Project Title:

A COST-EFFICIENT, AUTOMATED, MACHINE STRENGH GRADING SYSTEM FOR SAWN TIMBER

Project Acronym: WOODSONICS

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Final Report
Publishable Summary

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Executive Summary

WOODSONICS was a project funded by the European Commission´s Seventh Framework Programme (FP7) under the "Research for SMEs" Capacities Programme with the aim of developing a new cost efficient, inline wood grading machine which uses an ultrasonic transducer to identify and localize specific defects along the length of the sawn timber board and grade it automatically. The project started in January 2013 and had a duration of 27 months. The 1.1 million Euros contribution from the European Commission allowed bringing together European technology companies, researchers and applied research centres, universities and sector institutes, as well as sawmilling and woodworking SMEs, from four different countries in Europe: Germany, Italy, UK and Spain.

The result of the project was an industrial prototype designed for inspecting and grading timber with dimensions up to 260 mm width, 100 mm thick and 6 m length. The prototype integrates dual ultrasonic roller sensors, an electronic system for sensor excitation, data acquisition/processing, and overall machine process control, a computer running the grading algorithms and providing a user interface through screen and keyboard as well as auxiliary electrical and mechanical systems.

The ultrasonic system consists of a separate transmit and receive roller arrangement. Information is extracted from the received signal after propagating through the wood thickness. Defect detection is based on amplitude, time of flight and energy data of the ultrasonic signal. A multi-channel, FPGA-based processing circuit extract these parameters in real-time as the timber passes through the roller sensor, generating an image for each parameter. Image processing techniques are used to detect the defects and to assign them to a specific type correctly and automatically. Then, some indicating parameters that have physical meaning are calculated and used to predict timber strength and stiffness based on regression models.

The WOODSONICS prototype was calibrated for French oak and Norway spruce. However, the prediction strength of the prototype is low compared to the prediction accuracy of the reference methods used in the project and lies between 17-21% for strength and 16-17% for the stiffness. The visual grading criteria in accordance with German grading standard – the method most commonly used in central Europe – explains 25.7% and 31% variance of timber strength for the oak and spruce sample respectively and only 23.0% and 19.4% for the stiffness. High end grading machines such as GoldenEye-706 provides the best prediction.

All partners contributed in dissemination of WOODSONICS project, especially among partners' network of contacts and in some local events. Paper-based material as well as a public website were created to enable effective and wide dissemination. Articles about WOODSONICS project were published in newsletters and local media, as well as in *Cordis* News site. In the academic domain, a scientific article was published by TUM in the Journal of Acoustical Society of America.

The SME partners MiCROTEC and Alba gained relevant knowledge in ultrasound technology applied to automatic wood grading processes. MDF and BSW as end users would benefit from a product with the characteristics expected in WOODSONICS. The project ended in March 2015 and results were promising. However, technical issues that compromise the performance of the prototype deserve further research and extended validation and optimization is required before the product can be introduced in the market.

Summary description of project context and objectives

The use of structural timber in construction is ubiquitous; wood is valued for its strength, renewability and aesthetic qualities. However, the same properties which make wood-based material so attractive also make it very difficult to process. Environmental factors, decay, insect damage, splits, checks, and knots can change wood density substantially, negatively affecting the quality and strength of the wood. Detecting defects in wood and separating wood according to quality is essential to the EU's Construction Products Regulation. Reducing maintenance costs and improving brand recognition for European wood products are also industrial priorities.

The production of structural timber is hugely dependent on the construction industry. The EU-27's construction activity accounted for 6.0 % of GDP in 2010 and generated €655.388 million of added value. In 2009, the construction industry suffered its largest annual decline when production fell by 8.9%, followed by a further drop of 4.1% in 2010.

Structural timber processed at sawmills must be marked by piece according to strength grade. Visual grading and machine grading are both accepted forms of determining strength (as detailed in section 1.2). Machine strength grading systems are faster and more accurate. The EU-27 sawmill industry is comprised of around 35.000 sawmills, however, less than 300 machine grading units are currently used as the high cost of the systems makes them affordable only to large sawmills.

