Deliverable D.4.02

On-field survey data for trees characterization

WP 4 – Multi-sensor model-based quality control of mountain forest production

Task 4.1- Data mining and model integration of stand quality indicators from on-field survey for the determination of the tree "3D quality index".

Revision: Final

Authors: Alex Poveda, James Hurley (Treemetrics)

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Contributor(s)	Mariapaola Riggio (CNR) Jakub Sandak (CNR)
Reviewer(s)	Federico Prandi (GRAPHITECH)
Editor(s)	Raffaele De Amicis (GRAPHITECH)
Partner in charge(s)	TREEMETRICS
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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This deliverable contains original unpublished work except where clearly indicated otherwise.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

TLS	Terrestrial Laser Scanner
DBH	Diameter at Breast Height
h	Tree height
DTM	Digital Terrain Model
b	Bow
SED	Small end diameter
LED	Large end diameter
CTL	Cut-to-length

1 Abstract

Information on the quality of available timber is essential for wood procurement planning, because the technical quality of standing timber directly affects the production potential and its value in the forest industry.

This document aims to define a methodology to evaluate the timber quality based on external stem characteristics of the standing trees, calculated from the Terrestrial Laser Scanner (TLS) forest inventory analysis, and timber log quality specifications defined by the wood processing industry.

The combination of the Terrestrial Laser Scanner (TLS) measurement with traditional stem measurement, such as tree height (h) and Diameter at Breast Height (DBH), provide a significant improvement of the tree stem characterization. This includes an accurate stem profile, including the stem lean and sweep. Additional stem defects that affect to the timber quality have been recorded in field, e.g. dead tree, broken top, scar defects, cracks, decay, etc.

Local timber log quality specifications from the regional timber mill industry have been taken into account to estimate the quality and productive indexes. These quality specifications include log straightness, log length, Smaller End Diameter (SED) and Larger End Diameter (LED) and specific rules for timber defects.

The virtual harvesting simulator used in this study allows the combination of stem and industry parameters in order to estimate the suitability of each stem to generate the different types of timber products defined by the timber. This can be easily related with the quality index regarding the productivity of each tree or the forest stand.

In this study different quality indexes have been proposed. These indexes can be used to estimate the productivity of the forest stand based on TLS forest inventory. This new approach for assessing the quantity, quality, and value of timber represents a significant improvement in the forest stand characterization. This will allow a better understanding of the forest for a more optimal and sustainable management.

2 Rationale

Information on the grown standing timber resource is an essential requirement for the wood processing industry and is used as a basis for major and long-term investment decisions. Forest managers also require information on the timber resource to manage forests sustainably and to maximise economic return. The long-term stability and profitability of the timber industry are dependent on both the availability and the quality of the grown timber supply.

Forest inventories are based on detailed standards, but usually carried out in a very traditional way. Some of these standards are hard to develop accurately in practice, due to the rudimentary tools used. Most basic parameters, such as diameter at breast height (DBH) or total tree height (h) often include error depending on the operator. Although traditional instruments for forest inventory have been continuously improved, the improvements were based on the same principles without a significant change in the inventory procurement.

Defects in the stem reduce the total volume of usable wood in the tree. Traditionally the forester will note the percentage of defect in each tree stem by product type. This measurement was based on a visual inspection in the field, resulting in different results for different foresters. In addition, this percentage of defects is then deducted from the overall estimate of tree volume. However, because tree diameter decreases with increasing height in the tree, a defect occurring near the top of the tree will require a smaller percentage volume deduction than a similarly occurring defect near the base.

The use of Terrestrial Laser Scanning (TLS) is a significant change in the way how the measurement is performed and the number of data collected is clearly superior, allowing a full 3D model of the stems measured. The TLS analysis support automated analysis regarding lean and sweep. In addition, the proposed system allows the field operator to manually input the quality attributes associated to a stem section.

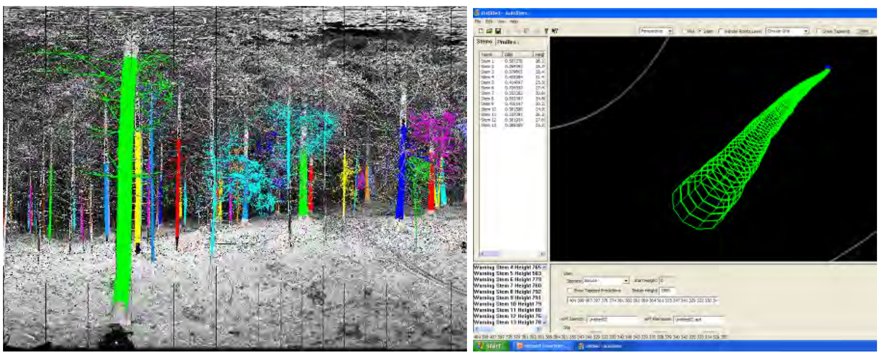

Figure 1: stem extraction from the point cloud (left). 3D model of one sample tree (right)

The proposed system includes an objective measurement and analysis of the timber defects to overcome these issues.

The stem defects are potential indicators of the timber quality, however these can have different impact in the in the final timber product, depending on how there are cut. Standing timber defects cannot be considered as stand alone features, without take in account the impact of these features in the final timber products.

Treemetrics has developed a system to define and characterize the stems defects for SLOPE project, including shape defects and other potential timber quality features.

3 Goals of this report

Traditionally the shape of tree stems has been studied in forestry in order to create taper models to allow estimate stem volume. These models can be used for determining diameters in certain tree heights, the volume of stem sections for various tree species. However, the traditional taper equations are general models that do not include quality parameters such as sweep and lean of stems.

This study aims to use Terrestrial Laser Scanner (TLS) to allow a detailed characterization of single stems, including stem quality indicators such as straightness and potential timber products. The specific objectives of this document are:

- Demonstrate the improvement of the TLS measurement in the calculation of stem quality indexes.
- Establish an objective Standing Timber Defects Measurement
- Demonstrate the feasibility of the Treemetrics harvest simulator measurement in the calculation of timber quality indexes.
- Define stem quality indexes based on the stem external characteristics and potential timber products analysis.
- Define stem quality indexes based on the stem external characteristics and potential timber products analysis.

AutoStem software is used in order to detect trees and generate a high-resolution stem profile. This model is very accurate with resolution of 10mm in the tree profile. The software locates and extracts the tree form the point cloud. The stem is broken in 10 cm discs. Each profile disc comprises the centre point coordinates and a diameter measurement, but other attributes, such as lean and quality characteristics, can be also associated to each disc. This structure in the stem definition is very powerful because quality indicators can be associated to each disc and taken into account when the cutting simulation is performed.

The TLS analysis is limited by the low visibility in the crown section of the tree. This fact does not allow extract the stem characteristics above certain height. In order to estimate the full stem profile, general taper equations based on allometric stem relationships are used in the top section when the stem can not bee extracted from the point cloud. These sections does not support automated analysis regarding lean and sweep but the system allows the field operator to manually input the quality attributes that can be associated to each disc.

4 Tree Characterization

The analysis of the TLS point cloud in combination with other manual measurements allows an accurate characterization of the tree stem characteristics on standing trees. In a first phase the TLS data is analyzed to identify and extract the stem profile, in a second phase this profile is refined by other manual measurements and forestry models.

