Deliverable D.4.06

Establishing cutting power measurement protocol

WP4 – Multi-sensor model-based quality of mountain forest production

T4.5 – Evaluation of cutting process (CP) for the determination of log/biomass “CP quality index”

Revision: **Final**

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REVISION HISTORY AND STATEMENT OF ORIGINALITY

Revision History

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Statement of originality

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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Acronyms

CA	Consortium Agreement
DM	Data Manager
GA	Grant Agreement
GA	General Assembly
OM	Operational Manager
PC	Project Coordinator
QRM	Quality and Risk Manager
SB	Stakeholders Board
TB	Technical Board
TL	Task Leader
WPL	Work Package Leader
AE	acoustic emission

1 Abstract and problem statement

The overall objective of the whole WP4 within SLOPE project is to develop an on-line/in-field system for determination of selected wood properties and technical characteristics by taking advantage of the novel measurement technologies available in the research laboratories and market. The specific focus of the task T4.6 is to investigate a possibility of using cutting forces associated with processing of logs for determination of the raw materials quality at the early stage of process chain. The modern processor heads allows monitoring of the process by means of installed sensors and/or integration of alternative sensor with the machine. Two possible strategies for measurement of cutting forces will be tested within SLOPE:

- **Cutting resistance of the chain saw cross-cutting the log**; the hydraulic pressure and oil flow will be measured. It will be later regressed against wood density and cross-section geometry.
- **Resistance of the de-barking knives as measured during the stroke**; the hydraulic pressure, mechanical deformations of the knife holder (by means of strain gauges), acoustic emission (AE) associated with the cutting out branches (by means of AE sensors or microphones) will be monitored during log processing. The presence, number of branches and its health will be detected as a result.

Measurement of cutting forces for monitoring of the process has been successfully used in the secondary wood processing for machine/process control and monitoring [1, 3, 6, 7, 10, 13, 14]. However, the methodology as proposed with SLOPE is a pioneer approach especially when considering its application on the harvesting machines working directly in the forest.

2 Introduction and theoretical background

2.1 What is "cutting process"?

The cutting is defined as a process resulting in **material separation**. In most cases the **cutting edge** splits material converting mechanical energy in to generation of new surface, deforming material and removing chip. The quantity of energy needed for cutting wood is depending on the process conditions (both kinematics and configuration), cutting edge geometry, tool sharpness, cutting direction in relation to the grain and fibers as well as on the processed **material properties**. The wood anisotropy, density, chemical composition, physical and mechanical properties are mostly affecting the cutting process.

2.2 The process of cross cutting with the chain saw

The cross-cutting of log with a chain saw is a process where several cutting edges are involved in the cutting at the same time. The angle between the main cutting edge and fiber direction is ~0°, while the angle between feed direction and grain angle is ~90°. The values of angles may vary depending on the cutting tool design and usage history (the geometry may vary after tool replacement, sharpening or reparation). Therefore, according to the classification established by Koch [9] the cutting mode corresponds to the 90-0 or "C" according to Kivima [8].

The cross-cutting with a chain saw is rather difficult to direct monitoring due to peculiarties related to the processing in the field/forest. It is related to the selection of suitable sensors, capability for acquisition of the proper energetic effects of cutting, but being at the same time resistant to various sources of noise. An important issue to be considered is a great effect of the tool sharpness gradually changing along the processing time/period. It is due to both, progressing wear following the tribological rules, but also catastrophic changes related to the frequent processing of contaminations or minerals-rich materials such as bark.

On the other hand, the cutting conditions (cutting speed and/or feed speed) changes considerably between (and within) cutting cycles. It is highly related to the quantity of the material to split (log diameter) and variation within the material itself. The substantial presence of the **reaction wood, knots, small ring width results in increasing of the energy use** for material cutting. Conversely, **exceptionally low wood density or decayed/rooted logs will result in minimised energy requirement**.

2.3 The process of tree debranching

The cutting of branches with a knife is slightly different than that of cross-cutting with a chain saw. Only one cutting edge is involved in the branch cutting-out (or series of branches). The angle between the main cutting edge and fiber direction is ~90°, while the angle between feed direction and grain angle is also ~90°. The cutting angle (defined as a sum of clerance angle and cutting edge angle) is very small. All angles values may vary depending on the machine design, growth direction of branches as well as the cutting tool design and usage history (in analogy to the chain saw tool, the geometry may vary after tool replacement, sharpening or reparation). Therefore, the cutting mode corresponds to the 90-90 according to the classification established by Koch [9] or “A” when using the Kivima’s approach [8]. It is the most demanding cutting configuration as the cutting forces foreseen in that arrangement are the highest.

The monitoring of debranching is simpler to asses than of cross-cutting with a chain saw. It is due to the peculiar design of the processor head where the cutting knife if fixed to the machine body and not any high-frequency changes to the process occures. Depending on the processor design, the wood may be moved against knives or alternatively the knives may be feeded along the trunk. The configuraton of ARBRO 1000 processor head allows the most objective evaluation of the cutting power while debranching, as the log is static during the process and only set of three knives is strocked along the trunk with the hydraulic piston. Consequently, it is expected that by simple measurement of the hydraulic pressure some rough estimation of the cutting efforts would be possible. The fixed knifes system may be also relatively resistant for external sources of noise/errors allowing measuring of the cutting power by means of various senors.

As in any cutting process, an important issue to be considered is an effect of the tool geometry and sharpness. It is especially a case of debranching when depending on the **branch size, health state** and **moisture** the wear kinetics may vary very much.

2.4 Potential applications of the cutting energetic effects measurement within framework of SLOPE project

Task T4.5 is an original and novel approach of the process monitoring implemented at the earliest stages of the tree transformation chain. It provides unique possibilities of material characterization, including defect detection, abnormal cutting recognition and machine/process monitoring.

2.4.1 Monitoring of the log cross cutting with chain saw

The main goal of the chain sawing process monitoring within the SLOPE project is an authomatic determination of the material characteristics. It is based on the physical laws derived from the generalized cutting theories (still under development), stating that the cutting forces are determined on the wood density, fracture toughness and shear strength (among the others). More theoretcial and mathematical explanation can be found in the related literature [2, 4, 11, 15] and also patent proposal by author [12].

1. On that theoretical base, it is possible to assume that it will be possible to estimate the **wood density** on the base of the cutting test.

2. On the other hand detection of the abnormal cutting may be utilized for both determination of the **material deficiencies** (such as decay or reaction wood, etc.) and **wood defects** identification (excessive knots, voids, cracks, etc.).

3. The monitoring of the cutting forces while chain sawing might be also used for optimisation of the **tool usage**, providing more precise indications (suggestions) for the chain replacement or sharpening.

