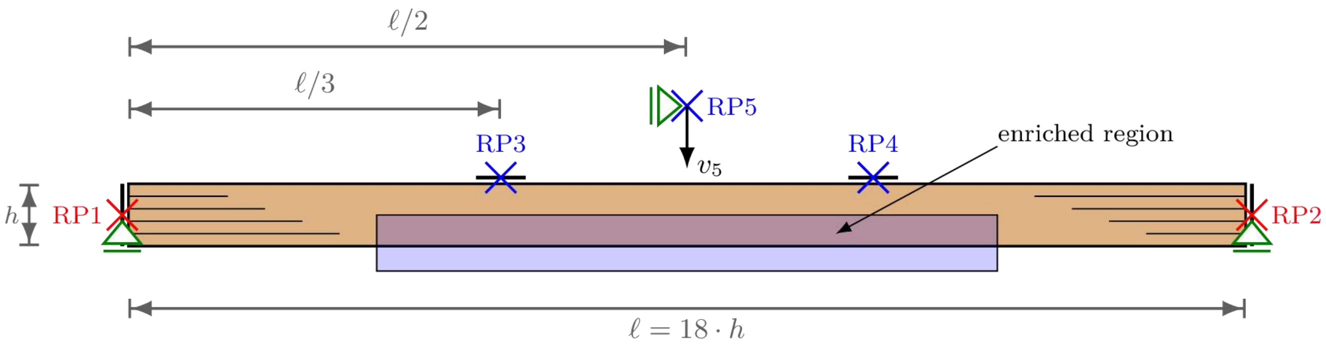


Figure 27: Finite element model – geometry, enriched element region and boundary conditions

Regarding the load application and boundary conditions, they were chosen in such a manner that a convergence of the results during the progressive failure evolutions guaranteed. In order to achieve this, the application of the load has to be displacement controlled. A direct application of displacement at points RP3 and RP4, however, would lead to an uneven distribution of loads in both points. To overcome this, the loading of the beam was controlled by a vertical displacement in the point RP5 (v_5) related to the vertical displacements of the points RP3 and RP4 (v_3 and v_4, respectively) by

$$v_5 - 0.5 \cdot (v_3 + v_4) = 0.$$

This procedure ensures that the loads applied at each one of the loading points RP3 and RP4 are equal at every time increment, allowing for a good convergence during the process of crack propagation. For further improvement of the convergence of the analysis, the horizontal displacements of the left and right supports (here applied at mid-high of each end of the beam) were restrained, so that the horizontal displacements on both support are always equal and in the opposite direction.

- RESULTS

Figure 28 a-b show exemplarily the FE model for one inhomogeneous oak glulam build-up configuration, as shown in Figure 24, in its failed state. The position of the finger joints can be clearly identified by the red colored areas. The example shows two important behaviors which were successfully captured by the model: the first one is the fact that the crack that first initialized did not cause global failure of the beam as its propagation was constrained by a “stronger” lamination on top of it.

This features the well known “lamination effect”, which improves the overall mechanical properties of the beam as compared to the single boards that compose it. Hereby stronger and stiffer adjacent laminations result in stress redistribution and hence postponement of ultimate load. Figure a shows the load-displacement curve of the example, where the load-deflection points of crack onsets are indicated. The graph exemplarily and roughly illustrates the magnitude of the influence of the lamination effect for the specific simulation. The second observation regards the position of crack initiation, which for this case are located at finger joints, which are considered to be normally the weakest points in hardwood glulams. This helps to verify the correct assignation of the material properties to the glulam.

