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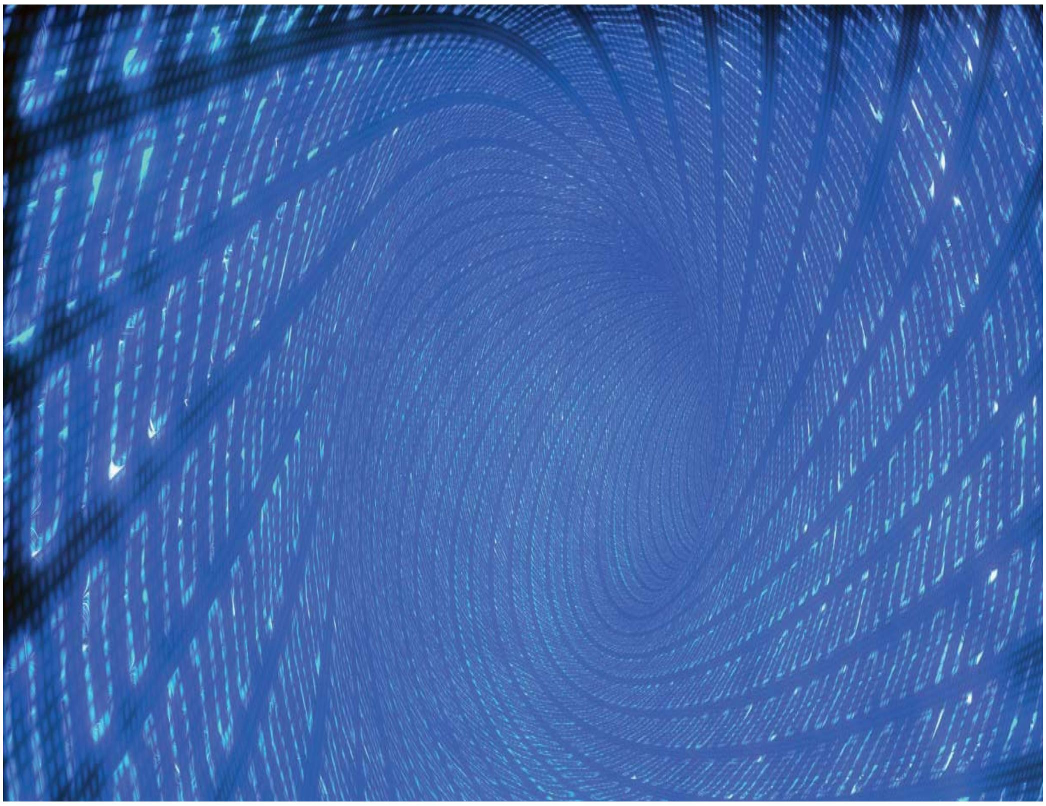

Project no: 34732

D3.2 Existing models and model gap analyses for wood properties

Responsible: Jean-Denis Lanvin & Fahrudin Bajric, FCBA, France
Participants: Lars Wilhelmsson, Lennart Moberg, John Arlinger, Johan Möller, Skogforsk, Sweden, Jan Bramming, NTI,Norway, Urban Nordmark, Sveaskog, Sweden

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Existing models and model gap analyses for wood properties

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Following companies and contact persons are involved in INDISPUTABLE KEY:
• SP Technical Research Institute of Sweden (SP), Co-ordinator, Dr. Richard Uusijärvi
• Kungliga Tekniska Högskolan (KTH), Prof. Jan Wikander
• CIRIS Engineering (CIRIS), Mr. Christophe Augerias
• Institut Technologique FCBA (FCBA), Mr. Robert Golja
• IVL Swedish Environmental Research Institute (IVL), Mrs. Åsa Nilsson
• Technical Research Centre of Finland (VTT), Dr. Kaj Nummila
• TietoEnator Forest & Energy Oy (TietoEnator), Mr. Jari Mäkipää
• Confidex Ltd (Confidex), Mr. Matti Ritamäki
• Idesco Oy (Idesco), Mrs. Anu-Leena Arola
• Tampere University of Technology (TampUnit), Dr. Kari Kolppo
• Lappeenranta University of Technology (LappUnit), Prof. Timo Kärki
• Tallinn University of Technology (TallUnit), Prof. Mart Tamre
• Oskando OÜ (Oskando), Mr. Kalle Tiisma
• AS Hekotek (Hekotek), Mr. Avo Raigla
• Skog-Data AS (Skog-Data), Mr. Bjørn Karsten Olsen
• Norwegian Forest and Landscape Institute (NFLI), Mr. Erlend Ystrøm Haartveit
• Norsk Treteknisk Institutt (NTI), Mr. Audun Øvrum
• Forestry Research Institute of Sweden (Skogforsk), PhD. Lars Wilhelmsson
• Sveaskog Förvaltnings AB (Sveaskog), Dr. Urban Nordmark
• Scierie Ducerf (Ducerf), Mrs. Nathalie Bonin
• Raunion Saha Oy (Raunion), Msc. Olli Raunio
• Eidskog-Stangeskovene AS (ESAS), Mr. Leif Arve Ulfsbøl
• ScanPole AS (ScanPole), Mr. Stian Skarpnord
• Etablissements Pierre Mauchamp S.A (MAUCHAMP), Pierre Mauchamp
• SETRA Group (SETRA), Mr. Rickard Westerberg
• Rolpin (Rolpin), Mr. Emmanuel Pawliez
• Rottne Industri AB (Rottne), Mr. Roland Axelsson

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1 Summary

This document gives an overview of models estimating or predicting log properties judged, from the expert's point of view, to be of relevance for efficiency in wood manufacturing processes and/or the quality of final products. It starts with a general presentation of the perspectives of models in the context of the Indisputable Key (IK) project. It also comprises an overview of systems aimed to facilitate the conversion from stems in the forest to wood components aimed for different end-products. The possibilities to apply harvester measurements and model predictions for enrichment of adapted raw material from forestry, and integration with modern scanning techniques (3D, X-ray, surface images etc) at sawmills and further ahead in the supply chains are discussed briefly. A detailed documentation of models applicable in forestry systems for characterising logs and stems at planning and harvesting is given in an appendix. The perspectives to use models in forestry and sawmill processes have been concentrated to the context of the six case studies in the project (chapters 7.1-7.6 in deliverable D3.1 Initial analysis of drivers and barriers). There are numerous models, relevant for the business cases. Many of these can already be operationally used (chapter 4) based on standardised (StanForD) harvester production files (pri=production files individual stems, including ordinary measurements from the harvester felling head) and commonly available data from forest stands such as tree (stand) ages and geographic coordinates. "Pri-analyses" is a tool that demonstrates the ability to predict log properties at harvesting. The same tool can be also used to simulate harvesting at the planning stage, improving selection of the most suitable stands and bucking options before harvesting.

The identified models are in at least one of the six IK case studies linked or closely related to the concerned production chains. In other words, these models state how the scientific work (published models) can be of use to the business cases involved in the project. The pertinence of different models are presented in tables 5, 6 and 7. In parallel the business case by identification of their practical needs provides the base for further scientific work and implementation. In such case, the difference between wood properties examined by the experts and those required by the business cases shows the gaps in knowledge. Another question to investigate is at what degree the latter is expected to be satisfied by the traceability tool which brings new and additional information on the wood raw material through the wood supply chain. The IK traceability system may also provide efficient possibilities for further validation and development of existing models and evaluation of their economic and environmental impact in different value chains, like the examples given by the IK case studies.
An IAD-system makes individual traceability possible. This can be used to establish improved interrelationships between the information presented after a logging operation and the measurements performed on logs, boards and components at sawmills/wood industries. Here backtracking of the final results may be analysed including relationships within the chain of measurements by processing simulation on virtual logs, multivariate statistical analyses, training of neural networks etc.