For example, the GoldenEye-706, a high-end machine grading system manufactured by an SME in the consortium, costs up to €500.000 per unit. Additionally, climate change has introduced new species in forest stock – particularly hardwoods - which machines cannot grade. As a result, visual grading is the standard procedure for analysing sawn timber at the large majority of sawmills. However, visual grading is slow and produces a very low yield in terms of material performance.

Therefore the sector needs to incorporate cost-effective machine strength grading systems at SME sawmills to:

1. grade timber more quickly and accurately,
2. remove localised defects in wooden boards to be able to sell the defect-free wood at a higher price;
3. automatically separate aesthetically appealing defect-free piece timber beams
4. introduce new species in their production line.

In consequence, the need is not only to improve productivity and flexibility at lower costs for sawmills, but to provide added value for structural wood by promoting its use in construction.

The majority of the machine strength grading machines on the market are unable to detect localised defects in timber. SME MDF estimates that it could increase production by 10% by using machine grading systems which detect localised defects. Furthermore, there is a need for a customisable system which can be placed on the sawmill line, eliminating the costly and time consuming process of grading after sawing.

To cover these needs, the consortium suggested developing a new cost efficient, inline wood grading machine which uses an ultrasonic transducer to identify and localize specific defects along the length of the sawn timber board and grade it. WOODSONICS will be installed on the sorting line without disrupting sawmills´ production activity.

End-users like Manipulacions de Fusta (Spain) or BSW Sawmills Ltd (UK), participants of the project, will benefit directly from the WOODSONICS in the form of savings in production costs, optimized yield and more efficient and accurate grading by having access to effective technology solution that can be amortized in the first 2 years at average SME sawmills, determine the location of external and internal defects in a wooden board, incorporate new species at their facilities, and increase the added value of the sawmills, guaranteeing aesthetically pleasing defect free structural timber.

WOODSONICS was a project funded by the European Commission´s Seventh Framework Programme (FP7) under the “Research for SMEs” Capacities Programme. The project started in January 2013 and lasted 27 months. The 1.1 million Euros contribution from the European Commission allowed bringing together European researchers and applied research centres, universities and sector institutes, as well as sawmilling SMEs, from four different countries in Europe: Germany, Italy, UK and Spain.

Description of the main scientific and technological results and foregrounds

WOODSONICS was developed by a consortium of organizations including companies of the wood sector, technological companies, universities, research institutes and technological centres. The project partners included: the timber grading and processing technology provider MiCROTEC (Italy), the ultrasonic transducers manufacturer Alba Ultrasound (UK), the woodworking company Manipulacions de Fusta (Spain) and the sawmilling company BSW Timber Group (UK). The R&D and demonstration activities were performed by the R&D company Ateknea Solutions (Spain), the Catalan Institute of Wood INCAFUST (Spain), the Technical University of Munich (Germany) and the Center of Ultrasonic Engineering at the University of Strathclyde (UK).

Working together since January 2013, the cooperation between these organizations has led to the following scientific and technological results, which are summarized below:

- System specifications
- Characterization of defects in wood samples
- Ultrasonic roller sensor
- Electronic subsystem
- Grading algorithms
- WOODSONICS software
- WOODSONICS prototype
- Industrial validation

System Specifications

At the beginning of the project general requirements for WOODSONICS prototype were defined. A summary is presented below:

- The species studied during the project are spruce, pine and oak. The first two species are considered as softwood and the other as hardwood.

- The defects to be detected with WOODSONICS are knots and splits larger than 5mm and 0.5mm respectively. Other parameters such as modulus of elasticity (MoE), density and bending strength could be used to determine the strength class.

- WOODSONICS will be able to inspect both wet and dry woods.

- Boards would be graded by WOODSONICS correctly with wane to the limits of EN 14081-1: 'The maximum wane permitted shall not reduce the edge and face dimensions to less than 2/3 of the basic dimensions of the piece'.

- To cover as much market as possible, the timber dimensions to be inspected with WOODSONICS will be in the following ranges: width: 90-260mm, thickness: 15-100mm and length: 1-6m.