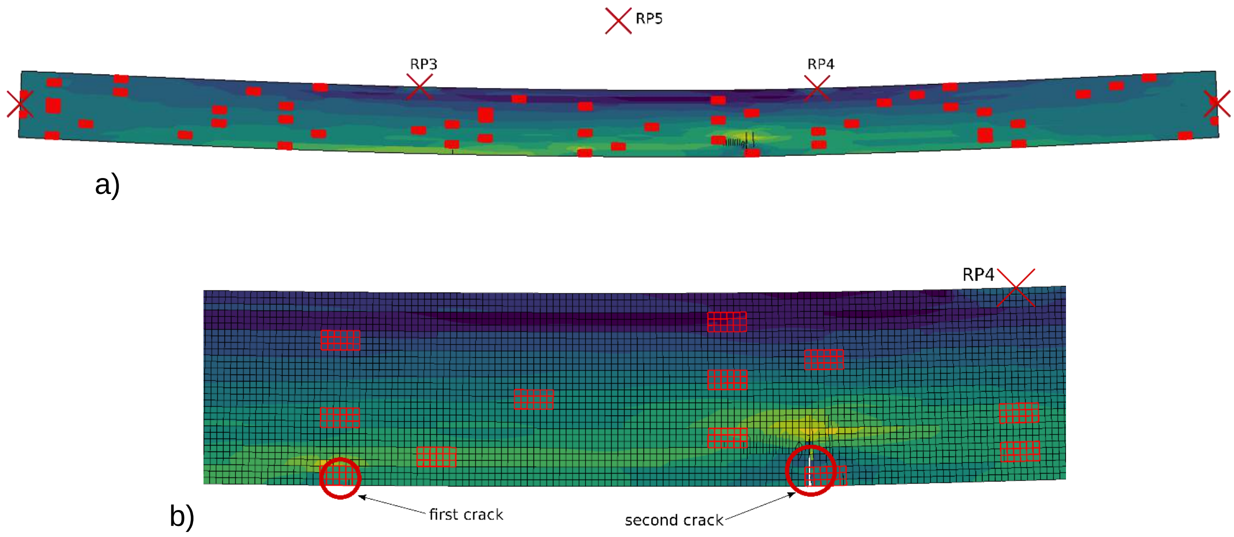
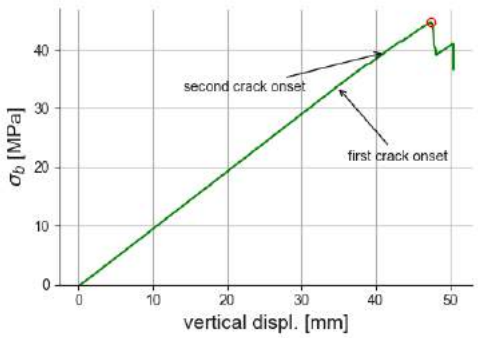


Figure 28: Bending stresses in a simulated glulam beam (see Figure :.
(a) position of the finger joints is marked with red.
(b) $F = F_u$, second crack has fully developed; detail of cracked areas

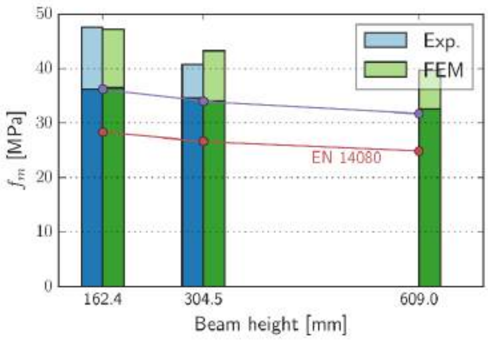
Further observations only become evident when comparing the results of a large set of simulations (Montecarlo analysis). This is shown in Figure 29 b, where the data of a large set of simulations is compared against the experimental data for different depths of the investigated oak glulam beams. The experimental data shown in the graph was obtained by FCBA, Bordeaux, France, in the context of this project and corresponds to oak glulams beam of depths 160 mm and 300 mm (8 and 15 laminations, respectively) and a cross-sectional width of 160 mm with grade class D24 (see

Tab. 9 and Tab. 11). The input data used in the FE-Model also corresponds to exhaustive experimental testings of boards and finger joints performed at FCBA.

The first observation is that there exists a good correlation on the 5% quantile level (characteristic level), which corresponds to the darker colors on the bar plot. Further, the calculated so-called "size effect", corresponds to the experimentally verified decrease in the bending strength of glulams with increased depth of the beams. The presented observations indicate that the assumptions and simplifications used to build the FE model are sufficiently accurate.



a)



b)

Figure 29: (a) Bending stress in constant moment area vs. vertical displacement at RP5 for the example shown in Figure 27;
(b) Comparison of Montecarlo simulation results and experimental results for hardwood glulam beams. Mean values are represented by the lighter colors whilst the darker colors represent the characteristic values obtained