2 Introduction

For sawmills that produce a wide range of products by orders from customers, which is typical for many European sawmills, getting the right product to the right customer in a timely manner is critical. However, a growing share of the sawmills are getting more and more specialized, producing specific products which are generally more demanding in terms of optimal log dimensions, while also additional properties, like knot properties, strength properties, durability, surface properties, aesthetic properties etc. may be of larger or smaller importance depending on the target products. Determining which logs to order and process, with which sawing patterns to achieve an optimal result is a demanding problem to solve. Add to this, the need to consider different log purchase options, market opportunities and production constraints, and it becomes obvious that making truly optimum operating decisions with conventional planning methods is impossible. Consequently there is a need for decisions support systems and technology that facilitates accessibility to decisive information. Furthermore, the best (optimal) solution must not be an enemy to the second best.

Within IK, models and/or systems of models characterizing wood properties are worth considering as long as they provide perspectives to increase economic (increased economic gain/product unit), environmental (e.g. decreased emissions/product unit) and/or energy productivity (decreased energy needed/product unit) of the value chains. The use of different models and model components has to be sorted out. For example when using statistical mixed models both fixed and random effects are included. Generally the fixed effects could be estimated at the individual log level, while prediction of random effects (e.g. "tree effects" = similarities within stems) could only be utilized to express the structure of expected variation at the population level. Consequently, if not detected by e.g. one per tree measurements, the random effects can only be used in simulations of the outcome from a pile of logs (population). Nevertheless the accuracy (bias) and precision (e.g. expressed as RMSE or prediction error) of the models and the value of this information will determine the suggested level of marking (individual level, sample of individuals, pile level, assortment level etc. See D3.1. Initial analysis of drivers and barriers, Figure 1; Table 4).

When producing lumber from a log the development of sawing strategies will be based on the following parameters:

- volume recovery i.e. the total volume or number of products that can be produced per unit of incoming raw material or intermediate product (e.g. logs of adapted length, diameter and/or other properties, sawn blanks for windows, floors etc.).
- value recovery per unit of products produced
- cost of complete deliverance of logs, stems or intermediate products i.e. wood supply
- cost of stock management at sawmill, measuring, sorting, feeding, production control, sawing, sorting, trimming, (before and/or after drying) drying, planing, quality control, packaging, labeling, storing and haulage to customer
- cost of marketing, selling and administrating business
- cost of inability or extraordinary expenses to fulfill customers orders - "just in time"

The best possible sawing strategy will then be based on:

- Maximum economic gain achieved by maximizing the sum of different product units multiplied by the value per unit, minus all costs.
- Lowest possible environmental load achieved by minimizing the load of CO_2, NOX etc. per unit of each product over a life cycle.
- Lowest possible energy needed per unit of product over a life cycle.

In a holistic perspective (WP3, task 3.6) an optimal solution will be based on balance between high economic gain, acceptable environmental load, and acceptable use of energy.

Maximizing board volume is not necessarily equivalent to maximizing board value in terms of end price. In this field, a better understanding of relationship between stand characteristics, silviculture treatment and product quality will lead to an improved utilization of an increasingly sought forest resource (Fig 1).

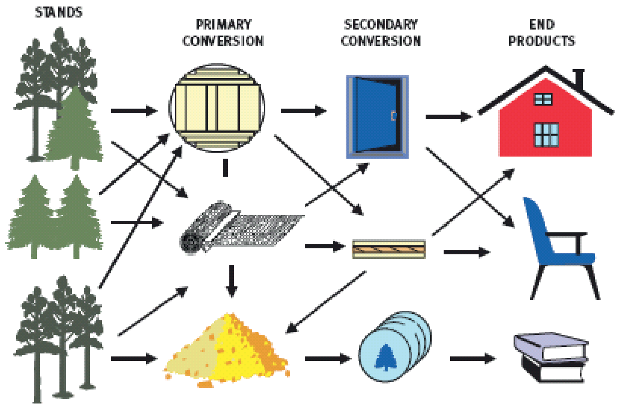

Figure 1. The phases in wood conversion chain are interacting to achieve maximum profitability. When using CTL-harvesters the primary conversion may start in the forest by selecting, bucking and sorting logs to fit desired combinations of lengths and diameters and suitable wood properties.

The use of models to enhance efficiency within value chains will be based on different complexity in calculation of gain. The relevance of different models will depend on the strategy for their deployment.

1. By keeping the properties and numbers of the end-product constant a simplified case, free from possible dynamic effects caused by changes in quality and/or quantity of products. In such a case the total production cost (from the total production chain) for a fixed number of products of a fixed quality should be minimized.
2. Adding a lifecycle perspective to this (in monetary terms by LCC, see D3.1 Initial analysis of drivers and barriers) also include differences in rates of depreciation and discounted costs of recycling. Similarly, environmental load and total energy consumed could be analyzed by Life Cycle Analysis.
3. To include the full span of progress possibilities of improving sawmill products also possible dynamic effects should be included. Examples of such effects may be:
   - increased product quality and value
   - changes in competitiveness
   - gaining market shares
   - substitution of non-wood materials
   - increased stringency in product definitions
   - increased ability to meet more advanced customers demands

Different kinds of “models” are available and published. In the context of IK it is of specific importance to distinguish between some different categories.

a. Models providing virtual logs including distributions of relevant properties, from pith outwards make it possible to simulate the outcome by different sawing patterns, products etc. When well adapted to the real stems in available forest resources such simulations will be able to reflect a realistic volume and value recovery at the population level. If the properties could be predicted with relevant accuracy and precision at the individual log level already at harvesting these kind of models might justify the use of unique ID:s on logs to keep track of the log information. When combined with tree growth models virtual stem structures may be simulated. The relevance of such models depends on the availability of necessary input data of high quality and the model precisions.

b. Models providing cross-section or log averages of relevant properties. These are useful for decisions concerning destination of logs into different assortments and customers. Such models are most suitable for bucking procedures at harvesting and may serve as input information and possible magnification of e.g. 3D-scanner information at a sawmill to improve the pre-sawing information. Cross-section averages could also be used as an input to construction of virtual logs in lines with (a) above.

c. Multi-regression models based on multivariate analyses providing complex statistical relationships between forest data, tree data, stems and log properties etc. and log grades, product recovery grades etc.

The accuracy and precision of the output information from the different kind of models will be strictly dependant of the quality of the input data. Furthermore, the need for one final product is not the same as for another one. In order to understand the benefit of one “model”, we should keep in mind the wood production chain as indicated below (Table 1) and clearly identify the difficulty to link all kind of input parameters to final products.

Table 1. Forest information (Forest & Trees), common procedures and typical products along the forest to final product chain

Forest	**Trees**	**Stems/ logs**	**Sawing**	**Materials**	**Final products / market**
Stand Rotation age Stocking Site fertility Climate Thinning Other …	Species Genotype Tree age Growth rate Position/height Diameter Branches (size, type, structure) Pruning	Selection Measuring Delimbing Bucking Sorting	Measuring Sorting Debarking Sawing pattern Sorting Drying Peeling	Lumber Components Veneer Fiber (chips) Dust	Building struct Windows Carpentries Decking Panels Furniture …

2.1 Objectives of the report

The objective of this report is to give an overview of models estimating or predicting log properties judged, from the experts’ point of view, to be of relevance for efficiency in wood manufacturing processes and/or for the quality of final products. The identified models are in at least one of the six IK case studies linked or closely related to the concerned production chains. In other words, these models state how the literature can be of use to the business partners of the project; similarly the identification of business practical needs provides a solid base for further scientific work. In such case, the identification of wood properties examined by the experts and those required by the business shows the gaps in knowledge that need to be over passed. These gaps in knowledge are expected to be, at least partially, satisfied by the traceability tool which brings new and additional information on the wood raw material through the wood supply chain.