4.1 TLS analysis

4.1.1 Pre-processing

A TLS scan will contain noise and unreliable point measurements. Before any analysis can be performed these points must be filtered from the scan. Each point is represented by and stored as three parameters of a spherical coordinate system with the scanner laser at the origin and a reflectance value. i.e. inclination angle, azimuth angle, radial distance and reflectance.

The first stage of filtering compares each scan point with its nearest neighbours by azimuth and zenith angles. If the point's distance value is greatly different from most of its neighbouring points' distances, it is discarded as an outlier.

The second stage removes points with a reflectance value too low to provide a reliable distance measurement.

The next step is to limit the boundary of the point cloud. A typical measurement area is a cylinder of 10-15m radius, according the size of the field plots where the number of stems has been counted. All points outside this section of interest are discarded.

Detection and measurement of trees is also adversely affected by foliage and branches between the scanner and tree bole. These points are indentified and excluded for analysis of the main stem. An example of the filtered TLS cloud point is presented in Figure 2.

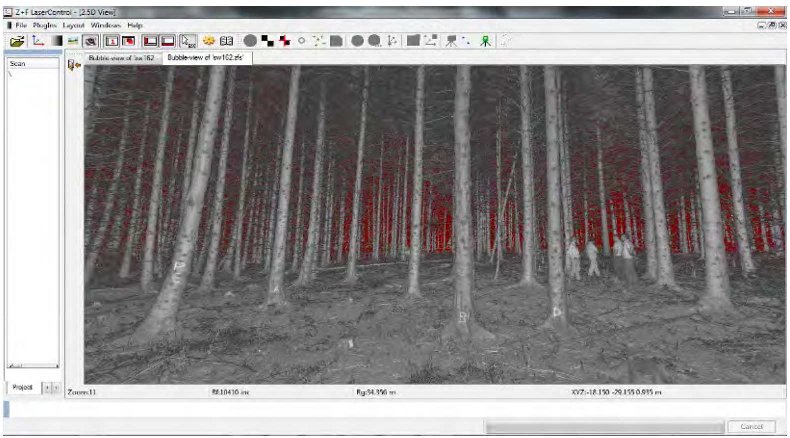

Figure 2: TLS point cloud filtered

4.1.2 Local DTM Generation

Autostem™ is Treemetrics' software package for detecting and measuring stems in a TLS scan. After the pre-processing the next step is generating a local Digital Terrain Model (DTM). Ground points are identified by analysing the point density of the cloud along the z-axis. A best-fit plane DTM is created where the point density analysis suggests the ground is lying. Once the DTM is defined, tree profiles can be defined relative to it.

4.1.3 Single Tree Detection

AutoStem initially detects trees by analysing a 0.1m thick slice of the point cloud around the DBH plane. DBH is defined as the diameter 1.3m above the ground. High density clusters of points are identified as possible trees. If a cluster of points approximate a 160º circular arc a tree object is assumed. Analysis is then performed on the sub-section of the point cloud in a cylinder surrounding this object and profile discs are fitted to the point cloud at 10cm intervals from the ground up, thus creating the stem profile. Each profile disc comprises the centre point coordinates and a diameter measurement. If there are insufficient points to assign a disc at a specific height, a disc is interpolated using discs above and below (Figure 4).

The upper section of the tree from the highest measured disc to the tree top is completed using a local taper equation for each species.

Where the DTM is sloping, heights including DBH are measured from the highest DTM point adjacent to the base of the tree object.

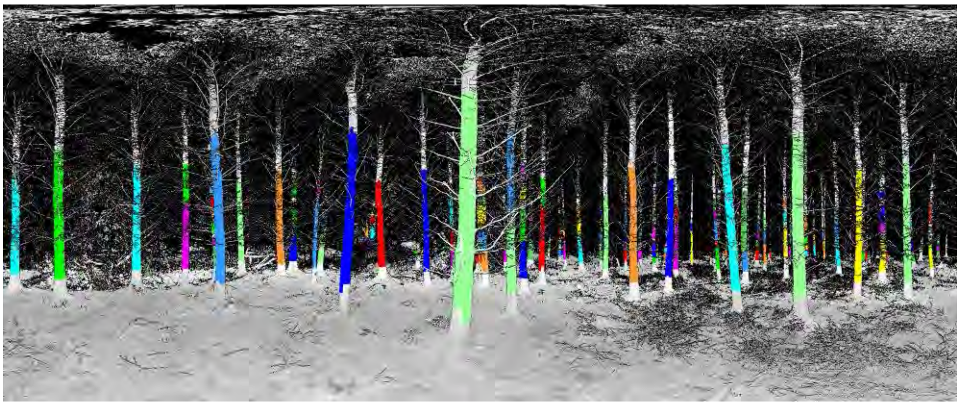

Figure 3: Stem 3D profiles trunked

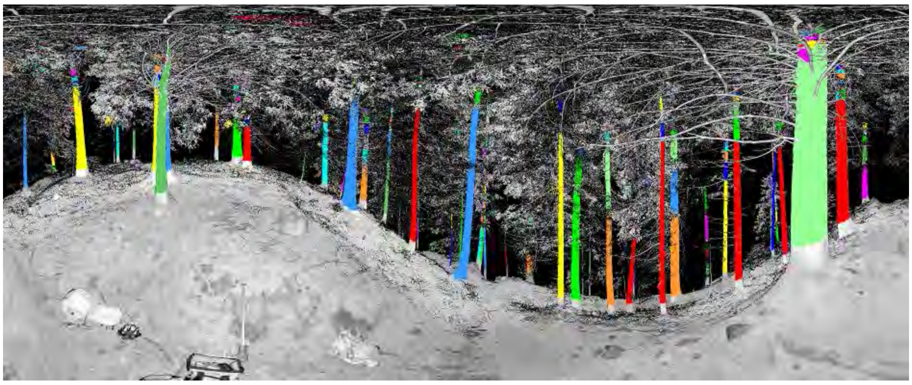

Figure 4: Tree detection after filter.

4.1.4 Tree Location

The position of a tree is defined as the co-ordinates of the centre point of the DBH disc. If the scan is not aligned north-south while scanning, the entire scan rotated by a bearing offset in order to estimate the global coordinates. This steps is important in order to combine Earth Observation with field data as detailed in D2.03.

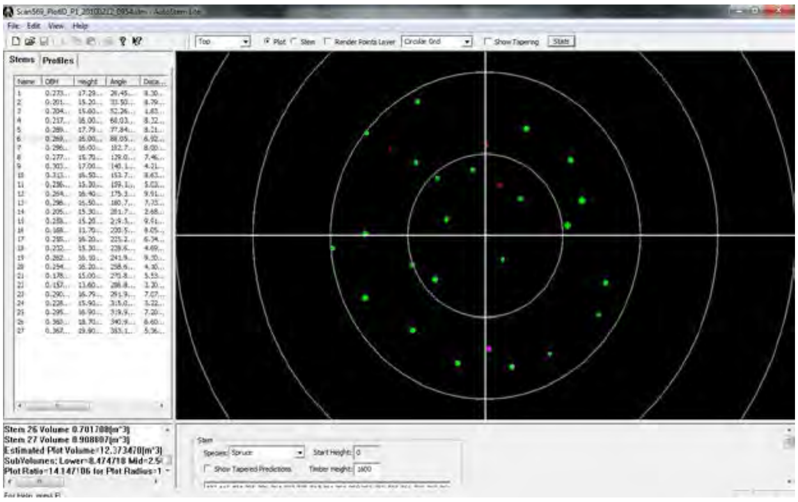

Figure 5: Tree position for a sample plot in Autostem.