- The industrial scale prototype would be able to scale-up to handle an inspection speed of 50m/min

- The estimated price of WOODSONICS would be around €60,000

- Two different WOODSONICS prototypes will be developed:

Characterization of defects in wood samples

Two different reference methods were defined:

The primary reference method is based on the grading machine GoldenEye-706. This machine combines the GoldenEye-702 based on X-ray measurements to determine knots and density of a board and the VISCAN based on laser vibrometer to determine dynamic modulus of elasticity. The benchmarks are the following three Indicating Properties (IP): i) IP1, Indicating strength based on dynamic MOE and knottiness; ii) IP2, Indicating stiffness based on dynamic MOE only; iii) IP3, Indicating density based on the density measured.

The secondary reference method is based on the visual grading. The benchmark is the knottiness.

Different wood samples were selected and tested following non-destructive tests. The following parameters were measured:

- Cross section

- Mass

- Density using the hydrometer GANN HYDROMETTE M 4050

- Dynamic modulus of elasticity. This parameter was measured using two methods: by recording the resonance frequency of the free vibrations and by the measurement of the time-of-flight of the ultrasonic pulse with the SYLVATEST 30kHz and the PUNDIT Mark V 54kHz devices.

Finally the position and the size of every knot on each sample wood were measured following the German standard DIN-4074-1 for the softwood and DIN-4074-5 for the hardwood.

Also, a basic scanning system was built and using the PUNDIT 54kHz one board was scanned with 5mm step in XY-plane in order to obtain an ultrasonic time-of-flight map. A total of 2,800 measurement points of time-of-flight were needed to obtain a grey-scale image of 14x200-pixels. The image processing revealed change between the radial and the tangential directions, knots of 3mm and larger, appearance of pith and fibre deviation.

Ultrasonic roller sensor

The work performed to validate the proposed technology led to the following conclusions:

- The ultrasonic characterization system should consist of a separate transmit and receive roller arrangement.
- Information would be extracted from the received signal after propagating through the wood thickness. This data was processed and recorded as a function of position during the scan to produce an image plot which is representative of the ultrasonic interaction with the wood sample.
- Application of advanced signal processing by TUM demonstrated that the mechanically scanned through thickness ultrasonic array system could extract relevant information pertaining to the characteristics of the wood sample.

There were two stages in the journey towards the development of a full-scale prototype ultrasonic array roller system for the characterisation of wood in an industrial environment. The first stage was the production of a small prototype roller sensor system. Subsequently, the knowledge and experience gained was applied to the design and construction of the full-scale roller sensor. This involved modelling, design, selection and construction of the roller sensor components, manufacture of materials for roller tyres, selection and incorporation of a device motion encoder, design and construction of a system test fixture and finally trial inspection scans of wood samples. A summary of the work carried out in the development of each of these systems is presented below.

Development of Small Prototype Roller Sensor

Finite element modelling was used to design the transmitter and receiver transducers. These transducers were mounted into cases for trials as the small prototype roller sensors. Optimisation of the design was performed before construction of the full-scale prototypes.

Fully-functional transmitter and receiver roller sensors were constructed and filled with water. An encoder was fitted to one of the devices to enable measurement of wood position. A simple test fixture was constructed to enable measurement tests to be performed quickly and thus enable an assessment to be made regarding the performance of the system. No couplant was used between the wood and the tyres.

Measurements were made by scanning dry-coupled wood samples using this small prototype system. Both manual and automatic scans were performed using wood samples which had been inspected previously. The signals were recorded at intervals along the length of the wood. Parameters were extracted from the received signals at each position in the wood and these were used to produce 2D images of the samples. The results indicated that defects in the wood could be detected.

Development of Full-Scale Roller Sensor

Finite element modelling of the array design for the full-scale roller sensor identified potential improvements to be made. The receiver electronics were configured to optimise the sensitivity of the revised design of transducer. The piezoelectric materials for each transducer were manufactured. Matching and backing layers were employed to improve transduction. Modifications were also applied to improve reliability and reduce manufacturing costs thus advancing from laboratory equipment to commercial devices. The receiver transducer has an aperture which accommodates the widest timber to be inspected. The system is suitable for use in dusty and high-vibration environments such as a sawmill.