The report is organised as follows. Chapter 3 *Description of models* gives an overview of existing systems and models aimed to predict wood properties, which are the most relevant for the business cases established in the IK project. Chapter 4 *Business cases and wood properties* provides the link with properties identified in the business cases. After an assessment of the knowledge gaps, which may be partially filled by the traceability tool, chapter 7 gives a conclusion, focusing on the limitations and the following needs of this work. In addition, an appendix is provided with technical details (parameters, etc.) of some models used in the report (Chapter 9).

3 Description of models

3.1 Model systems providing virtual logs

Below some existing model systems operating with virtual logs are described. Generally speaking, different sawing simulators are mimicking log conversion operations in a rather similar way. The modelling of virtual stems may, however, vary between dynamic growth simulators, empirical regression models or CT-scanner measurements. At the present stage, for use in operational logging, (generally the case in IK) comparatively simple and robust regression models (including mixed models) not dependant on non-gatherable input data will probably be preferred. However, this is to be proven by validation. Tree growth simulators may be preferred when extreme silviculture regimes should be modelled or future scenarios should be preformed.

3.1.1 Win-EPIFN©

In the recent past, INRA and ENGREF teams have jointly developed a simulation tool called Win-EPINFN© in order to assess the lumber quality of standing forest resources by using forest inventory data. The Win-EPINFN© software (primarily developed for use with Norway spruce plantations in north eastern of France) works in three steps, see Fig 2:

1. Modelling of the past growth of each individual tree (described by age, height and diameter at breast height) in order to know the stem shape, branch pattern and internal stem wood properties.
2. Simulation of stem conversion in log and boards with their respective properties such as ring width, wood density, number and characteristics of knots (KAR, …).
3. Simulation according to grading rules in order to provide a standard value for each product.

The needed models for the assessment of the wood quality are for:

- Stem reconstruction: height-age curves, stem taper, bark thickness, ring width profile.
- Crown characteristics: height of the first dead branch, height of the first living branch, height of the first living whorl.
- Branch pattern: number of branches per whorl, branch position within whorls, diameter of branches, insertion angle of branches, relative position of branches in whorl.
- Wood properties: wood density given by old SIMQUA software

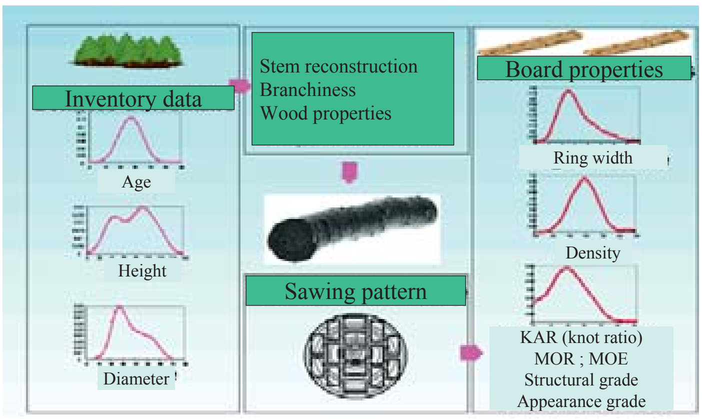

Figure 2. Illustration of components in Win-EPIFN©

3.1.2 Predicting lumber volume and grade recovery by log models and SAW2003

A system of models published by Moberg & Nordmark (2006) [Title: Predicting lumber volume and grade recovery for Scots pine stems using tree models and sawmill conversion simulation]. Through application of tree models, stem shape and internal knot structure of Scots pine stems could be predicted using site, stand, and tree variables. Stem shape was described by stem taper and cross-sectional eccentricity. Knot properties included were knot diameter, sound knot length, loose knot length, number of knots per whorl, and longitudinal inclination (Fig 3). This model system was then integrated in a sawmill conversion simulation system (Saw2003) in order to evaluate lumber recovery in terms of lumber dimension distribution, volume, grade, and value (Fig 4-6).

These applications showed that it was possible to predict the lumber grade recovery on the basis of stand and tree measurements. When comparing results of tree models against empirical data for 194 Scots pines from 33 stands in Sweden (604 logs), the volume recovery of side boards was overestimated with the modeling approach, but the volume recovery of center boards and the grade recovery showed good agreement. For both methods, the recovery of the strictest grade decreased slightly with increasing diameter at breast height class, but increased with increasing lumber dimension. The results of this study illustrate how the Saw2003 system can be applied to estimate the lumber volume and grade recovery of standing Scots pine trees. The system is described in flowchart in Moberg & Nordmark (2006) and model components are presented in chapter 9 *Appendix - description of models*.

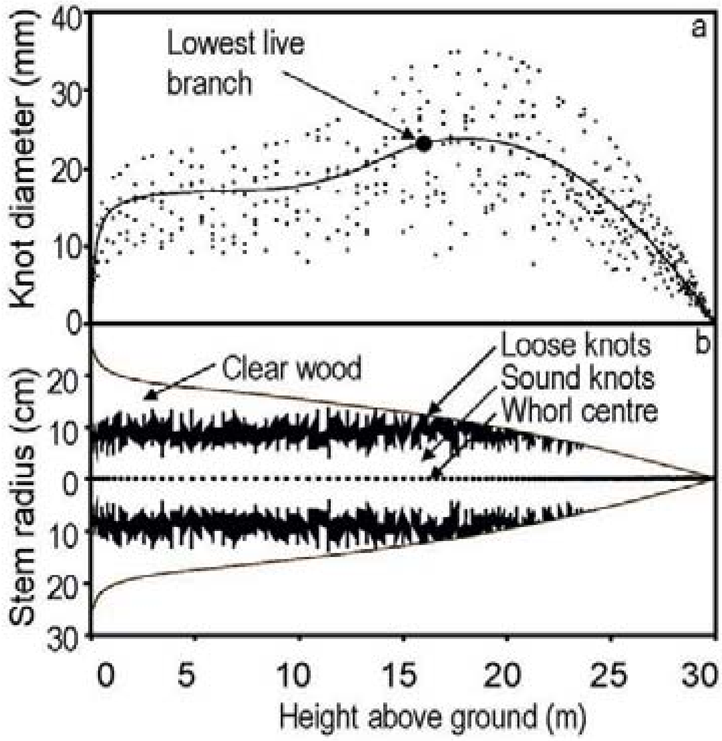

Figure 3. Illustration of simulated knot diameter, knot type, whorl location, and stem taper. (Moberg, 2000; Moberg & Nordmark 2006)

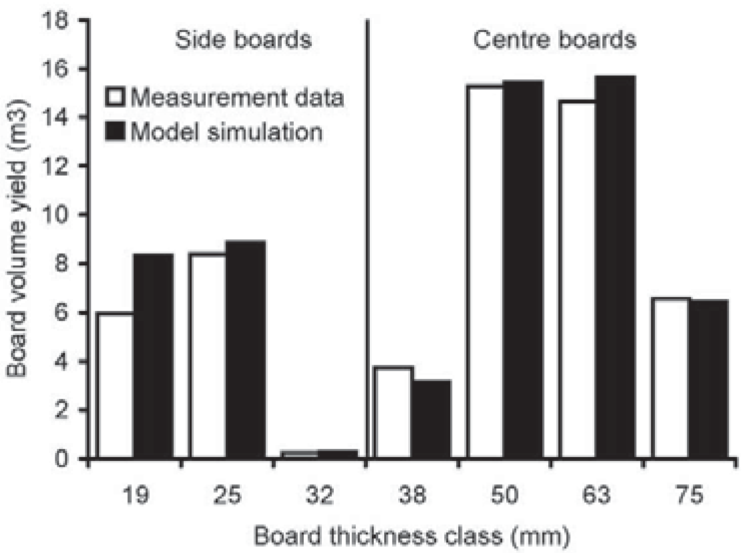

Figure 4. Lumber volume yield by board thickness class using tree model and empirical data respectively. (Moberg & Nordmark 2006). This information could be used by sawmills producing quality grades based on Nordic lumber rules (Anon. 1994) or adapted to similar kind of alternative customer specific or general grading systems.