2.4.2 Monitoring of the de-branching with knives

The main purpose of cutting forces monitoring while debranching is to detect location (along the log length) of the first dead (and whenever possible to distinguish live) branches/knots. Secondly, the branching index will be determined on the base of the cutting forces (and other related features) and presented as a quality index used for further sorting of logs.

4. The **location** and rough estimations of the **knot size** will be determined and used for quality grading of logs and assisting operator in decision making while choosing the log length.

5. Overall **knottiness quality of log** will be estimated on the base of cutting force results and the dedicated quality index provided for each processed log.

6. The monitoring of the cutting edges condition will be possible, allowing **optimal conservation and maintenance of the cutting tools** involved in the debranching operation.

3 Description of the cutting process monitoring hardware

The main challenges for the implementation of cutting power monitoring are related to:

- determination of the physical bases for monitoring/measuring of cutting power
- identifcation of the suitable sensors, considering the machine configuration and harsh environmental conditions
- integration of sensors with the machine
- data acquisition and pre-processing
- data mining on the central computer
- multisensor fusion (to be conducted with Task T4.6)

The characteristics and description of the hardware foreseen to be realized in the prototype processor head are discussed here separately for the chain saw and de-branching system.

3.1 Chain saw

3.1.1 Chain saw operated by forest worker during tree felling

The standard tool used by the forest worker during harvesting trees is a high-performance chain saw equipped with a sharp and properly tensioned tool. Even if it is technically possible to monitor cutting forces during tree felling operation, it is rather not practical as requires weight addition to the already heavy equipment. Moreover, the limited advantage of the low reliability data to be obtained do not encourage for exploring cutting forces at this stage.

3.1.2 Experimental scale chain saw installed on the laboratory scanner

3.1.2.1 Machine and tool used

The chain saw that will be used in the laboratory scanner consists in an electrically powered chain saw specially modified for research purposes. The machine will be controlled by the CompactRio system (on-off switch replicated by the computer-controlled device). The cutting tool (chain) will be adopted from that provided by the machine manufacturer. Modifications to the cutting edge geometries are not foreseen with the SLOPE project.

3.1.2.2 Sensors to be used for monitoring of the cutting on the laboratory scanner

Sensors to be tested for monitoring of the cutting forces while chain sawing on the laboratory scanner includes:

Load cell: indirectly measuring the cutting force. The 3-directional load measuring device will be installed on the scanner providing continuous information about XYZ cutting force distribution. This sensor type is most accurate, but at the same time seems to be most complicated with implementation and is of relatively high cost. The other limitation is a risk of easy sensor damage due to excessive forces possibly appearing while cutting logs. The sensor will be connected to the control system by using 3 channels analog input of the CRio module.

Strain gauge: will be installed on the selected mechanical parts of the chain saw support at the laboratory scanner being firstly identified as to be deformed while sawing. Strain gauge will not provide direct information on the cutting forces, but will be rather used for rough estimation of its value. The clear advantage of applying strain gauges is its simplicity and low cost. The sensor will be connected to the control system by means of dedicated CRio module.

Electrical multimeter: is an electrical analogy for measuring the oil pressure. A four channels digital meter will be used, measuring (separately for each channel) the electrical current, voltage and passive/active powers. The foreseen measurements will include: power needed for electrical chain saw (motor) and actuator (electrical motor) used for feed of the chain saw toward the wood while cross-cutting. The digital meter will be connected to the control system by means of the dedicated CRio module.

Acoustic and audible emissions: a trail test will be performed in order to determine if acoustic emission (signal frequency > 50kHz) and cutting sound (signal frequency < 20kHz) may be anyhow related with the log cross-cutting with chain saw. The test will be an extension of that to be performed while debranching logs. Consequently, the experimental set-up including the cabling and signal processing will be identical as for the debranching configuration (described below).

3.1.2.3 Hardware configuration of the laboratory scanner

The general concept of the laboratory scanner is presented in Figure 1. The detailed description of the hardware has been provided within Deliverable D1.04. The same device will be used for testing performance of other sensing techniques considered as useful within SLOPE, including NIR, hyperspectral and stress wave. The list of modifications related to the cutting power measurements will include:

- installation of the electric chain saw ❶;
- installation of the feeding actuator of the chain saw ❷;
- installation of the 3-axis load cell ❸;
- installation of the series of strain gauges ❹;
- trial for installing AE sensors ❺ and microphones ❻;
- connection of all electrical components to the electric multimeter ❼;

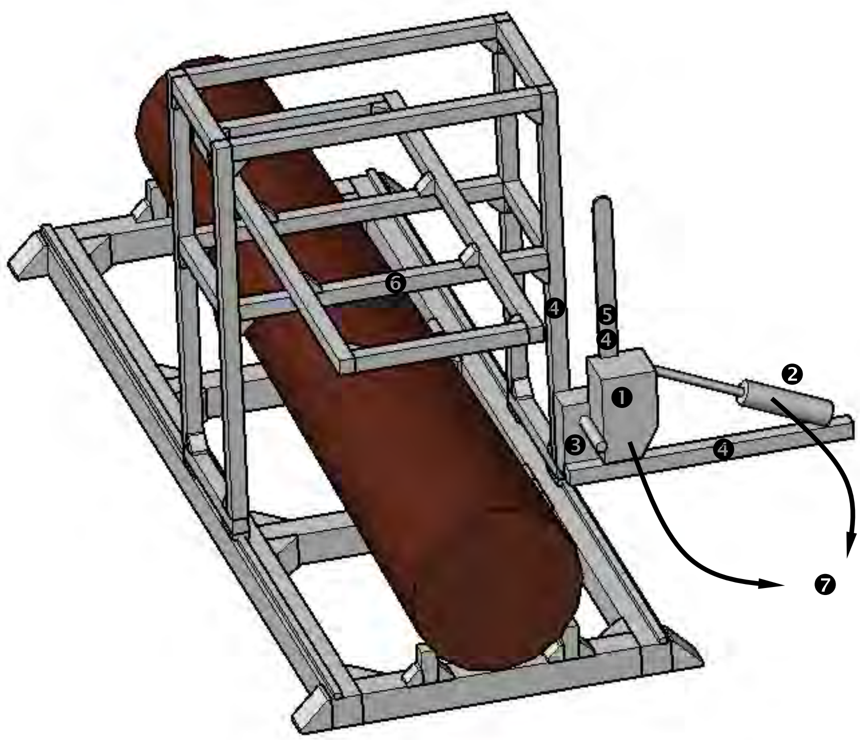

Figure 1: The general concept of the laboratory scanner and processor head simulator

3.1.3 Cross-cutting chain saw installed on the processor head

In the contrary to the manual operation of the three felling, the measurement of the cutting forces on the processor head is an optimal solution.