A short set of trial measurements was made with the completed roller sensors dry-coupled on a wood sample. The ultrasonic signals from the transmitter passed through the wood, were detected by the receiver and recorded across the width of the wood. The signals were of the form previously observed during use of the small prototype and parameters at each position in the wood were extracted. The values obtained for these parameters were in line with the expectations and the system was functioning as predicted.

Electronic subsystem

A versatile pulser circuit board for excitation of ultrasonic emitter was designed and implemented. This circuit is capable of generating a broad variety of excitation signals with parameters selectable by the user using the WOODSONICS software. At the same time, the circuit has sensor inputs to measure the thickness and the width of each wood board scanned, as well as their length. Moreover, with the help of the external encoder, the distance interval between two subsequent signal acquisitions can also be adjusted. By default the acquisition is done every 5 mm.

A custom acquisition circuit board was designed and implemented. This circuit is capable of acquiring 8 input channels in parallel and process them in real time to extract relevant parameters from the ultrasonic input signals. This parameters are used by the grading algorithms to classify the wood board. The electronic system is based on a FPGA (Field Programmable Gate Array), which provides the system high flexibility and high processing speed. The acquisition circuit board is provided with an Ethernet connection for exchanging data with a computer (parameters setting, acquisition start and stop, data transmission, etc.). The WOODSONICS full-scale prototype includes 4 acquisition circuit boards thus being capable of processing up to 32 ultrasonic channels.

Grading algorithms

The general aim of the grading algorithms is to predict timber strength and stiffness based on the visual defect detection and estimated elastic-mechanic properties.

Definition of the indicating properties

At first different indicating parameters were defined that can be used to predict timber strength and stiffness. This includes the parameters that have some physical meaning of density, modulus of elasticity and knottiness as well as the knottiness parameters determined using the image processing techniques. Thus, based on the raw data of amplitude, energy and time of flight different indicating parameters, such as indicating bending stiffness, indicating average density, etc. were defined. Due to coupling problems (cf. analysis of the data quality) only a number of them could be implemented.

Defect detection is based on amplitude and energy data. These wave parameters are used to distinguish between clear wood and defects (lower amplitude). The image processing is used to detect the defects and to assign them to a specific type (classify) correctly and automatically. The steps of the image processing are: a) data improvement using different filters (pre-processing); b) segmentation of the objects of interest out of the image (segmentation); c) calculation of the properties vector for each single object (representation) and d) assignment to a specific defect type (classification). Some parameters are calculated from time of flight and maximal amplitude for each region. The idea was to classify the objects to the defect type based on this information but technical issues prevented training the classifier properly.

Based on the segmentation output, without classification results, knottiness criteria were calculated. The first class corresponds to the detectable knots. The knottiness parameters differ in the weight the detected knot has in the center of the beam or at the edge of it. The parameters differ between no weight (parameter KAR) to the higher weight of the knots at the edge. These features are used in following to predict the strength and stiffness and are implemented into the grading algorithm.

Measurements & data acquisition

To derive the grading algorithm a large number of timber specimens were tested. Two species French oak (*Quercus robur*) and Norway spruce (*Picea abies*) were assessed. In overall 512 oak specimens and 703 spruce specimens were measured. The measured parameters include the visible (knots position and knot dimensions) and non-visible grading parameters (density, dynamic modulus of elasticity and moisture content) as well as destructive test data (strength and stiffness in acc. with EN 408).

Regression analysis

Based on the measurements of 453 French oak pieces and 142 Norway spruce pieces a functional relationship between the indicating parameters of the WOODSONICS machine and timber strength and stiffness properties was obtained. Using the stepwise regression different models were created for each species separately.

Integration of the results into the algorithm

The grading algorithms are implemented in MATLAB and includes the calculation of the indicating properties, image processing techniques, as well as the regression equations. Based on the input – timber beam, nominal dimensions and species - the end user obtain thee indicating properties: bending strength (IP MOR), stiffness (IP MOE) and the knottiness (IP KNOTS).

WOODSONICS software

A software has been developed using LabVIEW to control WOODSONICS machine and visualize the results. For each timber inspected, this software allows to acquire and store ultrasonic signal parameters extracted by the processing circuits. The user interface includes control to auto calibrate the system. For advanced users, the user interface also allows configuration of the electronics parameters, such as gain and time acquisition parameters, and is also used for manual calibration.