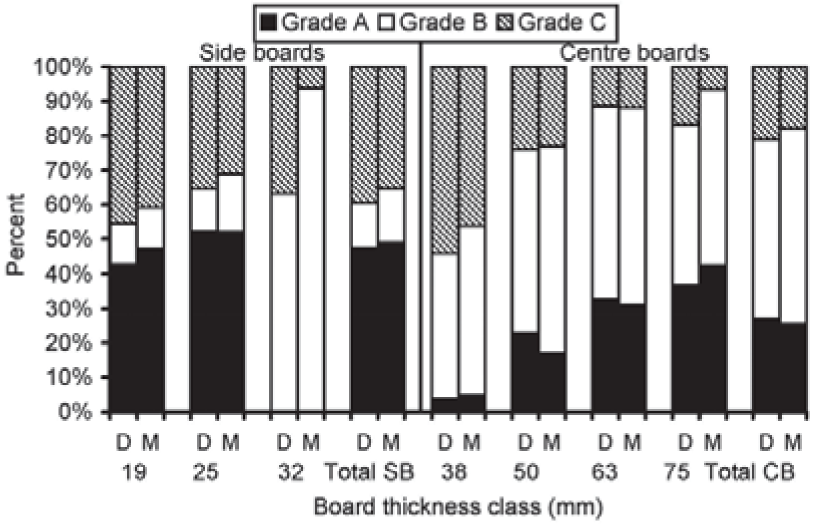

Figure 5. Lumber grade (in Nordic lumber rules) distribution by board thickness class using tree model (M) and empirical data (D). (Moberg & Nordmark 2006).

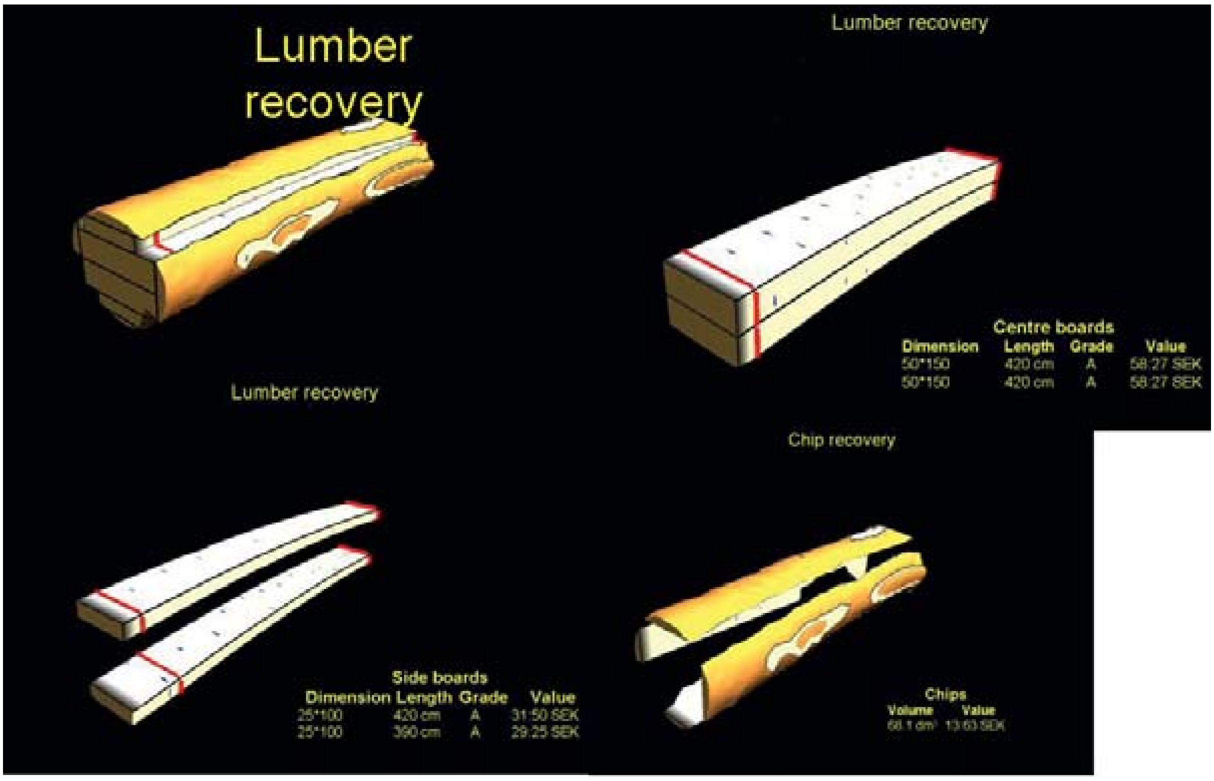

Figure 6. Simulated lumber recovery (Saw2003) based on virtual logs constructed by tree models. The tree models are based on either ordinary inventory data or inventory data and harvester measurements in combination.

3.1.3 WoodCIM®

With the development of scanning technologies, several research teams have created scanner-based simulation tools. These use data based on scanning of logs or boards and reconstruction algorithms producing a 3D description of a log or stem concerning its internal defects and shape. Raw material data were derived from computed tomography or scanning of boards (Usenius 2000). The model is based on information from scanned boards and matches the quality requirements of the end products to the quality of raw material.

WoodCIM (Usenius 1999) has been developed at VTT with several software modules and can be linked to the product and material flow control system or other computer systems at the sawmill (Figures 7 and 8):

- Software for optimising selection of stands and bucking of stems
- Program for optimising the limits of sawlog classes
- Simulation program for predicting the value yield in sawmilling
- Software for optimising manufacturing of components
- Sawing model based on linear programming for production planning.

WoodCIM has been developed for the wood conversion chain of Scots pine and Norway spruce and has also been adapted to Maritime pine (Pinto et al 2003).

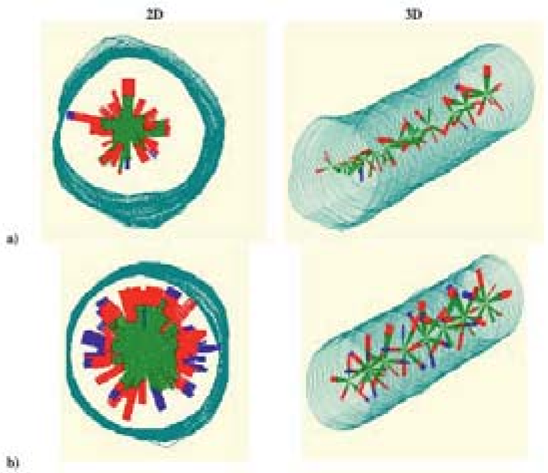

Figure 7. Mathematically reconstructed logs of maritime pine showing the geometry of the log and the internal knots in 2 and 3 dimensions. (a) butt log; (b) middle log.