3.1.3.1 Tool

The saw to be monitored in the processor head is the hydraulic-driven chain saw being a standard part of the ARBRO processor head (the max cutting length

~500mm). The cutting tool will be adopted from that provided by the machine manufacturer and no modification to the cutting geometries are foreseen in the SLOPE project.

3.1.3.2 Sensors to be possibly used for monitoring of the cutting

Sensors to be possibly used for monitoring of the cutting forces while chain sawing with the prototype processor head includes:

Pressure sensors: continuously measure oil pressures both in the hydraulic motor (for the cutting power together with the information provided by the oil flow meter) and feed piston (for the feed force). The set of sensors will be directly connected with the hydraulic system of the processor head and will provide a continuous flow of information. Each sensor will be connected to the control system by means of the dedicated module of CRio. The analog signal generated by the pressure sensor may be in form of electrical voltage 0÷10 V or current 0÷20 mA.

Oil flow meter: is a sensor measuring volume of the oil passing through the hydraulic system. This information may be used for indirect evaluation of the cutting speed and its changes due to cross-cutting progress. This sensor will be integrated only with the hydraulic motor of the chain saw. The output is an analog signal to be acquired by the dedicated module of CRio control system.

Strain gauge; in analogy to the laboratory scanner, the series of strain gauges will be installed on the selected mechanical parts of the chain saw system, assuring secure position and sensitive enough detection of the machine part deformation. The sensor(s) will be connected to the control system by means of dedicated CRio module.

Acoustic emission, sound and load cells: will be eventually integrated with the chain sawing system of the processor head in case if the preliminary tests on the laboratory scanner will be successful. The sensor configuration, wiring and signal processing will be adopted from that developed in laboratory, in case of encouraging results.

It has to be mentioned that other sources of information available from the SLOPE control and quality grading systems will be used for supporting the correct interpretation of results and reliable performance of the processor head. The list of external information will include:

- **working time** of the cutting tool (chain) since the replacement/re-sharpening; for estimation of the tool wear and correction of the cutting forces as well as a saw tensioning;
- **position of the saw bar** while cross-cutting; to be used for monitoring of the cutting progress, and correction factors related to the determination

of the cutting forces and material characteristics. The sensor used for this measurement is an absolute encoder, being a part of the modified processor head.

- the **log diameter** (combined with position of the saw bar); to be used for determination of the cutting length at each moment of the cross-cutting. The diameter will be estimated by the rotary encoder(s) being a standard accessory of the processor head. The information regarding the diameter will be provided by the control system when requested and will be used as a reference for all further calculations.

3.1.3.3 Hardware configuration of the processor head

The general concept of the chain sawing system implemented on the processor head is presented in Figure 2. Compatibly with real processor head constraint due to geometry, available room and environmental stress and request on reliability, the list of modifications related to the cutting forces measurements will include:

- installation of the hydraulic pressure sensors ❶;
- optional: installation of the 3-axis load cell ❷;
- optional: installation of the series of strain gauges ❸;
- optional: installation of the AE sensors ❹;
- installation of microphone(s) ❺;
- appropriate wiring and connections of all electronic components to the control system.

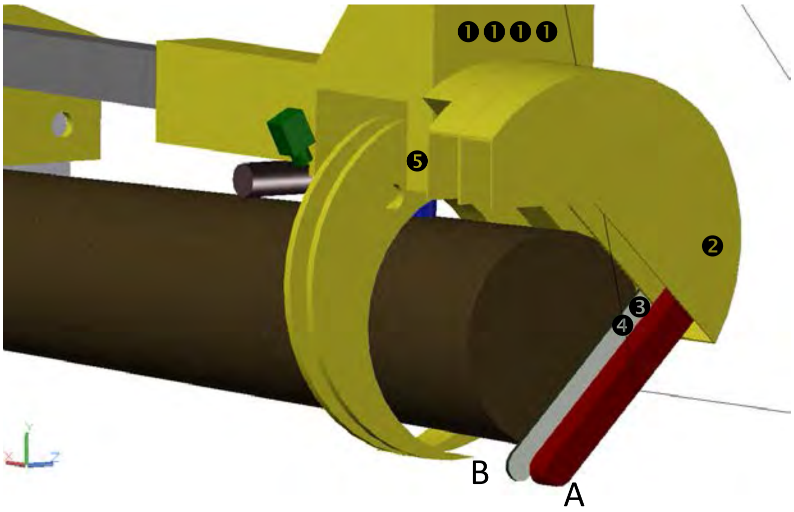

Figure 2: Schematic of the log cross-cutting system of the ARBRO1000 processor head; the scanning bar holding sensors used in SLOPE quality sorting system A and the chain saw B in the working position.

3.2 Debranching knives

Various methods can be used at different process stages for measuring cutting forces related to the removing branches from the trunk after tree felling.

3.2.1 Delimbing with chain saw

As already stated in chapter 3.1.1, the chain saw operated by the forest worker can be used for various operations within forest, including debranching. However, the complicated instrumentation of the tool and low reliability of the possible results makes this approach not-practical.

3.2.2 Experimental delimbing with model knives installed on the laboratory scanner

3.2.2.1 Machine and tool used

The cutting knife to be researched in the laboratory scanner is a modified knife of the straight edge commonly used in woodworking machines (such as planer). The tool will be installed on the scanner carriage in order to control both the cutting position and speed. The motion of the scanner will be controlled by the CompactRio system. The cutting parameters, including cutting edge geometries, cutting velocity and toll stiffness will be selected in order to simulate as much as possible further cutting conditions on the processor head.

3.2.2.2 Sensors to be used for monitoring of the cutting on the laboratory scanner

Sensors to be tested for monitoring of the cutting forces while debranching on the laboratory scanner includes:

Load cells; indirectly measuring the cutting force. The same as for the chain saw 3-directional laboratory load cell will be used for screening of the cutting forces kinetics and directions. It will be possible to optimize the setup on the base of such preliminary tests. The load cell will be installed on the frame of the scanner providing continuous information about XYZ cutting force distribution. The risk of easy sensor damage due to excessive forces will be considered and the cutting tests will be continuously monitored in order to avoid the damage to the sensor. The sensor will be connected to the control system by using a three channels analog input of the CRio module.

Strain gauges; will be installed on the selected mechanical parts of the cutting knife support being firstly identified as to be buckled while debranching. Several strain gauges will be installed simultaneously in order to identify the best suited machine part affected by the cutting forces. The sensor, as in a case of the chain saw, will be connected to the control system by means of dedicated CRio module.

Electrical multimeter; will be used as an electrical analogy for measuring the oil pressure in the real working machine. The electrical power of the feed motor (and its variation during the debranching cycle) will be continuously monitored. The digital meter will be connected to the control system by means of the dedicated CRio module.