4.2 Stem 3D Characterization

4.2.1 Stem Profile

The diameters of previous profiles are used to generate a high-resolution stem profile. This model is very accurate with resolution of 10mm in the tree profile. However, the TLS analysis is limited by the low visibility in the crown section of the tree. This fact does not allow extract the stem disc above certain height. In order to estimate the full stem taper, general taper equations based on allometric stem relationships are used in the top section when the stem can not bee extracted from the point cloud, as in case of the tree presented in Figure 6.

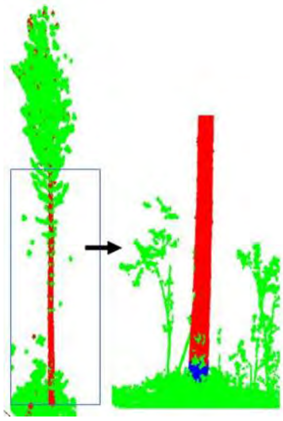

Figure 6: Stem 3D profile trunked

Stem taper equations are widely used to estimate diameter at any given tree height. These models are less accurate that the 3D stem profile calculated from the point cloud, but the combination of the both methods optimize the use of the data currently available and allow generate an accurate stem profiles (Figure 7).

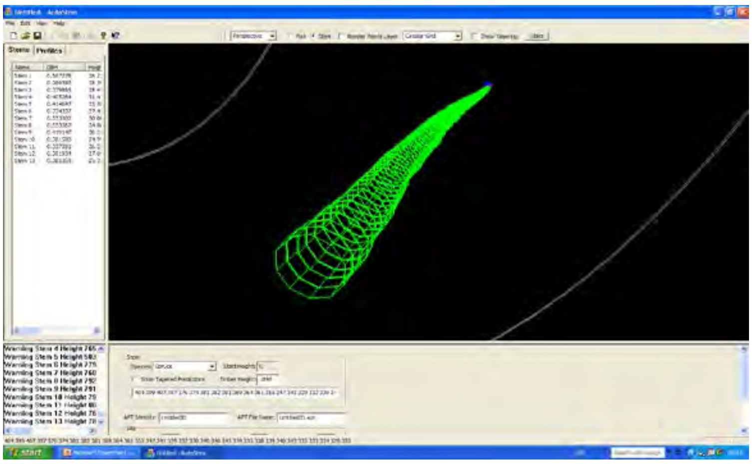

Figure 7: Stem 3D profile in Autostem

4.2.2 DBH and Tree Height

The tree height is defined as the difference between the lowest point and the highest point inside of the cut cylinder that contains a tree stem. However, this height is not always visible from the point cloud due to the branches in the crown (Figure 8a).

In order to determine the expected tree height, DBH-height allometric relationship is created with the pairs of DBH-heights measured in the field for each sample plot (Figure 8b).

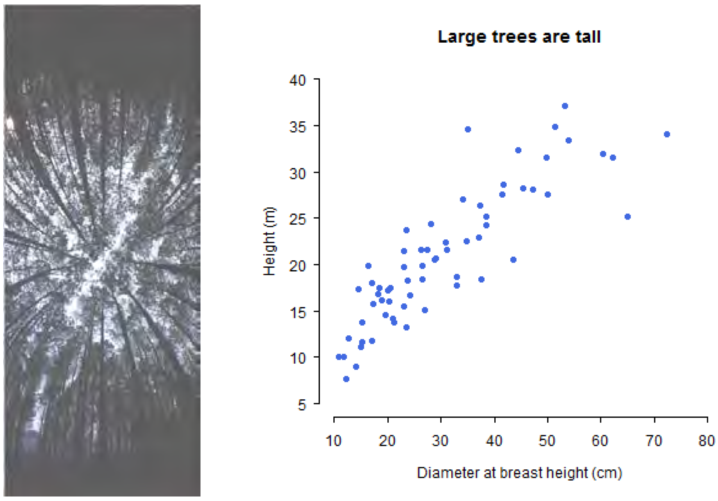

Figure 8: a)View of the tree crowns from the ground (left). b) DBH-height relationship (right).

4.2.3 Sweep and Lean

The stem profile created from the TLS analysis contains the information to determine the Sweep and the Lean of the tree stem. This information is stored in the tree definition, however the system does not estimate the full stem length sweep nor lean. Instead the lean is only estimated when the timber logs are defined.

The lean of the tree can be measured in the plane where the slope relative to the z axis is at its greatest. While a tree growing on a slope does not make right angles to the ground it is not considered to be leaning unless its spine is not parallel to the z axis. To calculate the lean the x,y,z coordinates for each disk on the tree can be taken to calculate the best fit line in 3D space. By using the DTM the lean can be estimated.

4.2.4 Additional Stem Features: Defects

In addition to the basic tree parameters (i.e. DBH, height, Sweep and Lean) the current system used in this study allows to associate several "*features*" to a defined section of the stem profile. This capability allows the definition of defects in the stem profile. These defects will be taken into account by the harvesting simulator.

A detailed explanation of how to measure and add the defects to the stem definition is described in section 0.

4.3 SLOPE file exchangeable format (SEF)

SLOPE file exchange format is inspired in Stemfile format. Stemfiles are generated to fully support the Standard for "Forestry Data and Communication" (StanForD) standard. According this standard the stem profile can be stored, according the parameter 273, in a widely accepted file with ".stm" extension. The allows for storing of x,y,z and diameter for each decimetre disk on the stem.

This format does not allow for extra stem quality information to be stored. Therefore information such as defect features should either be stored in a linked file to the .stm file or a new approach that does not support the StanForD standard can be used.

SLOPE exchangeable format has been defined in a JSON format, including the StanForD data and additional stem information such as information such as defect features. This JSON file will contain information for each stem.

The defects features are defined by the parameters defined in Table 1.

Table 1: Defect feature parameters

Variable	Values	Descriptions
Type	GRADE	Defect applicable to the entire stem
	SECTION	Defect applicable to the section between h0 and h1
Value	0,1,2...	Severity/Type of defect
End Height		Finishing point to apply the defect (stem height)
Start Height		Starting point to apply the defect (stem height)

An example of the JSON format for each individual tree is described in Appendix 11.1.

5 Defects

5.1 Standing Timber Defects Overview

Several studies have tried to study and categorize the different standing timber defects[1]. This study does not aim to define the different timber defects or establish timber defect classifications. This study is focus on establish a methodology to define the timber quality based on the effects that the different defects have when the stem is cut in different timber products.

The main stem is the most useful part of a tree for conventional wood products such as roundwood, pulpwood, posts, poles, and lumber. Defects reduce the total volume of usable wood in the tree. Defects that reduce the total volume of usable wood in the tree include sweep, crook, cracks, decay, forks, and imbedded objects (Figure 9).