Data acquired with this software is the input for the grading algorithms which are integrated as a separate stand-alone module. As a result, for each timber up to 3 indicators are obtained in order to grade them. This three parameters along with a reconstructed picture can be visualized on the screen for each timber.

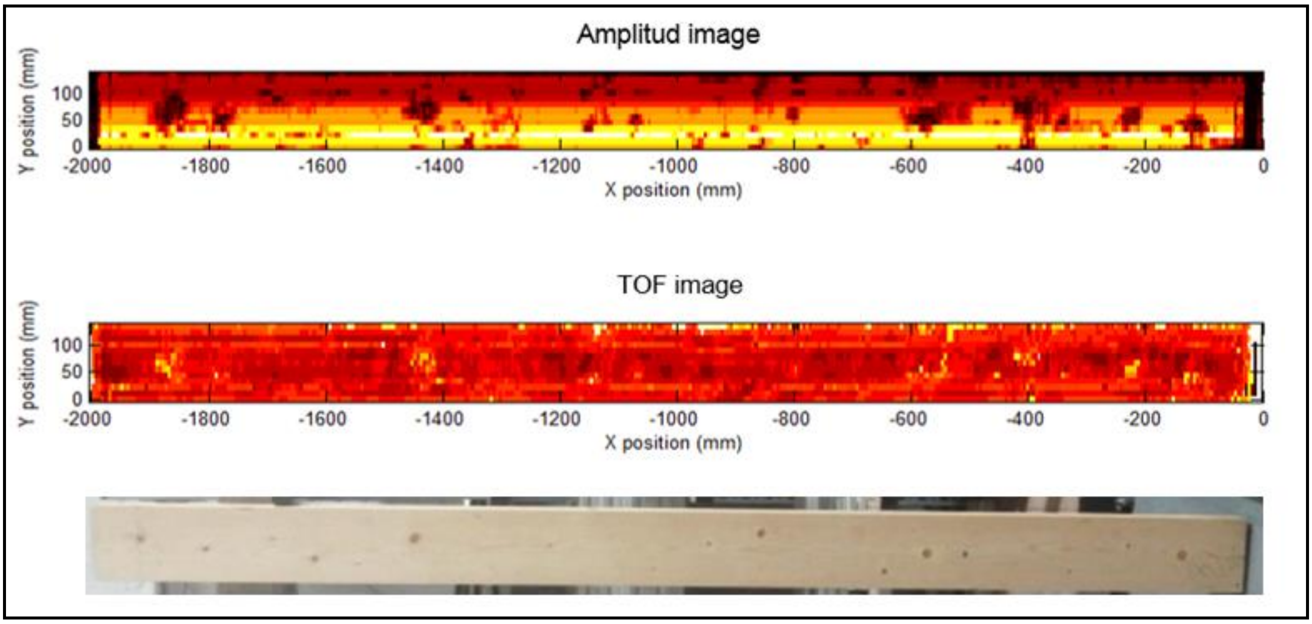

Figure 1 Example of image for a beech board sample

WOODSONICS prototype

A mechanical structure was designed and assembled to enable the operation of the system in industrial environments. The structure accommodates the roller sensors, the control and processing electronics, the power supplies, the computer as well as auxiliary systems. The machine is designed to be installed in automatic wood grading lines between two conveyors and include guiding systems to align the timber boards and board detection/size measurement sensors. Aspects concerning ergonomics factors and ease of operation by workers were taken into account.