Acoustic and audible emissions: a trail test will be also performed on the laboratory scanner in order to determine if acoustic emission or cutting sound generated while cutting out braches contain any usable signal useful for detection of the branch presence and/or its size and health status. The experimental set-up including the cabling and signal processing will be identical as for the chain sawing operation.

3.2.2.3 Hardware configuration of the laboratory scanner

The same laboratory scanner used for chain sawing process monitoring in the laboratory will be utilized for debranching analysis. The general concept is presented in Figure 3. The list of modifications to the hardware as related to the cutting power measurements while debranching will include:

- installation of the feeding system of the scanner frame ❶;
- installation of the instrumented cutting knife ❷:
    - installation of the 3-axis load cell ❸;

- installation of the series of strain gauges ❹;
- trial for installing AE sensors ❺;
- trial for installing microphones ❻;

- connections of all electrical components to the electric multimeter ❼.

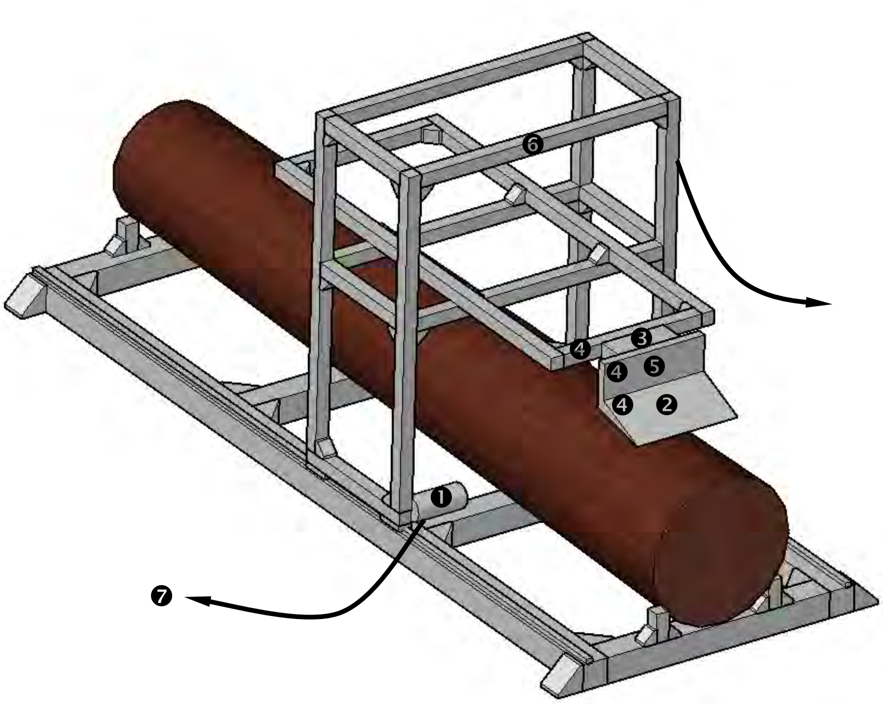

Figure 3: The general concept of the laboratory scanner and simulator of the debranching process

3.2.3 Delimbing with knives installed on the processor head

As already stated, the mechanical configuration of the ARBRO 1000 processor head is perfect for implementation of the delimbing monitoring process.

3.2.3.1 Tool

The cutting knifes to be monitored on the processor head are standard parts of the ARBRO processor head (the maximum log diameter to be processed is 45cm). The cutting tool will be directly adopted from the one provided by the machine manufacturer and no any modification to the cutting geometries are foreseen in the SLOPE project. Only some adjustment of the tool holding system is foreseen being an effect of the recommendation list developed on the laboratory scanner.

3.2.3.2 Sensors to be possibly used for monitoring of the cutting

Sensors to be used for monitoring of the cutting forces while debranching on the processor head includes:

Oil pressure sensor: is continuously measuring the level (and change) of the oil pressure in several hydraulic systems involved in the cutting-out branches:

- main feed piston (for the feed force)
- cutting arms (for determination of the friction force)
- holding arms (for determination of the correct fixing of the log during the cutting cycle

The set of pressure sensors will be connected directly with the hydraulic system of the processor head and will provide a continuous flow of information. Each sensor will be connected to the control system by means of a dedicated CRio module.

Strain gauges; in analogy to the laboratory scanner and chain sawing module, the series of strain gauges will be installed on the selected mechanical parts of the debranching system, assuring secure position and sensitive enough detection of the machine part deformation. The sensor(s) will be connected to the control system by means of dedicated CRio module.

Acoustic emission, sound and load cells: will be eventually integrated with the debranching system of the processor head in case if the success of preliminary tests on the laboratory scanner. The sensor configuration, wiring and signal processing will be adopted from that developed in laboratory.

It has to be mentioned that other sources of information available from the processor head control systems will be used for data meaning. The list of external information will include:

- **Working time** of the tool (cutting knife(s)) since the replacement/re-sharpening; for estimation of the tool wear and correction of the cutting forces
- **Position of the main hydraulic actuator** while cutting-out branches; to be used for monitoring of the progress, and determination/mapping of the detailed knot position. The sensor used for this measurement is an encoder, being an original part of the processor head.

3.2.3.3 Hardware configuration of the processor head

The general concept of the debranching system implemented on the processor head is presented in Figure 4. Compatibly with real processor head constraint due to geometry, available room and environmental stress and request on reliability, the list of modifications as related to the cutting forces measurements will include:

- installation of the hydraulic pressure sensors ❶;
- optional: installation of the load cell ❷ beside the cutting knives ❸;
- optional: installation of the series of strain gauges ❹;
- optional: installation of the AE sensor(s) ❺;
- optional: installation of microphone(s) ❻;
- appropriate wiring and connections of all electronic components to the control system