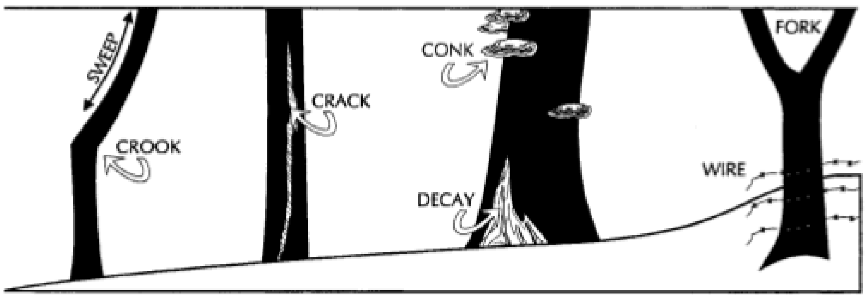

Figure 9: Standing timber defects

The stem defects are potential indicators of the timber quality, however these can have different impact in the in the final timber product, depending on how there are cut. Standing timber defects cannot be considered as stand alone features, without take in account the impact of these features in the final timber products.

Treemetrics has developed a system to define and characterize the stems defects, including shape defects and other potential timber quality features. A special case is the sweep and straightness that is automatically estimated by the system. The other defects need to be defined in the Treemetrics Forest ™ app, as explained in the section 5.2.

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[1] Partridge et al. 1995 http://www.fs.fed.us/fmsc/ftp/measure/cruising/other/docs/defect.pdf
Campeter et al. 1989
http://www2.ca.uky.edu/forestry/for250/Defects%20in%20Hardwood%20Timber_Handbook%20678.pdf
Campeter et al. 1963
http://naldc.nal.usda.gov/naldc/download.xhtml?id=CAT87209089&content=PDF

5.1.1 Sweep and crookedness

As explained in the section before, the stem profile created from the TLS analysis contains the information to determine the Sweep and the Lean of the tree stem. The system does not estimate the full stem length sweep or lean, however the lean is estimated in the harvesting simulator for each timber log.

The system applies quality criteria to the timber logs regarding straightness. If the log does not meet the quality requirements, this will be classified as a product with less restrictive criteria or as waste when the log is not meeting any product requirement.

Following these criteria, the "crooked" area in the tree stem will be excluded in the products and classify as waste.

Summarizing the tree sweep is implicit in the tree profile and is not required additional information from the field regarding "crooked" stem areas. The exception is the stem areas hidden to the TLS scan, such as in the top part of the stem. In these cases the defect need to be recorded in field as defined in the section 5.1.2.

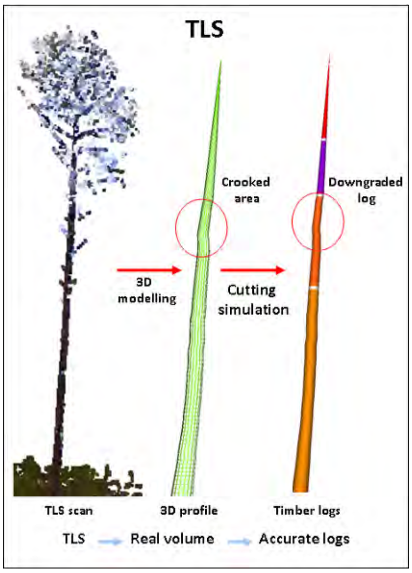

Figure 10: Automated detection of three defect based on Sweep

5.1.2 Other defects: Knots, Burl, scar defects, conk and similar.

The system defined in this document can record defects features for a defined section in the stem profile. These defects will be taken in account in the harvesting simulator according pre-defined rules for the different severity levels.

The type of defects and severity levels can be customized for each user in the current system. In addition the "rules" for each severity level need to be define in the harvesting processor. In this suited the following defects and severity has been defined:

- **Broken top**: the tree stem finished suddenly, usually due to storm damages. It is affecting the top part of the tree.
- **Defect grade 1** (Waste quality): This includes stem sections with severe timber defects due to scar damage, conk or similar. The severity grade 1 has been defined as non-commercial timber.
- **Defect grade 2** (Plup quality): This includes stem sections with scar defects, cracks, decay, potentially hidden crooked areas or similar that prevents to create quality timber logs. The severity grade 2 has will reduce the timber log quality to an inferior product.
- **Dead tree:** Sanding dead tree that will not be commercialized.

The defects and stem sections affected need to be defined in the Treemetrics Forest ™ app, as explained in the section 5.2.

5.2 Standing Timber Defects Measurement

Traditionally the forester will note the percentage of defect in each tree stem by product type. This measurement was based on a visual inspection in the field, resulting in different results for different foresters.

This percentage of defects is then deducted from the overall estimate of tree volume. However, because tree diameter decreases with increasing height in the tree, a defect occurring near the top of the tree will require a smaller percentage volume deduction than a similarly occurring defect near the base.

Due to this fact and the lack of information in the potential timber products, it is very difficult to get the exact percentage of timber that is affected by the defect.

The proposed system includes an objective measurement and analysis of the timber defects to overcome these issues.

These can be defined in the field by using Treemetrics Forest™ app. This application provides a system where the field operator can record the tree position (angle and distance to the centre of the plot) and measurements (DBH and height) for each tree. In addition, the application supports the definition of features that may downgrade the timber quality.

Each feature is defined by the section of the tree stem affected (minimum height and maximum height) and a flag that will define the type of feature (e.g. type of defect).

For each tree the field operator can define which sections of the trees are affected by a specific defect. Figure 10 shows an screenshot where the user has defined a stem section with severe damage, applicable from 17.5 m to 20.1 m height. In this section will be considered as defect with severity Grade 1 (waste).

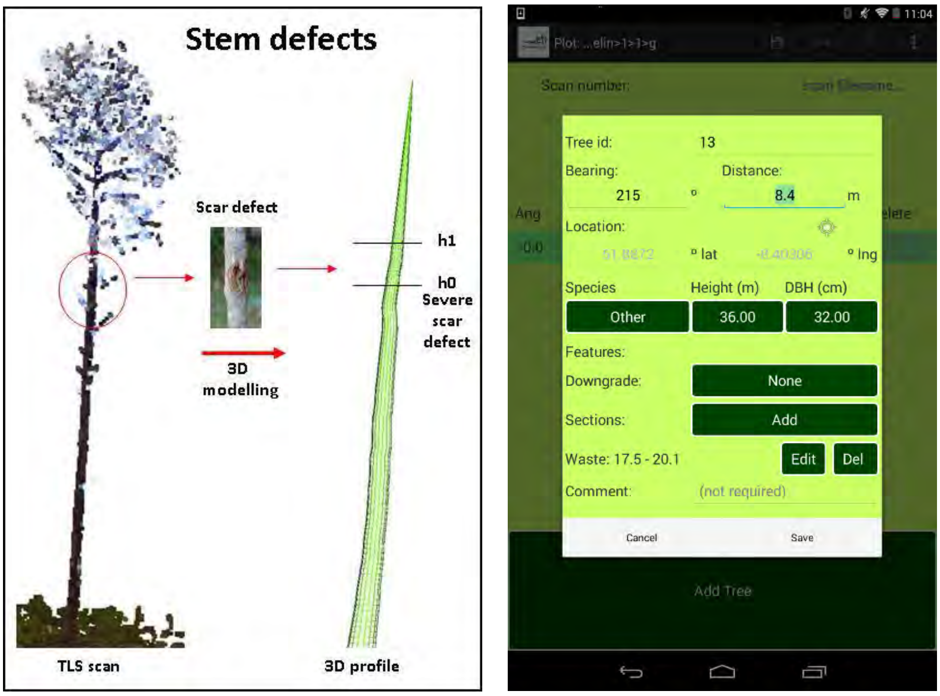

Figure 11: Treemetrics field app defect definition.