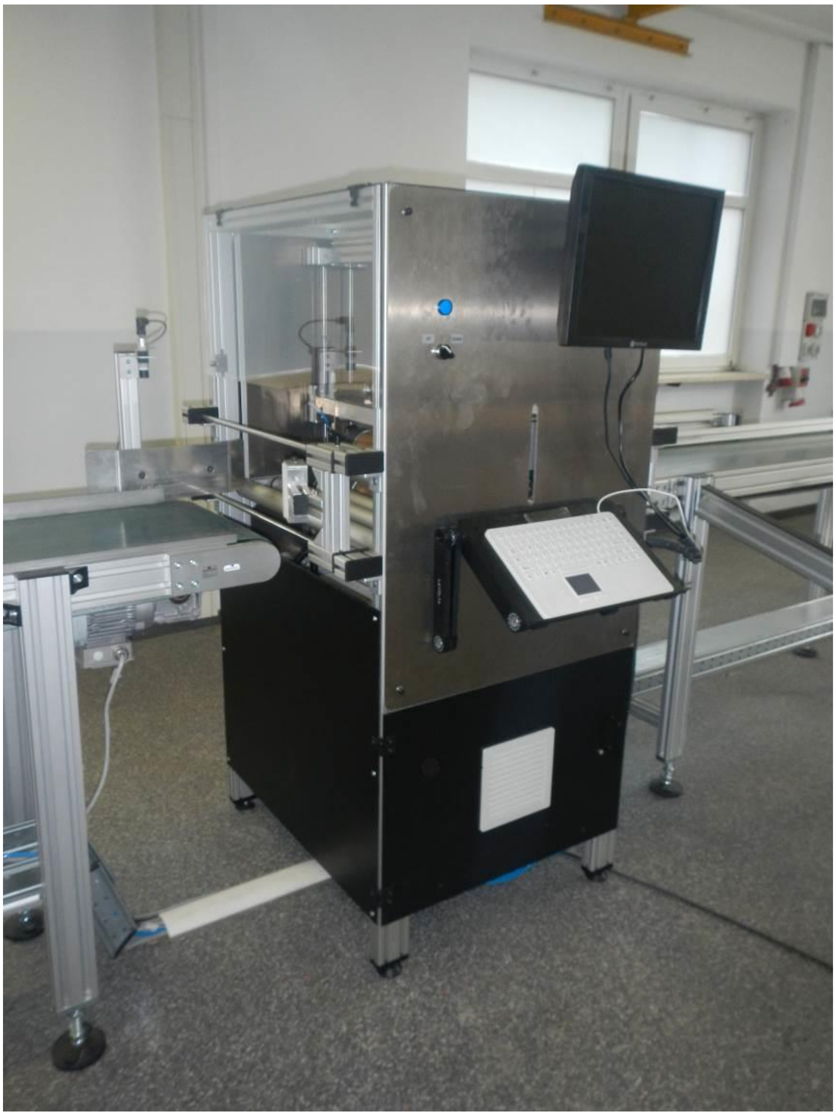

Figure 2 Picture of the WOODSONICS prototype

Industrial Validation

WOODSONICS vs. reference methods

The performance of the WOODSONICS prototype was compared to the industrial reference methods defined in previously to predict timber strength. A plan of tests was designed to reach comprehensive results. A total of 512 French oak beams split in six batches took part into the experiment. Each batch was different from the others on dimensions, surface finishing and wood quality. Moisture and weight of the samples were controlled all over the process. For spruce, a total of 703 beams were measured.

The regression analysis is a method used to calculate the prediction accuracy of the strength and stiffness properties and analyze the results. The reference methods include:

1) The visual strength grading - method frequently used in the central Europe. The knottiness parameter DEK in accordance with German visual grading standard DIN 4074 is used as a criterion in a model.
2) Grading using the dynamic modulus of elasticity as a single criterion – the method frequently used in the practice.
3) Models obtained out of the high end grading machine GoldenEye-706. It can combine such parameters as dynamic modulus of elasticity and knottiness to predict strength.

The WOODSONICS prototype gives possibility to predict timber strength and stiffness of the beams for both oak and spruce. However, the prediction strength of the device is low and lies between 17-21% for strength and 16-17% for the stiffness and is lower than the prediction accuracy of the reference methods. So the visual grading criteria in accordance with German grading standard – the method most commonly used in central Europe – explains 25.7% and 31% variance of timber strength for the oak and spruce sample correspondingly and only 23.0% and 19.4% for the stiffness. The target accuracy is given by the machine grading criteria. The prediction accuracy of the machine grading criteria such as dynamic modulus of elasticity is especially for spruce with 44.9% explained variance for strength and 75.9% variance high. It should also be mentioned that the prediction accuracy of the machine grading criteria for the oak is clearly lower (R^2 for MOR: 23.6%; R^2 for MOE: 29.1%) and the WOODSONICS machine differs less.