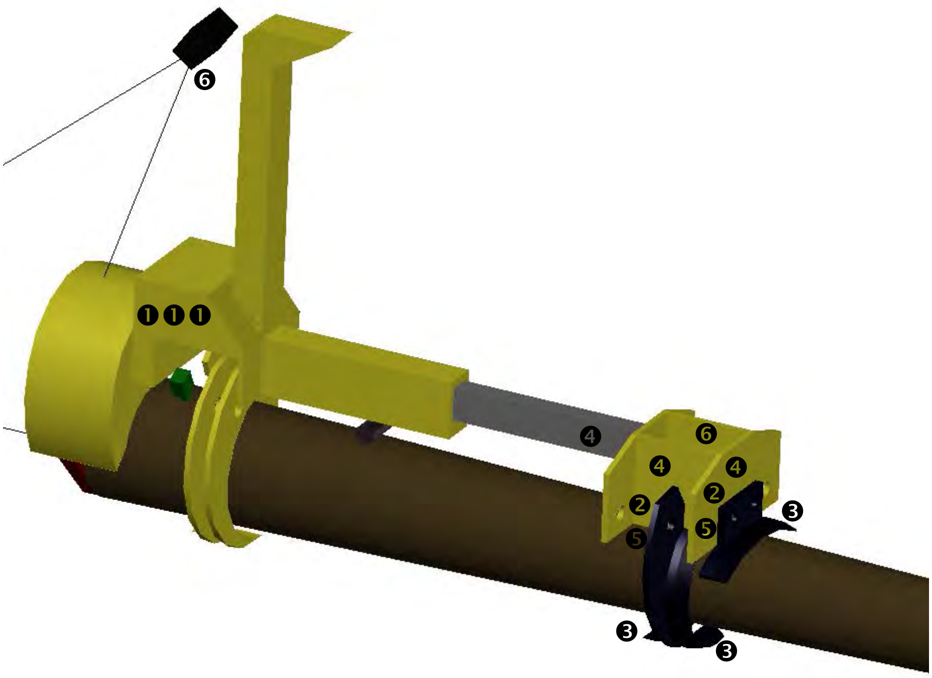

Figure 4: Schematic of the de-branching system of the ARBRO1000 processor head; cutting knives ❸ and hydraulic actuator❹.

3.3 Other techniques suitable for determination of the cutting process but not foreseen to be tested in SLOPE project

The use of cutting forces for prediction of the material properties has been implemented in various instruments. Most of them are used for the assessment of timber structures and integrity of buildings. Even the high advantage of indirect materials characterization these methods are not suitable for application within the SLOPE project. Some of these, having proven applications in wood are listed below:

- resistance drilling;
- Pilodyn;
- screw withdrawal.

3.4 Selection criteria for hardware most suitable for implementation in SLOPE

As stated before, the cutting forces can be measured by means of different sensing techniques. Each of these possesses unique set of advantages and limitations. The overall summary of the sensing techniques by considering several technical characteristics is summarized in Table 1. The possible implementation within both, lab scanner or processor head is also provided.

Table 1. Comparison of cutting process monitoring sensors to be used within T4.05 of the SLOPE project

sensor type	simplicity	reliability	information quality	easy interpretation	low cost	suitable for SLOPE laboratory tests	suitable for SLOPE in-field application
load cell		✓	✓	✓		✓	✓
strain gauge	✓				✓	✓	✓
electric multimeter	✓	✓	✓	✓		✓	
oil pressure	✓			✓	✓		✓
oil flow	✓			✓	✓		✓
AE		✓	✓			✓	✓
microphone			✓		✓	✓	✓

4 Results of measuring cutting power: raw signals

The results of all measurements with sensors foreseen to be implemented for measuring cutting forces are of analogue nature. Consequently, analog-to-digital converter will be used for signal digitalization. Dedicated electronic modules, being a part of the CompactRio hardware platform will be used both in the laboratory and in the field. The selection of due module will be according to the technical characteristics of each sensor and will take in to consideration:

- sampling rate (scans/second);
- signal range (0÷10 V or 0 to 20 mA);
- in-build power supply for the sensor (such as a IEPE);
- number of input channels needed;
- possibility for on-board signal pre-processing.

The overall summary for the raw signals characteristics is summarized in table 2:

Table 2. Comparison of cutting process monitoring sensors to be used within T4.05 of the SLOPE project

sensor type	Output	Number of channels required	Sampling rate	On-board signal preprocessing	CRio module (NI XXXX)	Other
load cell	0÷5 V	3	~250 Hz	NO	9205	
strain gauge	0÷10 V	4	~250 Hz	YES	9237	
electric multimeter	0÷10 V	12	~250 Hz	NO	9205	
oil pressure	0÷10 V	8	~250 Hz	NO	9205	
oil flow	0÷10 V	1	~250 Hz	NO	9205	
AE	±5V	1 (or 3)	100k Hz	YES	9234	
microphone	±5V	2	40 kHz	NO	9215	

5 Mathematical methods and algorithms suitable for post-processing of the cutting power data in SLOPE scenario

The raw electrical signals acquired from sensors are important information derived from the cutting process, but can not be directly interpreted for estimation of the quality indexes. Series of post-processing actions are therefore required in order to extract reliable information on the material properties. Some of the algorithms to be implemented within SLOPE project are briefly described below.

5.1 Algorithms for pre-processing of signals

The goal of signal preprocessing is to **minimize (or eliminate) variability within results** that is not related to the investigated property of interest. The most common signal pre-processing methods used when analyzing cutting forces of wood are:

5.1.1 Averaging

Averaging allows generation of a single scalar value from a set of original data of the same type.

5.1.2 RMS

Root mean square (*RMS*) is a mathematical/statistical algorithm defined as the square root of the mean of the squares of a sample. RMS is a very useful indicator, frequently used for describing properties of time-resolved signal such as waves.

5.1.3 Filtering

In most cases the signal acquired by the system is a superposition of various sources, including components of low/medium/high frequencies or diverse types of noise. The most frequent method for separation of these components is to use filers. Three types of filtering approach will be explored within T4.05 and are described in the following sub-paragraphs:

5.1.3.1 Electronic filters

This filters are dedicated electronic circuits designed to filter out (or highlight) particular signal features. Such circuits are frequently integrated with the sensor itself and combined with other modules such as amplifier, A/D converter, etc. Depending on the application and filter configuration, the signal filtering may be: low-pass, high-pass, band-pass or band-stop.

5.1.3.2 Digital filters

Digital filters are software analogy of electronic filters, being dedicated programs capable of extracting certain signal features. Various types of digital filters are available nowadays, where some are implemented in the LabView software package. The last is a development platform foreseen to be used during SLOPE software implementation.

5.1.3.3 Wavelets

Wavelets are an alternative to the Fourier Transform methods capable to extract spectral information from the time series. There are several advantages of Wavelets to be possibly explored within development of T4.05.

5.1.4 FFT and spectral analysis

Fast Fourier Transform (FFT) is a mathematical algorithm converting time-resolved signals (waves) into frequency space. FFT is frequently used for detecting any periodicity in the signal and is very useful for spectral characterization of data.

5.1.5 Counts/second

Counts/second is a mathematical algorithm providing number of events (signal features) fulfilling specified criteria in a period of time. In most cases it is when the signal value exceeding the given threshold and is refereed to the time laps of 1 second. This parameter is frequently used when dealing with Acoustic Emission signals.

5.2 Algorithms for cutting power data post-processing and data mining

The pre-processed (conditioned) signals obtained while cutting wood will be then subjected to extraction of the meaningful information, useful for both quality estimation of the processed wood products and overall monitoring of the wood cutting process. The custom software will be developed at CNR for this purpose and it will be integrated with the control system of the processor head to be developed by COMPOLAB.