6 Timber log quality parameters

6.1 Log quality specifications

The logging operations can be carried out by different methods, cutting the whole tree or cutting the tree in smaller timber pieces Cut-to-length (CTL).

CTL logging is the process of felling, delimbing, bucking and sorting (pulpwood, sawlog, etc.) at the stump area, leaving limbs and tops in the forest. Harvesters fell the tree, delimb and buck it, and place the resulting logs in bunks to be brought to the landing by a skidder or forwarder.

Harvesters are highly computerized to optimize cutting length, control harvest and utilize price list for each specific logs to archive most economical results during harvesting.

The definition of the specific logs used during the harvesting are defined in order to meet the wood processing industry requirements. The main indicators to define a log are defined in Figure 11.

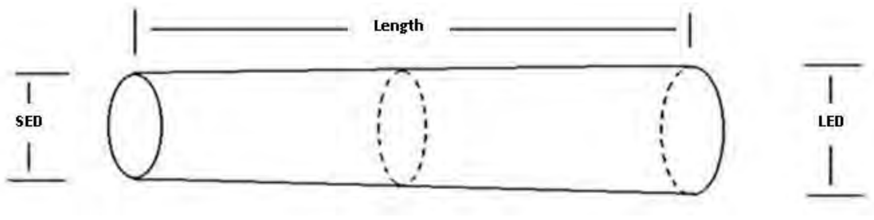

Figure 12: Log description

- Length: Targeted length of the log.
- Minimum Small End Diameter (Min SED) and Maximum Small End Diameter (Max SED): These parameters define the diameter allowed in the log's smaller section.
- Minimum Large End Diameter (Min LED) and Maximum Small End Diameter (Max LED): These parameters define the diameter allowed in the log's larger section.
- Straightness: Maximum deviation at any point of a straight line joining centres at each end of the log from the actual centre line of the log (cm/m)
- Additional quality indicators: such as knots, scar damage, etc.

6.1.1 Timber Size and Tree Profile

The log size is the most common quality parameter. This is defined by the (1) log length, (2) SED and (3) LED.

The size of the log is important in order to determine the type of industrial transformation. This is also the main parameter to determine the log price.

6.1.2 Straightness

To log straightness can be defined as "*bow not to exceed 1 cm for every 1 m length and this in one plane and one direction only. Bow (d) is measured as the maximum deviation at any point of a straight line joining centres at each end of the log from the actual centre line of the log*" [2]. An example of various bows of logs is presented in Figure 13.

Figure 13: Log leaning

Figure 14: 1-straight log; 2- maximum deviation (d) does not exceed 1 cm over 1 m; 3 - maximum deviation (d) exceeds 1 cm over 1 m; 4 - bow in more than one direction.

The bow of the log is calculated automatically by the harvesting simulator software. For each stem disc, the value of lean is calculated based on the x,y,z coordinates of the neighbours discs. The differential of each disc lean allows the system to calculate the total timber log bow or lean.

The straightness restrictions defined by the user will be applied to the log lean, ensuring that each log product meets the log quality criteria.

6.1.3 Log defects

Different quality criteria on the log products can be based on the defects features recorded in the field, such as presence of scar damage, broken top, etc.

Usually the log product will be devalued if effects are encountered. It can means that the a log can become a lower value product, but also that the log specifications need to change if a defect is found. That is to say that for section of the tree suitable for LOG 1

[2] Field Book 9 Classification and presentation of softwood sawlogs. Forestry Commission, 1993.

(see Table 6-1), if a defect is found the section of the tree need to be cut according new logs specifications, per example type of LOG 5.

6.2 SLOPE Logs Specifications

The harvesting simulator allows customized log products. In order to simplify the analysis process, regarding the Slope project, a set of default log products have been defined. These log products are based in the industry standards within the Slope project scope.

A Log Product is defined by it's:

- productName
- length (m)
- minimum small-end diameter, minSed (mm)

It may also specify the following options:

- maximum small-end diameter, maxSed (mm)
- maximum large-end diameter, minLed (mm)
- maximum large-end diameter, maxLed (mm)
- maximum allowable sweep, sweepConfig i.e. mm deflection per meter length
    - o sweepType:'FIXED' => sweepValue: absolute value (mm)
    - o sweepType:'FRACTIONAL' => sweepValue: reciprocal of the permitted fraction of SED
- list of allowable species

Errore. L'origine riferimento non è stata trovata. shows the definition of the log products defined for Slope project. Blank entries means that constraint does not apply.

Table 6-1: Log Constraints for Slope project for Species 1

Log ID/name	LOG1	LOG2	LOG3	LOG4	LOG5	LOG6
Length	4m	4m	5m	2.5m	4.8m	2.5
Min SED	20cm	40cm	40cm	20cm	20cm	40cm
Straightness						
Quality restrictions	No Defect	No Defect	No Defect	Defect grade 1	Defect grade 1	Defect grade 2

7 Harvesting simulation

Treemetrics has developed customizable harvesting simulator software that takes in account the log quality constraints described in section 6. This software is able to use the 3D models generated from the TLS, the log constraints and generates results according the user defined cutting instructions and quality rules.

7.1 Cutting Instructions

A Cutting Instruction is a collection of Log Products, weighted by priority (e.g. value). Treemetrics system needs a defined set of Cutting Instruction in order to run the cutting simulation. The cutting instruction needs to be defined by the user according the industry standards in his/her region.

The need to be provided to Treemetrics according the format defined in the example described in Appendix 11.2, this example inlcude 5 log products each with one or more SED class.

The Product Weighting ('weightInfo') specifies the priority of the log for the harvest optimizer. A log product can have a different weighting for different SED classes. Therefore, a 4m log with SED 200mm can be prioritised over a 4m log with SED of only 160mm buy giving the 20cm SED class a larger weighting.

The 'sedClassValues' element is an array of diameter (in mm) weight pairs. e.g. [[160, 300],[200, 500]] specifies that logs with SED of 160 - 200 mm have a weighting of 300, while those with SED of 200 mm or greater have a weighting of 500. Obviously, the SED classes must not begin at the minSed.

For the SLOPE project 3 cutting instructions will be used. For each cutting instruction Treemetrics will run the cutting simulation and the optimal cutting instruction will then be chosen based on the results (most valuable option). The 3 cutting instructions used have been provided by CNR, according the Italian timber industry standard.

7.2 Products assortment

Given a set of log products different combination can been extracted from a specific stem. Each of these combinations is defined as stem **assortment.**

Due to the different possible assortments some priority rules need to be added to the harvesting simulator (as the harvesting machine does). These rules are based in weight each product with a priority. The given a set of log products and weights for each product is known as Cutting Instructions.

An example is described inFigure 15. In this case for the same stem it is possible to cut a log product P3 or two log product P2. If the system decide to cut the option 2 the waste will increase but if P3 may be more valuable than two P2.