Design equation

Figure 29 b also shows the strength design curve according to EN 14080, which in this case lays clearly below the experimental and simulated results. The apparent strong discrepancy is owed to the special spatial distribution and the characteristics of the weak spots, which opposed to softwoods, are mostly represented by the finger joints. For this reason the present EN 14080 glulam bending strength equation has been modified (see Figure 29 b) to

$$f_{m,g,k} = \left[-2.2 + 2.5 \cdot f_{t,0,\ell,k}^{0.82} + 1.5 \cdot \left(\frac{f_{m,j,k}}{1.6} - f_{t,0,\ell,k} + 6\right)^{0.60}\right] \cdot k_h.$$

where $f_{m,g,k}$ is the bending strength of the glulam beam, $f_{t,0,\ell,k}$ is the characteristic value of the tensile strength of the laminations, $f_{m,j,k}$ represents the bending strength of the finger joints and k_h is a term that captures the size effect

$$k_h = \min\left\{\left(\frac{300}{h}\right)^{0.1};\ 1.1\right\}.$$

As compared to the present EN 14080 equation especially the exponents of the 2nd and 3rd term of the equation were changed whereas the general structure of the present softwood glulam equation has been maintained.

Development of a prediction model for the mechanical properties of hardwood GLT
Throughout this study, the grading of Oak GLT was established in relation to the existing grades for the softwood GLT defined by EN 14080. The aim is now to propose optimized grades, or even new grades for hardwood GLT whose mechanical properties can differ considerably (optimization relative to modulus of elasticity for example). Experiments conducted will contribute to forging these propositions and to elaborate a model of prediction of the mechanical properties of hardwood GLT from the mechanical properties of the constitutive lamellae.
Indeed, the EN 14080 standard includes a model of the bending strength of softwood GLT based on the mechanical properties, tensile and bending strength, of the solid and finger jointed lamellae. Since the properties of hardwood species differ from those of softwood species in many respects, it is not possible to apply this model directly to hardwood GLT. Consequently, hardwood GLT are currently marketed on the basis of National Technical Approvals and European Technical Assessments based on heavy experimental campaigns which represent an obstacle to the development of these new products. It is therefore essential to develop a numerical model applicable to hardwood GLT. This model is being developed by MPA Stuttgart (DE) and will be finalized in 2017. It is based on more advanced modeling techniques as well as breaking criteria, such as the use of the extended finite element method in conjunction with break-up energies, and a wider range of stochastic variables taken into account to obtain better correlations between simulations and experimental data provided by the prototype productions managed by FCBA.

Cross-laminated hybrid timber (WP 5)

Due to limited personnel resources MPA Stuttgart was not able to send Input for this section in the final report.

1.3 Conclusions

The most important contributions to the state-of-the-art, derived from the results and discussion.

EU Hardwoods proved that the hardwood resource in Germany, Austria, France, and Slovenia is still growing and thus posing a reliable resource for production. Strength grading of hardwoods is not common until now. Using a dataset of beech, oak, ash and Sweet chestnut the potential of the utilization of microwave transmission in addition to other grading techniques (e.g. dynamic MOE) improves the indicating property significantly. A sophisticated and verified simulation tool and FE model is capable of accurately modelling different GLT built-ups. It is now possible to test the effect and benefits of hardwood GLT. By improving the rolling shear behaviour of CLT plates a popular building product with high future potential is available for standardization.

All obtained data and conclusions from this project research have significant value and importance of knowledge of mechanical data of Slovenian beech wood and in the development of new engineered timber products (glulam or cross lamin
ated timber) in general. The evaluation of existing visual grading standards showed that in terms of grading rules there is strong motivation to improve the present methodologies. The first step