Several **mathematical**, **statistical** and **chemometric techniques** will be tested for identification of the most reliable models. In the simple case the average value of the parameter will be regressed against the reference data set. However, it is most probable that multivariate analysis will be implemented assuring multisensory integration and appropriate data fusion. Some brief description of the suitable methods has been provided in Deliverable D4.03 (Establishing NIR quality index) and will not be discussed in detail within this document.

The expected outputs of the cutting power data mining are two quality indexes associated to the wood properties and to the branch-related characteristics of the log. These indicators will be appropriately combined/weighted within Tasks T4.06 to define the overall quality index (grade) for all logs harvested according to the SLOPE scenario.

5.2.1 Cutting Process (CP) quality index #1 (chain saw cutting forces)

The CP quality index #1 will be in the range from 0 to 1 and will reflect the estimation of the wood quality as related to the cutting resistance. The value will be computed on the base of data acquired during cross-cutting of log by means of the chain saw. The list of variables to be included in the prediction model will incorporate (beside of the cutting power results):

- cutting process parameters (cutting speed, feed speed) and its variations during the cross cutting cycle;
- log geometry (diameter, ellipsoid shape, etc.);
- presence of any apparent defects (pith eccentricity, reaction wood, decay, knots, cracks, etc).

The CP quality index #1 will be, whenever possible, associated to the estimated value of the wood density. The prototype of the statistical model will be developed firstly in the laboratory, to be later transferred to the processor control system. The model will consider also the effect of varying wood moisture content and tool-related issues, such as wear.

5.2.2 Cutting Process (CP) quality index #2 (branches cutting-out forces)

Branching index will be estimated by means of signals associated with cutting out branches, including:

- hydraulic pressure changes along the log length;
- changes of cutting forces in time;
- number of AE events or sound pressure level (if successfully validated in the laboratory).

All these may be combined together (multi-sensor approach) in order to increase the reliability of the branch presence/size estimation. The distribution of knots along the log length will be obtained as a result. On this base the knottiness (branching) quality index will be computed considering existing grading rules. The foreseen output of this task may also be, beside of the CP quality index #2, a "quality map of log" to be used for the final grading assessment and/or assisting operator in cutting decision. The concept of such map is presented in Figure 5, and includes marking of different zones along the log length demonstrating presence (or absence) of knots of different characteristics.

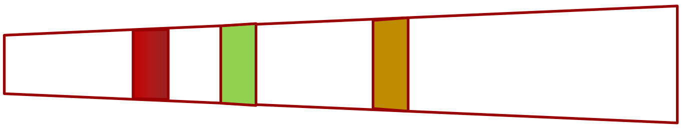

Figure 5: Concept of the "quality map" indicating as a color section selected log properties, geometries and presence of various defects (including these derived from the cutting-power analysis).

6 Protocol for testing of the cutting power along the whole process chain within SLOPE scenario (Task 4.5)

The applicability of cutting power both in field and laboratory will be extensively tested within Task 4.5 of the SLOPE project. The flowchart presented in Figure 6 summarizes all foreseen activities as well as flow of data and quality indicators. The following sub-chapters are providing further details and explanations of actions foreseen on each phase of the SLOPE process chain.

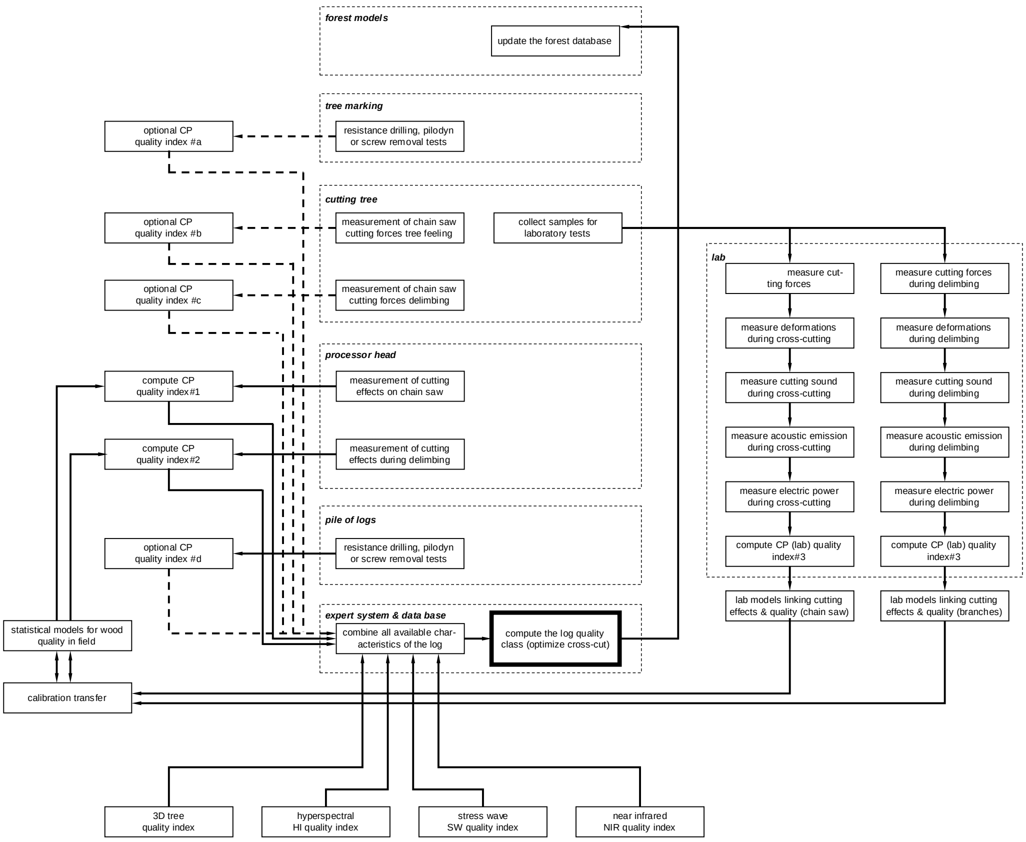

Figure 6. Collection of cutting power data at different stages of the harvesting process chain according to SLOPE.

6.1 Forest modeling

Data provided by the sensors and SLOPE quality systems will be used for filling the database with quality indexes and tree characteristics, to be possibly used in the future harvest planning.

6.2 Tree marking

It may be possible to determine the wood resistance for the cutting while removing bark by forester with an axe. However, due to very subjective and low reliability of the data acquired, it is not considered as a suitable moment for collecting the tree characteristics by means of cutting power requirements.

It has to be mentioned, that it is also possible to determine several wood properties by alternative to that used in the SLOPE methods. These may include resistance drilling, pilodyn or screw removal tests. However, due to time-expensive procedure and overall complexity of the test it is not considered for evaluation within Task T4.5.