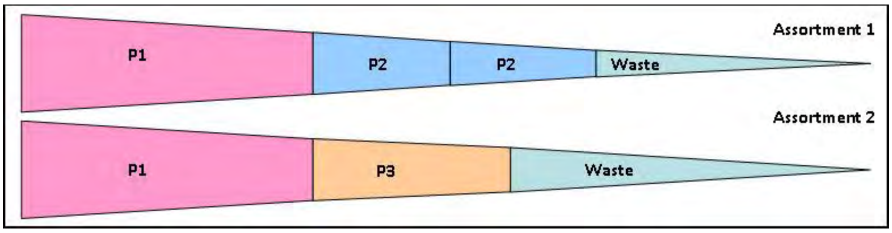

Figure 15: Different assortments of a stem

A simple way to understand the product weight is to compare it the product value. If the target is maximising the value, according with the weight (value) show in Table 2, the harvesting simulator will chose the option 2.

Table 2: Log weight example

	Assortment 1			Assortment 2		
Product	Volume	Value	Total Value	Volume	Value	Total Value
P1	0.5 m^3	36 €/ha	18 €	0.5 m^3	36 €/ha	18 €
P2	(0.25 x 2) m^3	10 €/ha	5 €	-	-	-
P3	-	-	-	0.3 m^3	30 €/ha	9 €
Total	1 m^3		23 €	0.8 m^3		27 €

7.3 Cutting Quality Rules

Automatically obtained attributes would include straightness, a diameter for each decimetre (for testing SED, LED), fork, ramicorn, spike and some other branch information (this varies depending on the species and stocking density).

7.3.1 Straightness in the logs creation

If a log product passes the basic constraint criteria (length, min SED, max SED, min LED, max LED, species) then that log is tested to see if it passes the quality constraints before it is accepted as a valid option and its value calculated. The most common quality constraint is straightness. The harvester driver uses judgement to try to predict if a log passes straightness criteria but the simulator applies the actual specifications to test if it is straight enough. It is calculated as follows. The x,y of the top and bottom disc of the log are use to calculate the straight line spine of the log. The perpendicular x and y distances for each disc of the log it calculated to this line. If either of these distances is greater than the threshold then the log is deemed to not be straight enough and rejected as an option for this section of tree.

7.3.2 Shape defects in the logs creation

The shape defects defined by the field operator are stored with the stem definition as explained in the next section. The processor designed for Slope project will apply the following rules in the harvesting simulator:

- **Broken top**: above the section defined as broken top the tapper equation will not be applied (Note that, as explained in previous section, the system tends to complete the tree top with the general taper equations, assuming that the lack of TLS data is due to an issue regarding the visibility in the crown)
- **Defect type 1** (Waste quality): the section of the stem defined as " Defect type 1" will be considered as waste, therefore not included in the products assortment . Note this will be include for the "profitability index".
- **Defect type 2** (Pulp quality): the section of the stem defined as " Defect type 2" will be considered as pulp product. Note that for this product does not apply restrictions of length nor log sweep.
- **Dead tree:** This tree will not be cut. (Neither included in the inventory results).

7.4 Logs creation based on cutting instructions and Cutting Quality Rules.

Given a set of log products the harvest simulator (as the harvesting machine does) needs a weighting for each product. This is how the more valuable logs are prioritised. The basic log constraints of length, min SED, max SED, min LED, max LED and species are common to both the harvest machine bucking software and the Treemetrics harvesting simulator. With only these constraints used the harvesting machine and simulator will give the same results. The machine driver uses his eye to try and apply the other constraints. For example the driver judges the straightness of each log and decides if it meets the constraint or not. In the case of constraints that he cannot judge, a forester would have marked the trees that pass those constraints. For example the forester could have used acoustic methods to estimate the stiffness of the trees in an area and marked the ones that are suitable for a particular log product. The simulator has these attributes already implemented, so it can apply them directly to the simulation. The advantage of this is that the user can find the forests that best meet their log product specifications. This would make finding forests suitable for unusual log products much easier.

As with the harvesting machine the simulator works as follows. It computes all the log combinations that can be cut for the next 3 logs of the tree. A log product can be cut if the entire decimetre disk on that section of the tree passes the constraints of that log product.

An example is shown in Table 7-3. This table shows the same 6 log products from **Errore. L'origine riferimento non è stata trovata.**. For this section of the tree (3.4m), LOG1, LOG2 and LOG3 could be cut but LOG4, LOG5, LOG6 fail when apply the min SED test (the min SED failed already at 3.3m). While the LOG1 and LOG2 passed the constraints LOG3 log was chosen because its volume multiplied by the user defined weight gave the highest value.

Table 7-3: Sample stem cutting.

	Log ID/ name	LOG1	LOG2	LOG3	LOG4	LOG5	LOG6
Disk No	Diameter	Weighting	Weighting	Weighting	Weighting	Weighting	Weighting
		100	300	350	500	00	550
34	15.6	pass	pass	pass	fail	fail	fail
33	15.8	pass	pass	pass	fail	fail	fail
32	16.0	pass	pass	pass	pass	pass	pass
31	16.2	pass	pass	pass	pass	pass	pass
30	16.4	pass	pass	pass	pass	pass	pass
29	16.6	pass	pass	pass	pass	pass	pass
28	16.8	pass	pass	pass	pass	pass	pass
27	17.0	pass	pass	pass	pass	pass	pass
26	17.1	pass	pass	pass	pass	pass	pass
25	17.2	pass	pass	pass	pass	pass	pass
24	17.3	pass	pass	pass	pass	pass	pass
23	17.4	pass	pass	pass	pass	pass	pass
22	17.5	pass	pass	pass	pass	pass	pass
21	17.6	pass	pass	pass	pass	pass	pass
20	17.7	pass	pass	pass	pass	pass	pass
19	17.8	pass	pass	pass	pass	pass	pass
18	17.9	pass	pass	pass	pass	pass	pass
17	18.0	pass	pass	pass	pass	pass	pass
16	18.1	pass	pass	pass	pass	pass	pass
15	18.2	pass	pass	pass	pass	pass	pass
14	18.2	pass	pass	pass	pass	pass	pass
13	18.3	pass	pass	pass	pass	pass	pass
12	18.3	pass	pass	pass	pass	pass	pass
11	18.4	pass	pass	pass	pass	pass	pass
10	18.4	pass	pass	pass	pass	pass	pass
9	18.5	pass	pass	pass	pass	pass	pass
8	18.5	pass	pass	pass	pass	pass	pass
7	18.6	pass	pass	pass	pass	pass	pass
6	18.6	pass	pass	pass	pass	pass	pass
5	18.7	pass	pass	pass	pass	pass	pass
4	18.7	pass	pass	pass	pass	pass	pass
3	18.8	pass	pass	pass	pass	pass	pass
2	18.8	pass	pass	pass	pass	pass	pass
1	18.8	pass	pass	pass	pass	pass	pass

This example was simplified down to the next log to be cut for illustration purposes only. The real simulator (and harvesting machine) takes the next three logs into account, including the ability to add in a waste log at any given point on the tree and for any given length.

The waste log has a value of zero but the sum total of all the log values with waste logs often is more valuable than what can be cut without a waste log. So cutting waste is often the optimal thing to do. The second stem in Figure 16 illustrates where this might occur. It has 1m of crooked stem and 5m of straight stem. If no waste was cut a 3m pulp log would be cut from the base of that stem, which would only leave 3m of room above it so another 3m pulp would be cut. If 1m waste was cut there would be 5m of straight stem left which would fit a valuable 4.9m sawlog. The value of the 4.9m sawlog plus 1m waste at the bottom and 0.1m waste at the top would be worth 4.9*500 =2450. The two pulp logs would be worth 2 *(3*100) = 600. Both values represent the importance, according with the user weight specifications. Because the user has decided that is preferable 4.9 m logs instead of 3m logs in ration 500:100, in this example the system will prioritize the 4.9m log (importance ratio of 2450) against the 3m log (importance ratio of 600), as result cutting waste has greatly increased the overall value of the stem. Different user settings may prioritize the reduction of timber waste buy changing the weight parameters.