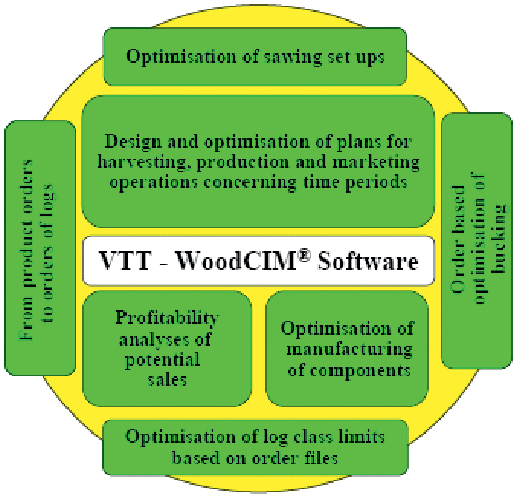

Figure 8. Wood CIM consists of integrated software modules.

3.1.4 *InnoSim*

InnoSim was developed as a tool for research and analysis of wood conversion chain of stems and logs for achieving better economical output. InnoSim simulates operations of the entire sawing process chain from tree, stem and bucking to final end products (i.e. lumber, wood components (Tiecheng 2007),

- The input stem (or log) are based on a log model which includes wood quality characteristics essential to product quality such as knots, heartwood and external shape etc.
- The output products are modeled for both standard dimension lumber and wood components defined by customers' specific need.

Therefore, InnoSim simulator imitates real life breakdown of logs into sawn products (Figure 9). The software can visually present the input sawlogs, sawing process, and output products. The sawing simulator was developed in an incremental manner in a series of research projects over the years with object oriented approach.

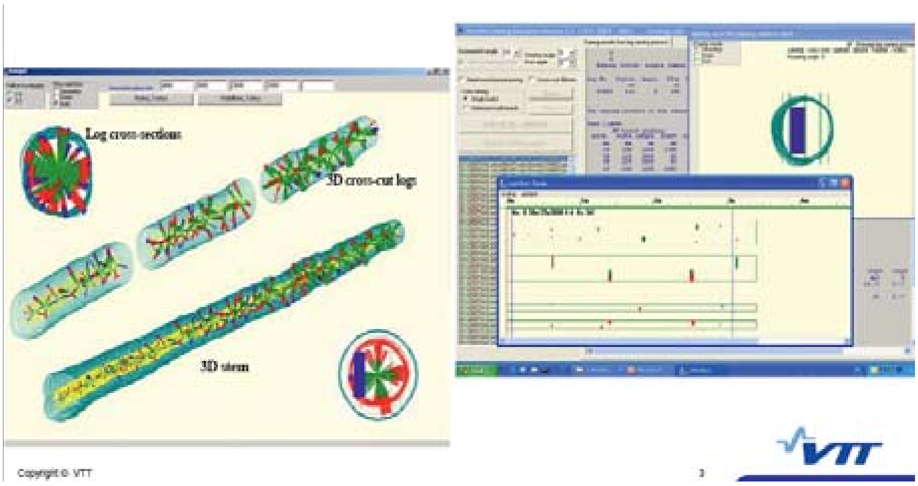

Figure 9. Examples of results from InnoSim simulations

The simulator is mainly used as a research tool for assessing efficiency of wood material exploitation in a wood conversion chain, for instance to match the most suitable raw material to the production of user defined lumber or wood components.

3.2 Model systems providing cross-section and log averages

In cut to length systems the physical manufacturing of products starts in the forest. In a future vision a CT-scanner combined with other high quality measurements like moisture content, grain angle, aesthetic properties etc. would provide a complete picture of the internal and external properties of each log. This vision may come true in the future. Meanwhile it is still possible to benefit from predicted properties of log cross-sections. Such information can be used to predict log end averages, construct simple models of internal log properties (like sound knot cylinder, heartwood cylinder, knot-free zone etc). These comparatively simple models can also be used to enrich desired wood properties in combination with specific log lengths and diameters.

Enrichment of logs with high probability to contain sound knots is already operational in CTL harvesters and in operation in wood supply chains to some sawmills in Norway and Sweden (Möller et al 2004). Similar implementation of a heartwood model for pine presented by Wilhelmsson et al (2002) into a test case for a Swedish sawmill has been reported by WM-Data, Silvinova and StoraEnso in cooperation (pers com. Tomas Bajer WM-data and Joar Stenslökken, SilviNova 2006)

3.2.1 Bucking of logs with sound knot cylinders

Sound-knot logs in Scots-pine trees can be bucked automatically, thus leaving the operator free to concentrate on stem defects. Automatic bucking is based on a simple function that uses input data consisting of the DBH of the tree, and indices derived from the requirements of local mills. Earlier studies have shown that the relationship between the quality grading of a tree based on external characteristics, and the actual quality of the timber after bucking, is a weak one. Automatic bucking of pine stems in either sound-knot logs or dead-knot logs, as determined by the bucking computer, is clearly a better option. These are the findings of a recent Skogforsk study conducted in collaboration with an industrial forest enterprise and an industrial sawmill group. The outcome at the sawmill of the grading done by the harvester revealed an accuracy of 78% for the sound-knot logs, and of 90% for the dead-knot logs.

At present, this automatic bucking function and options to use alternative functions e.g. developed by Öyen (1999) has been incorporated by all larger manufacturers of CTL bucking computers following the standard information and communication protocols for forest machines (StanForD).

3.2.2 StanForD Production files from harvesters + Pri-analyses

Modern CTL harvesters are able to produce pri-files (StanForD), i.e. production statistics for individual stems and logs. This concept makes it possible to add predicted properties to produced logs and depending on a cost/benefit analysis, connecting this information to a marked ID of individual log level, pile level etc. The marked (darker) parts of figure 10 show the objects that are directly connected with the pri-file information and pri-analyses. Figures 11-12 show screen samples from bucking control and figure 13 results from Pri-analyses. Figure 14 indicates the vision of a complete integration of the harvesting procedure into the industrial processes.