towards machine strength grading of Slovenian beech was made and also preparation for creating a Slovenian standard for visual grading of beech wood.
Comparison of three different species showed that beech wood has a great potential in terms of material quality. Especially when we think about using it as defect free in the production of glulam beams and cross laminated timber plates. The big scatter of the strengths, due to relatively large local defects in the boards, reveal the real problem with the production, the processing. Already more expensive than spruce, when one adds the cost of extra processing, the price of production goes up. Since the beech tree species is and, by our predictions, will stay in abundance and since a potential for high quality, and therefore high efficiency, exists, the benefits should eventually outweigh the price of production.
The study conducted on the valorization of the French Oak resource in the form of GLT shows that the origin of the constitutive lamellae is a factor which should be taken into account and the production of combined beams should be strongly considered in echo to the expectations of sawmills that wish to value all the sawn timber qualities.
From an economical point of view, the technical and organizational adjustments to be made in the medium term to ensure the emergence of these new products in competitive markets already occupied by softwood products have been highlighted. Trust is to be built between client and supplier by understanding the constraints of production lived on both sides. The adoption at sawmills of the visual grading for strength of sawn timber and the acceptance of various lengths and especially qualities by the glulam producer will facilitate the dialogue. Nevertheless, in order for the sawmills to position themselves on this new market, it is expected to constitute a contract market in terms of volume.
Finally, the information collected and / or acquired will make it possible to propose optimized strength grades, or even new grades, for hardwood GLT whose mechanical properties differ from those of softwood GLT. They also support the development of a model for predicting the mechanical behavior of hardwood GLT. The objective is to prepare the normative framework that will allow these new products to enter the market.

The developed hardwood glulam model has been verified for its capability to simulate glulam made out of hardwood in a satisfactory manner, being able to reproduce known essential characteristics of glulam, such as the size effect and the lamination effect. The inclusion of features not present in the model used to calibrate the current softwood glulam design equation given in EN 14080, such as variable length of the boards, use of fracture energies in combination with the XFEM method and an increase in the mesh discretization over the thickness of each lamination (n=3), increase the level of detail of the model, but keeps the analysis time within reasonable bounds (in the order of days for some few hundreds of simulations, depending on the sizes of the beams).

Based on the present calibration results obtained with the model, a modification of the current strength design equation in EN 14080 was made, which represents the failure behavior of the studied oak glulam beams in a satisfactory manner. Although not yet representing a universally applicable equation, a substantiated platform for a broadly applicable future design model for hardwood glulam beams has been developed and verified for several exemplary oak glulam beam configurations.

1.4a Capabilities generated by the project

Knowledge generated in the project / outcomes of the project, such as unpublished doctoral theses, patents and patent applications, computer programs, prototypes, new processes and practices; established new businesses; potential to create new business opportunities in the sector.

Knowledge was generated in the field of forecasting standing stock and annual round wood supply as well as for FE modelling. Knowledge was also generated for machine strength grading hardwoods. These capabilities will benefit future research and industry alike.
At UL FGG a step forward in the direction of getting an approval for machine strength grading of beech and creating a Slovenian standard for visual grading of beech. The data obtained during this project will be also further analysed in doctoral theses.
In terms of business opportunities, EU Hardwood will not only facilitate the recognition of new engineered hardwood products by markets subject to strong regulatory requirements, but also inform technical and organizational adjustments to be made in the medium term to ensure their emergence on competitive markets already occupied by softwood products.

Due to limited personnel resources MPA Stuttgart was not able to send Input for this section in the final report.

1.4b Utilisation of results

Give a brief description of how the results of the research and development have been used and/or what is the exploitation plan or plans for transferring the results into practice.

Dealing with hardwoods often means trial and error approaches. Since EU Hardwoods focus on industry and relevant building products the necessary foundation for standardization has been provided and first steps in strength grading has been taken. The results obtained will provide a good basis for further research and can be used as guidelines for future hardwood glulam standard. The preparation of a CLT production guideline has started, an allocation report for Austrian beech in the European strength class system is in progress.
On the basis of EU Hardwood recommendations, France will start market and cost studies so that hardwoods find their own place on the softwoods side in the construction sector, and work on the gradual introduction of supply chains for the production of GLT and CLT between the 1st and 2nd transformation, and even from the forest, with support of companies in the managing change.

Due to limited personnel resources MPA Stuttgart was not able to send Input for this section in the final report.

1.5 Publications and communication

a) Scientific publications

For publications indicate a complete literature reference with all authors and for articles a complete name. Indicate the current stage of the publishing process when mentioning texts accepted for publication or in print. Abstracts are not reported. Indicate the five most important publications with an asterisk.

1. Articles in international scientific journals with peer review

Aicher S, Christian Z, Stapf G (2015). Creep Testing of One-Component Polyurethane and Emulsion Polymer Isocyanate Adhesives for Structural Timber Bonding. Forest Products Journal. 65: 60-71.

Aicher S, Hirsch M, Christian Z (2015). Hybrid cross-laminated timber plates with beech wood cross-layers. Construction and Building Materials. 124: 1007-1018.