7.4.1 Use of straightness in the logs creation

If a log product passes the basic constraint criteria (length, min SED, max SED, min LED, max LED, species) then that log is tested to see if it passes the quality constraints before it is accepted as a valid option and its value calculated. The most common quality constraint is straightness. The harvester driver uses judgement to try to predict if a log passes straightness criteria but the simulator applies the actual specifications to test if it is straight enough. It is calculated as follows. The x,y of the top and bottom disk of the log are use to calculate the straight line spine of the log. The perpendicular x and y distances for each disk of the log it calculated to this line. If either of these distances is greater than the threshold then the log is deemed to not be straight enough and rejected as an option for this section of tree.

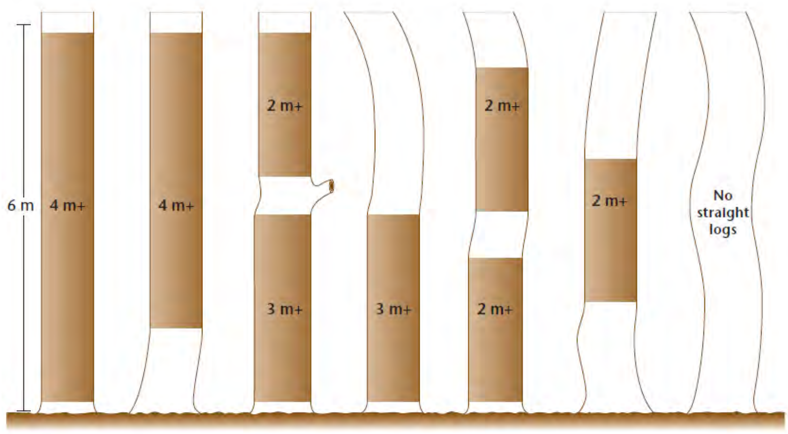

Figure 16: Sample Simulation Stems

7.4.2 Use of damage and punctual defects

As outlined in section 3.1 extra tree attributes can be added from field data or from TLS data. Some of these attributes affect the whole tree and rule out log products with related constraints. An example of this would be is the tree is dead. Others are calculated per disk based on the recorded attribute. For example the field recorded attribute might be *butt rot* on the first 3 m of the tree. Each decimetre disk for the first 3m of the tree is given this attribute and is the log quality constraints do not allow *butt rot* then these disk will not be allowed to be cut into those log products. Scars, forks, large branches etc can be treated in the same way when they have a start and end height. The 3rd tree in Figure 16 shows an example of what would happen with a large branch.

8 Product quality indexes

8.1 Waste Ratio

The waster ratio (WR) is the defined as the ratio between the waste and the sum on the other products in the tree.

$$WR = \frac{w}{\sum_{i=1}^{i=n} v_i + w}$$

v_i = volume of the products
w = waste volume

8.2 Product ratio

The products valuable ratio (PR) is the defined as the ratio between of the most valuable product and the other product in the tree, excluding waste.

$$PR = \frac{v_n}{\sum_{i=1}^{i=n} v_i}$$

v_i = volume of each product
v_n = volume of the most valuable product

8.3 Total profitability index

The total profitability index (TPI) is the defined as the ratio between the actual value of the product in the stand and the maximum potential value, assuming that all products are transformed to the most valuable product, including the waste.

$$TPI = \frac{\text{Total value}}{\text{Maximum potential value}}$$

This can be calculated using the VI and SPI, defined in the previous sections, as following:

$$TPI = PR \cdot (1 - WR) \cdot K$$

Where K is the ratio between the average product value and the highest product value:

$$K = \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{p_n \cdot v_n}$$

The total profitability index takes into account the highest value product and the amount of waste. When there is not waste (WR=0) TPI tends to 1 by a coefficient (K) that represents the ratio with others products. When the waste is high (WR near to 1) or the valuable products are low (PR near to 0), the TPI tends to 0.

A TPI equal or above 0.5 should be considered a good stand with and significant amount of valuable products.

8.3.1 Mathematical development

The total profitability index can be expressed in with a basic relationship between the PVI and SPI defined in the previous sections. The mathematical rational is the following:

$$TPI = \frac{\text{Total value}}{\text{Maximum potential value}}$$

Where:

$$\text{Total value} = \sum_{i=1}^{i=n} p_i \cdot v_i$$

$$\text{Maximum potential value} = p_n \cdot \left(\sum_{i=1}^{i=n} v_i + w\right)$$

p_i = price for each product
v_i = volume of each product
w = waste volume (it is assumed that waste has value of 0)
n = number of products (without include waste)
p_n= price of the most valuable product
v_n = volume of the most valuable product

According to this:

$$TPI = \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{p_n \cdot \left(\sum_{i=1}^{i=n} v_i + w\right)}$$

From the index described above we know that:

$$\sum_{i=1}^{i=n} v_i = \frac{v_n}{PR} \text{ and } w = \frac{WR \cdot \sum_{i=1}^{i=n} v_i}{(1-WR)}$$

Substituting in the TPI formula:

$$TPI = \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{p_n \cdot \left(\frac{v_n}{PR} + \frac{WR \cdot \frac{v_n}{PR}}{(1-SPI)} \right)} = \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{\frac{p_n \cdot v_n}{PVR} \cdot \left(1 + \frac{WR}{(1-WR)} \right)} = \frac{PR}{\left(\frac{1}{1-SWR} \right)} \cdot \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{p_n \cdot v_n}$$

for $K = \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{p_n \cdot v_n}$,

$$TPI = PVI \cdot (1-SPI) \cdot K$$

8.4 Modified Total profitability index

When the prices are not available the Modified Total Profitability index (MTPI) can be used this assume some basic assumptions about the products pricing.

$$MTPI = PVR \cdot (1-WR) \cdot K^{'}$$

Where K' is the modified profitability constant (K) assuming that the price of the highest volume is the double that the average price of the others products. As result the this assumption we can set the MTPI as following:

$$MTPI = (1-WR) \cdot (0.5 + PR)$$

The total profitability index takes into account the highest value product and the amount of waste. When there is not waste (WR=0) TPI tends to the PR value plus 0.5. When the waste is high (WR near to 1) the MTPI tends to 0, when the valuable products are low (PR near to 0), the MTPI tends to the half of the WR minus 0.5.

A MTPI equal or above 0.5 should be considered a good stand with and significant amount of valuable products.

8.4.1 Mathematical development

$$MTPI = PR \cdot (1-WR) \cdot K$$

Where K' is the modified profitability constant (K) assuming that the price of the highest volume is the double that the average price of the others products, and that other products are equally distributed.

$$K = \frac{\sum_{i=1}^{i=n} p_i \cdot v_i}{p_n \cdot v_n} = \frac{\sum_{i=1}^{i=n-1} p_i \cdot v_i}{p_n \cdot v_n} + 1 = \frac{p \sum_{i=1}^{i=n-1} v_i}{2p \cdot v_n} + 1 = \frac{\frac{v_n}{PR}}{2 \cdot v_n} + 1 = \frac{1}{2 \cdot PR} + 1$$

According to this:

$$MTPI = PR \cdot (1 - WR) \cdot \frac{1}{2 \cdot PR} + 1 = (1 - WR) \cdot (0.5 + PR)$$

9 Stand quality classification

The product quality indexes described above can be applied to each tree measured with TLS or by using the total timber products within a stand.