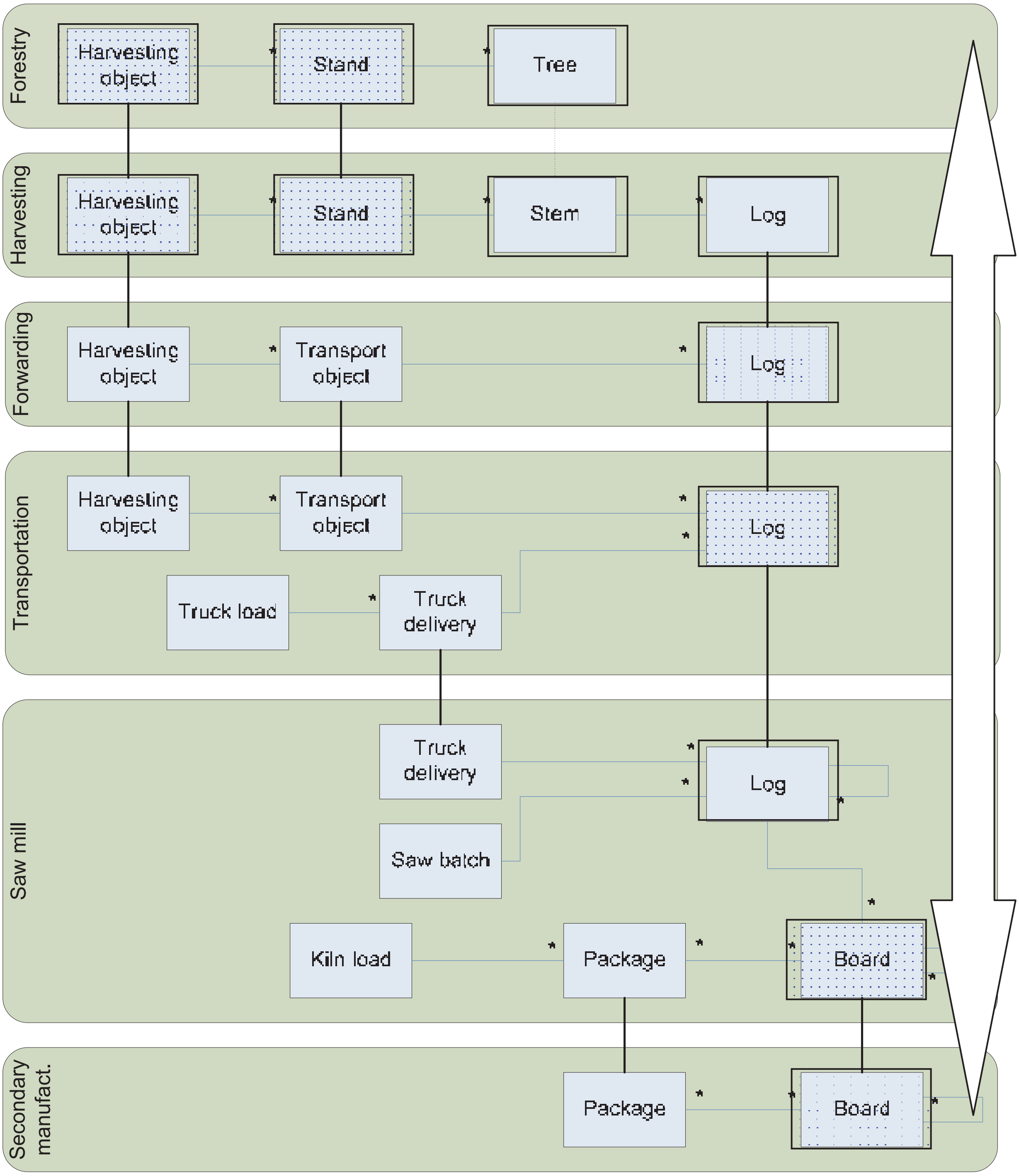

Figure 10. Information on harvesting object, measured stem and log dimensions, operators manual grading (downgrading) and predicted properties can follow the traceability objects (dark coloured) by StanForD production files from harvesters (pri-files, stm-files) and forwarders (prl-files). Picture from D3.1 Initial analysis of drivers and barriers, figure 2 "Traceability objects for a Scandinavian sawmill forestry value chain".

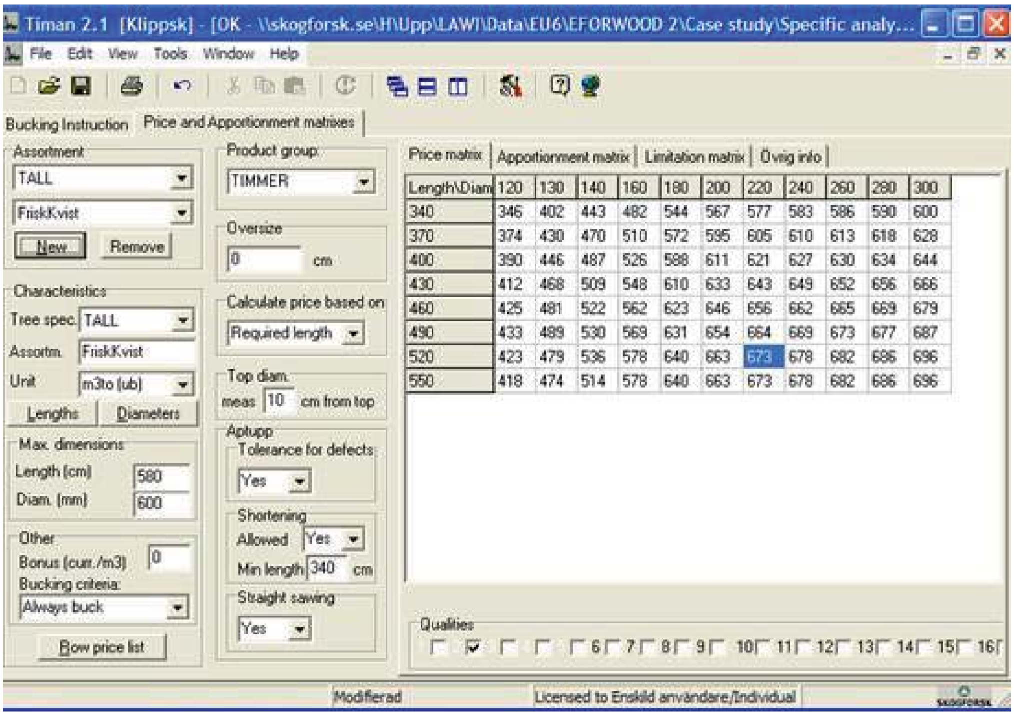

Figure 11. Screen shot from Skogforsk-TimAn2/Aptan which is a tool for simulation of CTL-harvester bucking control systems by price-list, harvester measurements, automatic or operator controlled quality control and defined restrictions at the log level. At this screen the assortment: Sawlogs of Tall (Pine), FriskKvist (Sound knots), max and min dimensions and price (price matrix) per Length/Diameter (top u.b.) combination are specified.

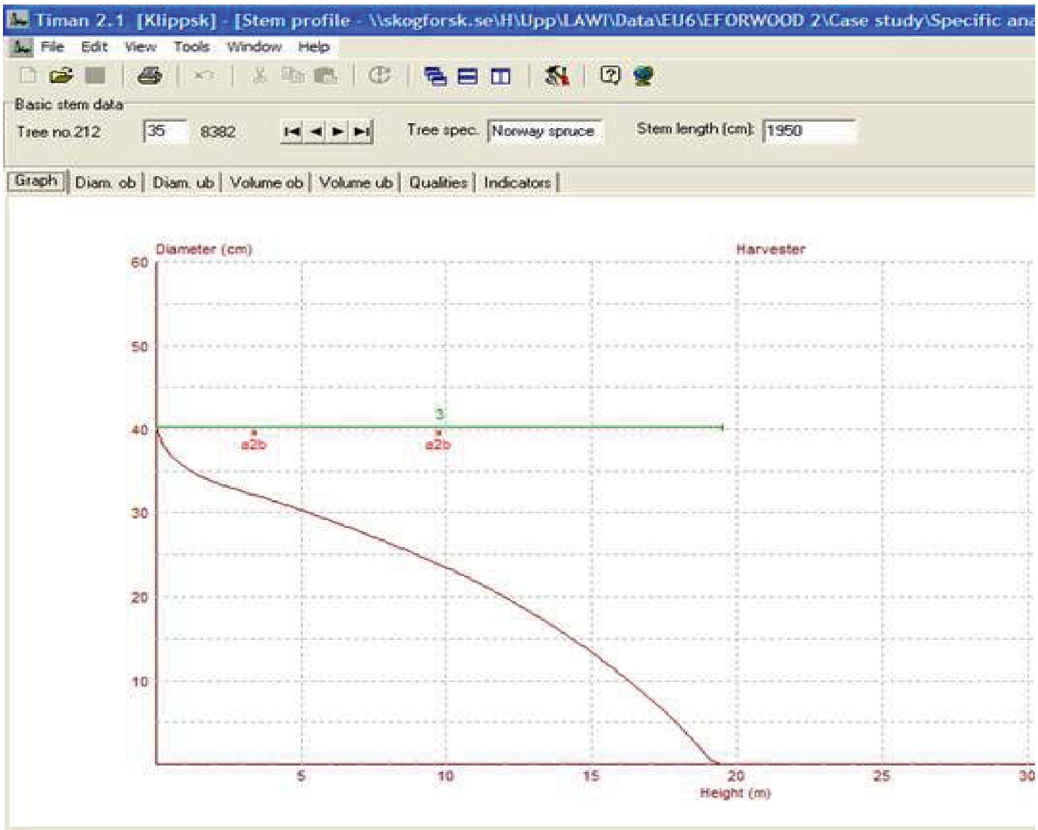

Figure 12. A CTL-harvester's measures of diameter and length and detected damages (causing downgrading of logs etc.) are logged into a stm-file (StanForD) per object. This is the basis for a pri-file (StanForD) which includes an extraction of critical information from each log and stem. This information can be connected to a marking system and forwarded along the value chain.