6.3 Cutting of tree

The operation of felling the tree is a great opportunity for early collection of the cutting power data. On the other hand, the minimal reliability of cutting forces information due to complexity of the handy operation, difficulties to control the cutting process and problematic data acquisition (feed force, cutting length, grain angle, among others) make this approach rather not usable. Even that, the careful inventory of the current tree felling procedure will be performed within SLOPE; the possibility (option) for at least rough estimation of the cutting power resistance (or any related abnormalities) by the forest worker will be provided within the portable electronic device used for RFID log marking.

All the samples needed for the laboratory tests and for the system calibration will be collected from the forest at this stage.

6.4 Processor head

The processor head is the optimal machine to be used for determination of the log quality indexes by means of cutting power. Most of activities within task T4.5 are dedicated to development of this procedure, and are described in detail within this Deliverable.

6.5 Pile of logs

The logs stored after processing might be possibly used for determination of some mechanical properties by means of the cutting forces. In that case, analogical approach as for the tree marking may be applied, including portable instruments such as resistance drillers, pillodyn or screw withdrawal. Again, such an approach can not be considered as a routine procedure, even if an excessive effort can be justified in exceptionally high quality/value logs.

6.6 Laboratory

The Cutting power system will be calibrated during the initial phase in the laboratory.

6.6.1 Important considerations

6.6.1.1 Calibration transfer

It is important to consider that the calibrations developed within the laboratory test will be of relatively low reliability and it will be necessary to develop an adaptive algorithm for its further refinement, preferably in an automatic way.

6.6.1.2 Availability of the full-size samples to be used for characterization

The important limitation of the laboratory scanner is restricted number of samples to be possibly used for preliminary testing and consequently, limited reliability/repeatability of the models developed.

6.6.1.3 Not direct mimicking of the hydraulic system of the real-world processor head by the electrical systems of the laboratory scanner

It is a common problem related to the technology transfer from the lab toward in-field application. The limitation of the present approach is that the laboratory scanner will operate on the base of the electrical energy and cutting power results will be of electric nature. Even if the energy used for cutting in both cases (hydraulic and electrical) may be considered as equivalent, the nature of measurements and signal kinetics is expected to be dissimilar.

6.7 Protocol for cutting power measurement while cross-cutting logs in the lab

It is considered that the instrumented chain saw will be installed on the laboratory scanner and connected to the control system. The detailed procedure of the cutting power measurement is described below:

6.7.1 Procedure

a. install the sample log on the stage of the scanner assuring correct log position for the cross-cutting

b. turn on all electronic components and run the control software

c. follow the automatic sequence of the actuator actions:

    a. turn-on electrical engine of the chain saw

    b. rotate the saw blade with an actuator

    c. perform the cross-cutting

    d. turn back to the parking position

    e. turn-off the electrical engine of the chain saw

d. continuously acquire following data:

    a. electrical power of the chain saw motor

    b. electrical power of the feed movement actuator

    c. position of the saw blade while sawing

    d. cutting forces with the load cell

    e. deformation of the scanner body with strain gauges

    f. optionally (acoustic emission and cutting sound)

e. visualize in real time (and save) results

f. post processing of raw results including development of models

6.7.2 Important considerations

6.7.2.1 Safety of the operation

The cross cutting of logs is a demanding operation and it is necessary to assure all means of the safety. The slice of the log to be cross cut will be of ~5 cm long in order to eliminate the manipulation of the heavy residuals. The process can be remotely stopped in case of any undesired situation. The movement of the scanner frame will be also blocked while conducting cross-cutting.

6.7.2.2 Time of the action and reliability of simulation

The usage of electrical chain saw is a great advantage when simulating the real-world cutting process on the processor head. On the other hand the mechanical power of the electrical system is far less than that of the hydraulic circuit. It is expected therefore, that the timing of operation will be different than that on the real machine.

6.7.2.3 Effect of wood heterogeneity (moisture variations and temperature) on the cutting power results

Even if all the efforts will be dedicated to assure as much as possible mimicking of the real operation conditions, it may not be always possible. Therefore an effect of the wood moisture content and temperature will be considered when developing models by applying due correction factors.

6.8 Protocol for cutting power measurement while cross-cutting logs on the ARBRO 1000 processor head

It is considered that the modified processor ARBRO 1000 will be equipped with an instrumented chain saw module and connected to the processor control system. The detailed procedure of the cutting power measurement is described below:

6.8.1 Procedure

a. Operator sets the log position as appropriate for the cross cutting operation

b. The control system of the processor performs the series of actions after trigger provided by the operator:

    a. turn-on hydraulic motor of the chain saw

    b. rotate the saw blade with an hydraulic actuator

    c. perform the cross-cutting

    d. turn back to the parking position

    e. turn-off the hydraulic motor of the chain saw

c. continuously acquire following data:

    f. oil pressure in the chain saw motor

    g. oil flow in the chain saw motor

    h. oil pressure of the feed piston

    i. position of the saw blade while sawing

    j. cutting forces with the load cell (if used in the prototype)

k. deformation of the saw parts with strain gauges (if used in the prototype)

l. optionally (acoustic emission, cutting sound, or others)

d. visualize in real time (and save) the acquired results

e. processing of raw results by implementing models previously developed

f. continuously upgrade the models with new results

6.8.2 Important considerations

6.8.2.1 Safety of the operation

The cross cutting of logs is a very dangerous operation since the log to be cross cut will be long and very heavy. The process can be remotely or automatically stopped in case of any undesired situations. The scanner head will be also blocked while conducting cross-cutting by the due software and hardware protections.

6.8.2.2 Time of the action and reference to the models obtained in the laboratory simulations

In opposite to the laboratory scanner, the operation in forest is very fast. As a consequence all the models to be used have to be properly corrected to fit different cutting conditions. The value of the tool sharpness, log temperature, diameter, and wood moisture content will be also considered when computing the quality index.

6.9 Protocol for cutting power measurement while de-branching logs in the lab

It is considered that the instrumented cutting knife will be installed on the laboratory scanner and connected to the control system. The detailed procedure of the cutting power measurement is described below:

6.9.1 Procedure

a. install the sample log (or single modeled branch) on the stage of the scanner assuring correct log position for the cutting-out branches

b. turn on all electronic components and run the control software

c. follow the automatic sequence of the actions:

a. move the scanner frame over the investigated sample

b. perform the cutting-out branch

   c. turn back the scanner frame to the parking position

d. continuously acquire following data:
   a. electrical power of the feed motor (servo)
   b. position of the saw scanner frame while cutting
   c. cutting forces with the load cell (in three directions)
   d. deformation of the scanner parts due to cutting with strain gauges
   e. acoustic emission (optionally)
   f. cutting sound (optionally)
e. visualize in real time (and save) results
f. post processing of raw results including development of models

6.9.2 Important considerations

6.9.2.1 Safety of the operation

Even if the delimbing process is not as heavy as cross-cutting of logs, it is still necessary to assure all means of the safety. The weight and length of the processed branches will be adopted in order to minimize the residuals and any springing parts. In analogy to all the processes, the debranching operations can be remotely stopped in case of any undesired situation.