The forest stand can then be classified according the quality index. The following classification will be used in the SLOPE project:

Table 4: Quality classes

Quality index (MTPI)	Quality class	Description
1+	1	Very high quality
0.5-1	2	High quality
0.3-0.5	3	Regular quality
0-0.3	4	Low quality
0	5	Very low quality

The different quality classes will be delivered for each stand according the format descried in section **Errore. L'origine riferimento non è stata trovata.**.

10 Conclusion and recommendations

The main conclusions about cutting simulation and quality indexes are the following:

- The basic indicators to define the log can be easily measured using the stem 3D model created using TLS data.
- The trees defects will be recoded by the field app. (except straightens).
- The defects recorded in the field app. will be taken into account by the harvest simulation to apply a product downgrading according the defect severity.
- The following quality indexes have been defined: (1) Waste ratio, (2) Products ratio, (3) Total profitability index, (4) Modified Total profitability index and (5) Harvesting loss risk

The harvest simulation is a good tool to estimate the optimal way of cutting the forest and support harvest operations in the field.

11 Appendix

11.1 Stem format (json)

{"stemHeight": 26.2,
"stemName": "70",
"stemSpecies": "NS",
"stemFormSetting": {
"source": "scanner",
"FromScan": "Slope_004",
"filterType": "i",
"filterValue": 80.0,
"taperType": "VFFdh NS",
"stumpHeight": 0.2,
"totalHeight": 26.4,
"taperHeight": 4.3,
"topDiamLowerBound": 0.0,
"heightType": "Manual",
"taperCo": {
"Coeffs": [0.316, 1.16, -6.97, -0.00448]
},
"heightCo": {
"Coeffs": [0.0, 0.0]
}
},
"features": {
"type": "GRADE",
"value": 0},
{"type": "SECTION",
"value": 12,
"endHeight": 7.2,
"srtHeight": 5.4}
},
"stemLocation": {
"proj": "WGS84",
"EPSG": 4326,
"coords": [
11.333271,
46.24455
]
},
"stemReadings": [
{
"diameter": 575.497,
"xCoord": 0.0,
"yCoord": 0.0,
"zCoord": -7249.0
},
....
],

"profileReadings": [
{
"diskNo": 0,
"diameter": 0.536816000000000007,
"xCoord": 13.677,
"yCoord": -0.636,
"zCoord": -7.249,
"reliability": 0.52296
},
]
}

11.2 Cutting instructions format (json)


```
{
 "name":"529f4d6e344ea91de10000f1",
 "instructionInfoItems":[
  {
   "logProduct":{
    "productName":"529f303b344ea91de100008d",
    "length":3.1,
    "minSed":120.0,
    "maxLed":240.0,
    "restrictedSpecies":[
     "NS"
    ],
    "sweepConfig":{
     "sweepType":"FIXED",
     "sweepValue":20.0
    },
    "logType":0
   },
   "weightInfo":{
    "weightingType":"SED_CLASS",
    "sedClassValues":[
     [
      120.0,
      325.0
     ],
     [
      160.0,
      440.0
     ]
    ]
   }
  },
  {
   "logProduct":{
    "productName":"529f2e78344ea91de1000040",
    "length":3.1,
    "minSed":140.0,
    "maxLed":240.0,
    "restrictedSpecies":[
     "SP"
    ],
    "sweepConfig":{
     "sweepType":"FIXED",
     "sweepValue":20.0
    },
    "logType":0
   },
   "weightInfo":{
    "weightingType":"SED_CLASS",
    "sedClassValues":[
     [
```

```
        140.0,
        305.0
       ],
       [
        160.0,
        400.0
       ]
     ]
   }
 },
 {
   "logProduct":{
     "productName":"529f2ddf344ea91de1000032",
     "length":4.9,
     "minSed":140.0,
     "maxLed":600.0,
     "restrictedSpecies":[
       "SP"
     ],
     "sweepConfig":{
       "sweepType":"FIXED",
       "sweepValue":10.0
     },
     "logType":0
   },
   "weightInfo":{
     "weightingType":"SED_CLASS",
     "sedClassValues":[
       [
        140.0,
        0.0
       ],
       [
        180.0,
        650.0
       ]
     ]
   }
 },
 {
   "logProduct":{
     "productName":"529f2f83344ea91de1000071",
     "length":4.9,
     "minSed":160.0,
     "maxLed":750.0,
     "restrictedSpecies":[
       "NS"
     ],
     "sweepConfig":{
       "sweepType":"FIXED",
       "sweepValue":20.0
     },
     "logType":0
   },
```

```
      "weightInfo":{
        "weightingType":"SED_CLASS",
        "sedClassValues":[
          [
            160.0,
            580.0
          ],
          [
            200.0,
            630.0
          ],
          [
            240.0,
            750.0
          ]
        ]
      }
    },
    {
      "logProduct":{
        "productName":"529f4dec344ea91de100192f",
        "length":3.0,
        "minSed":70.0,
        "sweepConfig":{
          "sweepType":"FIXED",
          "sweepValue":200.0
        },
        "logType":3
      },
      "weightInfo":{
        "weightingType":"SED_CLASS",
        "sedClassValues":[
          [
            70.0,
            250.0
          ]
        ]
      }
    }
  ]
}
```

11.3 Log product information format (json)


```
"stem_crosscut_solution":
[
 {
  "stem_profile_id": "556865d2344ea9a9e6000984",
  "stem_profile_rfid": "123456789abcdef123456789",
  "solution":
  [
   {
     "endIndex": 1,
     "sed": 245.952,
     "led": 249.544,
     "species": "SS",
     "volume": 0.004820954342316448,
     "logProductName": "waste",
     "startIndex": 0
   },
   {
     "endIndex": 32,
     "sed": 177.79,
     "led": 245.952,
     "species": "SS",
     "volume": 0.10259838630677454,
     "logProductName": "3.1m_package",
     "startIndex": 1
   },
   {
     "endIndex": 34,
     "sed": 175.248,
     "led": 177.79,
     "species": "SS",
     "volume": 0.004894564453381212,
     "logProductName": "waste",
     "startIndex": 32
   },
   {
     "endIndex": 65,
     "sed": 151.052,
     "led": 175.248,
     "species": "SS",
     "volume": 0.06401580734389904,
     "logProductName": "3.1m_package",
     "startIndex": 34
   },
   {
     "endIndex": 95,
     "sed": 106.845,
     "led": 151.052,
     "species": "SS",
     "volume": 0.04139576162945291,
     "logProductName": "3m_pulp",
```

```
      "startIndex": 65
    },
    {
      "endIndex": 125,
      "sed": 46.729,
      "led": 106.845,
      "species": "SS",
      "volume": 0.014246913521660326,
      "logProductName": "3m_pulp",
      "startIndex": 95
    },
    {
      "endIndex": 142,
      "sed": 12.586,
      "led": 46.729,
      "species": "SS",
      "volume": 0.001516704940665109,
      "logProductName": "waste",
      "startIndex": 125
    }
   ]
  }
]
```