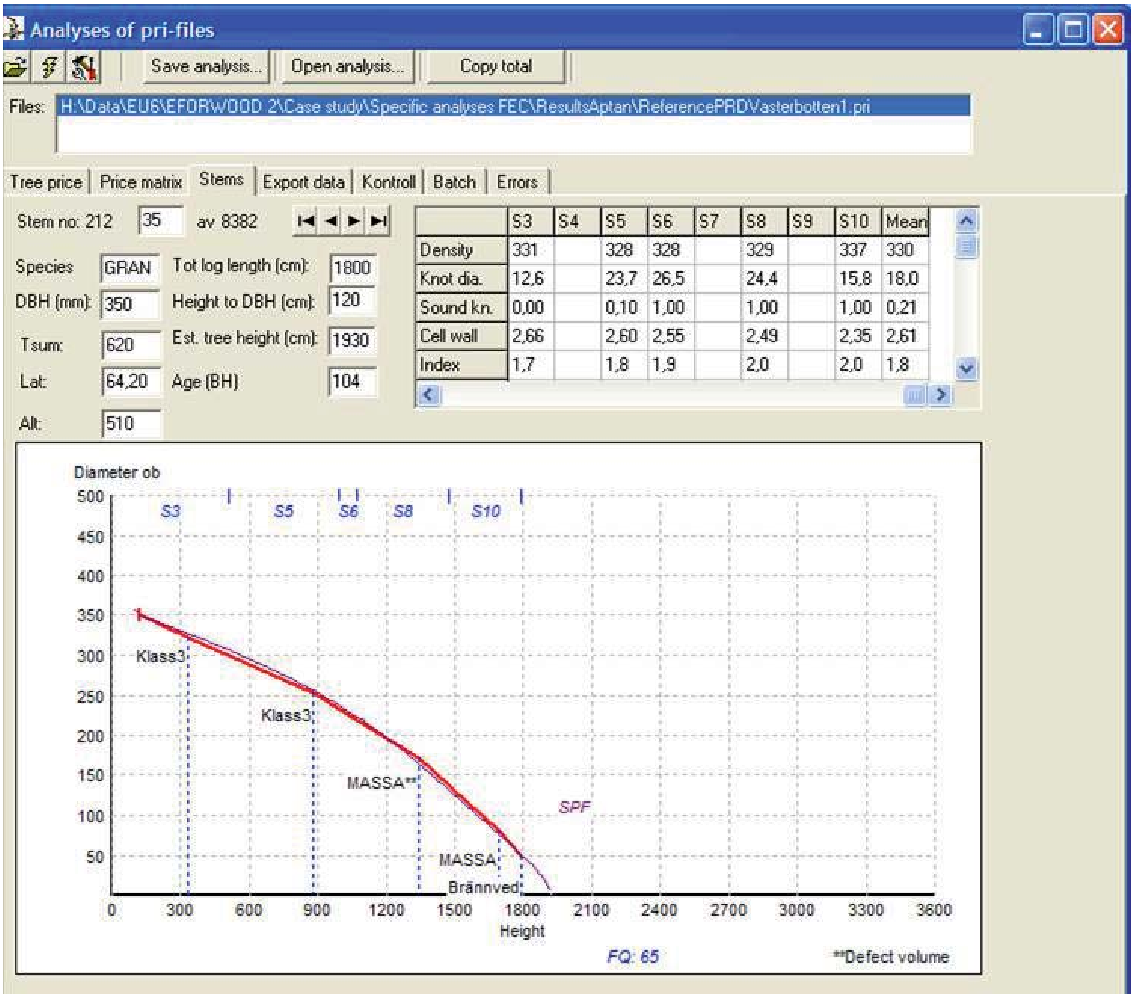

Figure 13. Results from Skogforsk-Pri-analyses. Predicted mean-values of basic density, knot diameter, sound knot etc. per stem section (S3, S5, S6, S8, S10). This information can be connected to a marking system and forwarded along the value chain.

Figure 14. Manufacturing starts in the forest. In CTL(Cut To Length) systems the selection, bucking alternatives and sorting of produced wood are all decided at harvesting (Photo Komatsu Forest)

3.3 Tree growth simulators

Forest growth simulators may be used to reconstruct internal stem and log properties if the specific historical growth pattern of a tree is known. A growth simulator may also be used to mimic a common variation between logs in different simulation procedures. In the context of forest operations in IK static models predicting stem and wood properties of the logs at harvesting may be a robust and simple alternative. Process models are generally more flexible to model e.g. extreme growth conditions “beyond statistical limits”. There is however a considerable risk that they produce less accurate and precise results within the borders of ordinary variation in forest stand conditions.

PipeQual

The forest growth model PipeQual (Figure 15) is used by e.g. the WoodCIM simulator. PipeQual was developed at the Department of Forest Ecology, University of Helsinki (Annikki 2000). It is a growth model based on the life processes of tree’s in which stand growth is measured by allowing each tree in a specific size category to represent the average tree of that category.

The top level of the growth model is constructed by employing a model for the tree as a whole in which its state is described in terms of biomass, length, diameter and other tree level indicators. Growth is measured on the tree level. The tree level model uses structural constants, which are calculated for each whorl of branches.

Tree level growth provides the input for the whorl level, on which growth is distributed between the whorls according to tree size and structure. The whorl level model updates the data for every whorl each year, which includes for example number of branches, needle biomass and stem diameter below the whorl. Thus, on the whorl level, the model is based on the life processes of the trees.

On the lowest level of the hierarchy, the total growth of all the branches that belong to a whorl is distributed between individual branches. Various properties of the branches are also estimated, such as branch angle and branch alignment. The calculations on the branch level are based on statistical models.

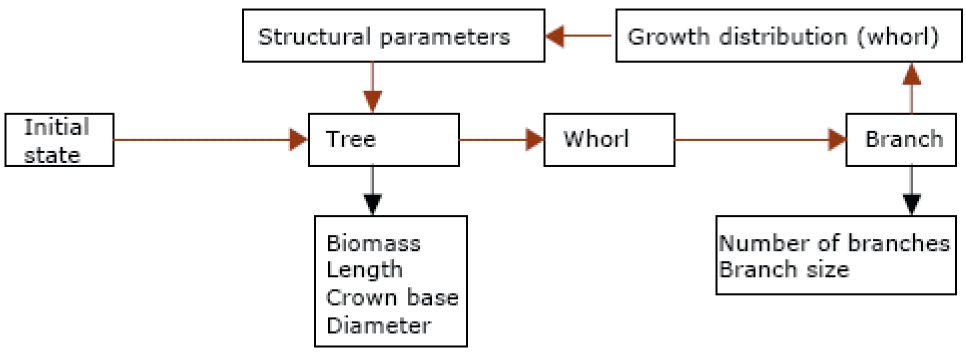

Figure 15 Structure of the PipeQual model

3.4 Log 3D- and CT-scanners

Log scanner measures the log’s surface with accuracy in a close check pattern along and across the entire log and thereby taking into consideration any concavity and convexities, knot enlargements, handling damages etc. Today 3D-laser scanners are commonly installed at larger sawmills and improve the possibilities to gain from better production control. (Nordmark & Oja, 2004)..This has been verified through practical use in the sawmills where increases of yield recovery in excess of 2% is not unusual (RemaLog 3D of REMA CONTROL). In a simulated analysis of the gain from different measurements of stems of young Scots pine, Nordmark (2005) concluded an increase in total value of 19% from bucking and prodcution control at a sawmill if a complete picture of external shape and internal knot properties (Full CT-scanning) was known, in comparison with conventional bucking in harvesters and conventional measurements at a sawmill. Part of this difference may be possible to gain if predictions of properties at harvesting are combined with measurements at sawmills and further along in the production chains.