Aicher S, Christian Z, Hirsch M (2016). Rolling shear modulus and strength of beech wood laminations. Holzforschung. 70: 773-781.

Breinig L, Linsenmann P, Bruchert F, Sauter UH. Mechanical properties of roundwood and structural boards of European beech and ash and their relationships. Submitted to European Journal of Wood and Wood Products. Submitted to the journal.

2. Articles in international scientific compilation works and international scientific conference proceedings with peer review

Breinig L, Bruchert F, Haas A, Sauter UH (2015). Evaluation of European beech (*Fagus sylvatica L.*) roundwood for improved production of strength-graded lamellas. Proceedings of the 5th International Scientific Conference on Hardwood Processing 2015. pp 50-57.

Lanvin JD, Legrand G, Simon F, Faye C, Prince C, Lemaire J (2015). Strength assessment and potential for use as glulam of French chestnut lumber. Proceedings of the 5th International Scientific Conference on Hardwood Processing 2015. pp 131-138.

Breinig L, Bruchert F, Haas A, Sauter UH (2015). Evaluation of European beech (*Fagus sylvatica L.*) roundwood for improved production of strength-graded lamellas. Proceedings of the 19th International Nondestructive Testing and Evaluation of Wood Symposium. pp 218-225

3. Articles in national scientific journals with peer review

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4. Articles in national scientific compilation works and national scientific conference proceedings with peer review

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5. Scientific monographs

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6. Other scientific publications, such as articles in scientific non-refereed journals and publications in university and institute series

Linsenmann P (2016). Europäische Laubhölzer im Bauwesen. Realität von heute – Möglichkeiten für morgen. Magazin für den Holzbereich 5/2016. pp 3-5.

a) Other dissemination
Such as text books, manuals, user guidelines, newspaper articles, TV and radio programmes, meetings and contacts for users and results.
Dissemination of results to industrial partners and industrial partners dissemination within the company.

EU Hardwoods homepage: eu-hardwoods.eu. Available since March 2014.

Presentation of the project at the 1st European research and forest value chain conference in Koper, Slovenia. (2014)

Presentation of the project at WW-Net seminar in Stockholm, Sweden. (2014)

Presentation of the project at the Swiss workshop on hardwood usage. (2014)

Presentation of the project at the Austrian FHP hardwood workshop. (2014)

Presentation of the project at the 2nd European research and forest value chain conference in Koper, Slovenia. (2015)
Presentation of the project at the WW-Net seminar in Duebendorf, Switzerland. (2015)

Presentation of the project at the annual meeting of the Austrian hardwood industry in Pram, Austria. (2015)

Presentations of the project and the results at the 1st EU Hardwoods workshop in Garmisch-Partenkirchen, Germany at the 22nd International Conference Holzbau-Forum (IHF). (2016)

Presentations of the project and the results at the 2nd EU Hardwoods workshop in Bordeaux, France. (2017)

1.6 National and international cooperation

Give a brief description of the cooperation/ networking (partnership between the project participants and how this has developed; industrial involvement; synergies of industrial and research expertise; Has the project collaborated with similar projects in the WW-Net countries or other regions, or established new links with/ between local or international organisations involved in the respective research field? Describe how these partnerships have supported the project.
National vs. transnational aspects in the project; added value for the project and its impacts which result from transnational cooperation.

Cooperation within the consortium was good. The concept of EU Hardwoods focused on thematic work packages lead by a specialist in this field. The participants collaborated in other projects before and thus knew each other. To strengthen the collaboration all participants took part in multiple work packages. This exchange lead to new ideas and widened as well as sharpened the focus of the objectives.

Contact has been made with different stakeholders of the scientific community. With the university of Göttingen some orienting research on microwave scanning has been performed on small clear hardwood specimens.
With EMPA in Zurich contact has been established in order to include their testing data on Swiss beech in the project. Since some delay occurred in this project, EU Hardwoods cannot benefit directly from that data. The collaboration will help future projects to start with a wide and divers data basis.

The project in Slovenia led to new synergies between the industrial and research key players the result of which is a new national project dealing with hardwood use in the production of building products (TIGR4smart). The national project will continue and upgrade the work done in the EU Hardwoods project as well as expand the data of hardwood mechanical properties.