Coupling and signal processing algorithm might be the keys to improve the performance of the WOODSONICS prototype. Wood surface irregularities and roughness significantly affects the measurement of the ultrasonic signal. The assignment – classification – of the knots and clear wood based on several additional criteria would most likely improve the prediction accuracy of the timber strength and stiffness.

Potential impacts, main dissemination activities and foreseen strategy for the exploitation of results

The main impact for the SME end users in the possibility to invest in machine strength grading systems at a reasonable cost, which currently, is practically impossible. The savings resulting from machine strength grading are enough to determine the survival of SME sawmills. Most importantly, WOODSONICS will be an affordable machine system which can be placed on-site to localize and identify defects throughout the length of the wood board. Added benefits in the optimizing of yield are:

- Detection of local defects throughout the length of the wood board which can be removed, and the remaining timber sold at a higher price (up to 20% more for grade C24 as compared to C18). Furthermore, sawmills can separate defect-free wood from wood in the same strength grade in order to meet clients' aesthetic requirements.
- More accurate grading. As machines are tested and calibrated with set configurations according to EU regulations, sawmills can sell timber at a higher grade than with visual inspection, which is less reliable.
- Production optimisation and customised installation. WOODSONICS can be placed directly on the saw line, allowing sawmills to streamline their sorting and grading operation.
- Separation of defect free wood. This provides an important added value for sawmills, as they can guarantee the aesthetic quality of the structural timber per their customers' requirements as well as grading the strength, thus promoting the use of wood in construction.

An average SME sawmill with 30 employees, producing 30.000m^3 of timber, typically employs between 1 and 4 individually full-time licensed graders to grade saw timber according to strength. At an hourly rate of 20€ average per grader, a typical saw mill can spend up to €166.400 a year in costs associated with visual grading. Therefore, machine strength grading machines reduces costs and optimized production.

The detection and localization of internal and external defects by WOODSONICS permits upgrading of sawmills. Optimizers are machines which removes defects from wooden boards based on information received from either markings made by visual graders, or machines able to detect localized defects such as WOODSONICS. When a severe defect, such as a cluster of knots, is detected in a piece or otherwise clear wood, the entire board must be graded at a level of the weakest section (the cluster of knots).

However, if the cluster of knots is detected and removed, the remaining clear wood can be sold at higher grade (as finger-joint timber, or not, depending on the size of the piece). The difference in price between a lower grade structural softwood, such as C18 and a higher grade, such as C24 is around 20%, depending on the market prices.

Additionally, the consortium SMEs cite significant demand - especially in the north of Europe - for structural softwood which is not only graded accurately, but which is aesthetically pleasing and free of defects such as knots or cracks. As the WOODSONICS system will localise defects throughout the length of the wooden boards, it allows sawmill operators to separate sawn timber of the same strength class based on visual characteristics. This is an important added value by which sawmills can sell defect-free structural timber per their customers' specific aesthetic requirements, encouraging the use of wood in construction. Furthermore, climate change has resulted in new species in forest stocks around Europe, for which SMEs have no suitable machine grading system options.

All partners contributed in dissemination of WOODSONICS project, especially among partners' network of contacts and in some local events. Paper-based material as well as a public website were created to enable effective and wide dissemination. Besides publication of articles about WOODSONICS in newsletters and local media, R&D information services with much larger coverage such as *Cordis* News site were also used. In the academic domain, a scientific article was published by TUM in the Journal of Acoustical Society of America. More information about the project can be found in the project website.

The SME partners MiCROTEC and Alba gained relevant knowledge in ultrasound technology applied to automatic wood grading processes. MDF and BSW as end users would benefit from a product with the characteristics expected in WOODSONICS. The project ended in March 2015 and results were promising. However, technical issues that compromise the performance of the prototype deserve further research and extended validation and optimization is required before the product can be introduced in the market.

WOODSONICS can open a potential market of almost 35,000 EU-27 sawmills which currently only use visual inspection and would benefit from machine strength grading. For the SME participants in this project, this represents a huge potential for a new market of up to €2,100 million.

Project public website and relevant contact details

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