6.9.2.2 Time of the action and reliability of simulation

The usage of electrical servo is a great advantage when simulating the real-world cutting process on the processor head as it can be continuously monitored, assuming very dynamic nature of the signals obtained. On the other hand the mechanical power of the electrical system is far less than that of the hydraulic systems available on the real processor head. It is expected therefore, that the timing of operation as well as the energy usage in time will be different than that on the real machine.

6.9.2.3 Effect of wood/branches heterogeneity on the cutting power results

The natural variability of solid wood is very high, though that of the branches is even higher. It is related to the nature of branches, health status, drying history, mechanical damages due to natural events and/or harvesting itself. It is expected therefore that statistical models to be derived will be very rough and rather qualitative than quantitative.

6.9.2.4 Uneven distribution of branches along the tree height and perimeter.

The location, size and mechanical properties of branches are related to several factors, including wood species, growth condition, silvicultural activities and position of the tree within the plot. It would be desired that the detailed mapping of branched within each log would be the greatest improvement to the current practices. Design and tests of the prototypes (both in the laboratory and in the field) will take into account the possibility of separated monitoring of each de-branching knife

6.10 Protocol for cutting power measurement while de-branching logs on the ARBRO 1000 processor head

It is considered that the modified processor ARBRO 1000 will be equipped with instrumented cutting knives (one or three) and connected to the processor control system. The detailed procedure of the cutting power measurement is described below:

6.10.1 Procedure

a. Operator collects the log with grabbers and prepares it for debranching.
b. The control system of the processor performs the series of actions after trigger provided by the operator:
    a. Lock the back grabs and slightly clench the cutting grabs
    b. Stroke the cutting grabs along the log length
    c. Slightly release the back grabs and lock the cutting grabs
    d. Stroke the back grabs close to the cutting grabs
    e. Repeat the cycle “a” to “d” up to the moment when the operator identifies the optimal position of the cross-cut
c. continuously acquire following data:
    a. oil pressure in main feed piston
    b. oil pressure in back grabs pistons
    c. oil pressure in the cutting grabs pistons
    d. position of the log while de-branching
    e. cutting force(s) with the load cell (if used in the prototype)

        f. deformation of the cutting knives (grabs) with strain gauges (if used in the prototype)
        g. optionally (acoustic emission(s), cutting sound(s), or others)

   d. visualize in real time (and save) the acquired results
   e. processing of raw results by implementing models previously developed
   f. continuously upgrade the models with new results

6.10.2 Important considerations

6.10.2.1 Safety of the operation

As in all stages of development, the safety of operation will be absolute priority and will be assured by available means.

6.10.2.2 Time of the action and reference to the models obtained in the laboratory simulations

As already stated above, it is expected that the models developed in the laboratory will not be directly applicable to the real-working machine utilization. The value of the tool sharpness, log temperature and wood/branch moisture content will be also considered when computing the quality index.

6.10.2.3 Disturbing factors related to the nature of wood

Even if the general concept of measuring cutting forces is relatively clear, it is expected that its implementation will face important challenges. One of that is related to the fact that it would be not possible to differentiate between energy used for cutting itself and wasted due to friction forces or de-barking.

7 Suitability of cutting power measurement for detection defects in logs

The detailed analysis of wood defects affecting the quality of logs has been summarized in Deliverable D4.01. It was clearly stated there that the cutting-power related measurements are rather limited in term of the wood defect detection capabilities. On the other hand, the measurement of cutting forces may be rather easily implemented on the processor. The reliability of results is foreseen to be high, especially when compared with other (far more sophisticated) sensing technologies to be explored within SLOPE.

Two quality indexes will be obtained from the cutting tests, one related to the wood density, while the second to the branches.

Other wood defects and material properties to be possibly detected (and classified) by measuring cutting power and forces are preliminary assessed and summarized in Table 3.

The set of above information is a very valuable input for determination of several essential quality descriptions, including among others:

- presence of abnormal (reaction) wood;
- presence of decay.

Especially the last descriptor may be extremely useful, as it would be possible to optimize the original cutting plan in order to eliminate any decayed wood from the commercial logs that was not visible at the earlier stages of the processing chain. In that case, the processor head operator will be instructed to cut-out the bottom log of ~1m length (depending on the decay intensity). The remaining logs may be of superior quality (higher than class D) and of significantly higher market value.

Both cutting techniques used within for the SLOPE scenario are evaluated; chain sawing and cutting-out branches. Both laboratory and in-field applications are considered. Various aspects of the quality; wood defects and other wood/log properties are listed in the first column of the table. The expected usefulness of each sensor is marked as:

"✓" – the sensor is capable to provide suitable info

"×" – the sensor is not capable to provide suitable info

Please refer to the SLOPE deliverable D4.01 for more details regarding wood defects and log quality grading.

All the knowledge base summarized in the Table 3 has to be considered as a preliminary and indicative expert assumption, and will be deeply validated during Task 4.06 progress.

Table 3. Potential for defects detection and for determination of selected material properties as measured by means of cutting process monitoring

Cutting process		chain saw		de-branching	
Surface of sample		laboratory	processor head	laboratory	processor head
Wood defects according to EN 1927-1:2008	knots	✓	✓	✓	✓
	resin pocket	✓	✓	✓	✓
	twist	✗	✗	✗	✗
	eccentric pith	✓	✓	✗	✗
	compression wood	✓	✓	✗	✗
	sweep	✗	✗	✗	✗
	taper	✗	✗	✗	✗
	shakes	✓	✓	✗	✗
	insects	✓	✓	✓	✓
	dote	✗	✗	✗	✗
	rot	✓	✓	✓	✓
	stain	✗	✗	✗	✗
Other wood properties/characteristics	lignin	✗	✗	✗	✗
	cellulose	✗	✗	✗	✗
	hemicellulose	✗	✗	✗	✗
	extractives	✗	✗	✗	✗
	microfibryl angle	✗	✗	✗	✗
	calorific value	✗	✗	✗	✗
	heartwood/sapwood	✓	✓	✗	✗
	density	✓	✓	✗	✗
	mechanical properties	✓	✓	✓	✓
	moisture content	✓	✓	✗	✗
	provenance	✗	✗	✗	✗
	resonance wood	✓	✓	✓	✓

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