In the past few years, computed tomography (CT) scanning technology has been applied to the detection of internal defects in both hardwood and softwood logs for the purpose of obtaining a priori information that can be used to arrive at better log sawing decisions. The potential gain from higher spatial resolution of scanner images for improved production control should be balanced against scanning cost and minimum time for measurements and decisions for production control. Considerable research concerning scanning technology has been published (e.g. Pietikäinen, M. 1996;.Grundberg & Grönlund 1997; Skatter 1998; Grönlund et al. 2005; Baumgertner et al. 2008. The results from this and similar research has formed part of the basis for new industrial scanning techniques. Recent research in harvesters measurement technology indicates that 3D scanning by line laser cameras may be operational in a CTL harvester felling head within a couple of years. (Andersson et al. 2008)

From REMA CONTROL & MiCROTEC's advertisement:

> "CT Scanning recognizes the quality of logs. Its unmatched measurement results are essential for realistic value estimates and subsequent production planning. CT Scanning produces a realistic, transparent 3D model of the log without the need to contact the material. It records bark separately and subtracts it from the calculation of the net cubic volume. In addition, CT Scanning also determines the 3D position and size of knots, foreign metals and contaminants, weak areas, and even the width of the annual rings."

Both 3D and CT scanners may be used to get detailed information from logs delivered to a sawmill. Today, in ordinary sawmilling a CT-scanner is not economically possible for production control online due to low scanning speed. To fulfil the demands on high scanning speed, industrially adapted X-ray log scanners have been developed and proven to be a useful tool for production control at a sawmill. Information from modern 3D scanners is used for detailed production control. But detailed surface measurements can also be used to predict internal properties and grades (Jäppinen & Beauregard 2000; Nordmark, U. Oja, J. 2004,) All type of scanners work with models to interpret the scanned information into the requested properties. Concerning product and process efficiency, however, an enrichment of logs of suitable dimensions (diameter and length) and wood properties should preferably be selected and bucked in the beginning (first link) of the production chain. Key property measurements like log length and log shape (including diameter) are measured in the felling head by CTL (Cut To Length) harvesters. Models for predicting properties at harvesting might be combined with sawmill measurements and models operating in scanners at the sawmills. By IAD-systems this kind of models operating on integrated information e.g. by multivariate analyses and/or neural network technology (e.g Nordmark, 2002) may result in considerable improvements in value recovery and/or automization of grading qualities for different purposes.

3.5 Grading machines

The main objective of grading machine is to improve the competitiveness of lumber as a structural material and to increase its market share in construction. Grading machines should replace human visual grading in industrial production, because human visual grading is both slow (expensive) and inaccurate. European machine strength grading machine (as X rays of MICROTEC or vibration of DYNAGRADE) are now available in market and certified according to requirements given by EN 14081 part 2-4 standards.

From MiCROTEC's advertisement:

> "MiCROTEC's innovative research team unveils the last secrets of lumber boards. The GOLDENEYE multi-sensor system not only determines strength but also recognizes knots, cracks, wane and dimensions of boards in longitudinal feeding at high speed in fractions of a second. This significantly increases performance levels. When combined with ViSCAN's non-destructive stress rating system, GOLDENEYE also maximizes value recovery based on the added value of stress-rated lumber. The GOLDENYE system combines X-ray and laser scanning technologies. Therefore it can not only recognize and measure the board's surface with absolute accuracy but it can also see inside the board. This is how GOLDENEYE recognizes the exact size and position of knots, cracks and other faults."

IK comment: This kind of equipment is also operated by models and its real accuracy and precision might be increased if log or stem information (measurements and predictions) from the logging procedure in the forest can be used as an input.

Machine strength grading needs to be combined in a near future with appearance grading (Automated visual machine methods, such as FinScan, LUXSCAN or WoodEye, are already in use), and should be done as early as possible in the production chain to enable the economic utilisation of the resulting rejects – these are unavoidable when strength grading is made in a reliable way.

3.6 Conclusion

So far, models predicting wood properties are only applied to a limited degree in manufacturing of wood products. The type of sawing simulators presented in this chapter are not yet implemented to online systems, but are considered useful especially for planning. In the context of Indisputable Key, however, one of the general objectives is to select and buck logs of suitable (economically and/or environmentally) combinations of diameter, length and wood properties to fit specific processes and products and to collect and deliver these logs to the desired production lines. This requires operational online systems, but so far only models providing cross-section and log averages have been implemented in bucking computers (chapter 3.2 above).

Prediction and sorting of logs having a high probability to produce boards with sound knots has been operational in a commercial scale in Norway and Sweden. Enrichment of logs with large heartwood diameter is operational in a test scale in Sweden. Both enrichment operations have been reported successful, despite a secure and automatically readable marking system is still lacking. Furthermore predicted wood properties are now introduced into stem pricing systems (Möller et al. 2005; Möller & Arlinger 2007) which will facilitate additional log purchase options and direct logs to be used where the relation between their properties and costs (at millgate) are more beneficially utilized.

The Indisputable Key project is a chance for saw millers to implement new measurement and modelling technologies to improve the utilization of available raw material resources by improved characterisation of stem and wood properties preferably in connection with selection and bucking (CTL) procedures at harvesting. This provides a potential to increase process efficiency and to sharpen product quality specifications, and to meet more advanced customer orders and expanding market opportunities.

4 Business cases and wood properties

The objective of this chapter is to determine the wood properties that are important in the business cases identified in the IK project (for more information please refer to deliverable

3.1.). As an introduction table 2 shows an attempt to make a gross list of properties that are considered to affect at least one or more links in the chain of processes from tree to final products.

Tables 3-4 indicate the information that is commonly available at harvesting, from the stand inventory data (table 3), harvester measurements by CTL felling heads (table 4). Table 5 indicates the possibilities to use this information together with models predicting properties. This information can be extracted from the forest operations and used to select, buck, sort and destine logs according to customers' requirements. Generally in the description of the IK business cases the required information is only a restricted part of all possible. Therefore the primary goals have been indicated by PG, while other information regarded as possibly valuable has been indicated by different "+ levels". Some information on measuring precision from modern harvesters (Möller and Arlinger, 2007) has been indicated in table 4 (Case 7.1).

Table 2. Gross list of properties and their possible relevance on process efficiency and/or product quality, **in the perspective of forest – to final product chain** (Wilhelmsson, In press).

Property	Units	Industrial relevance
Log averages		
Diameter (mean of major and minor axis)	mm	Sawing pattern. Yield of primary (beams, studs, boards) and secondary products (chips, dust, shavings).
Ovality (major axis – minor axis/mean)	% of diameter	- " - + reaction wood
Length of log	cm	- " -
Long crook	% of length	- " - + reaction wood
Green density at felling	kg/m³fub+ bark	Freshness criterion when compared with actual density at delivery to industrial site.
Green density at haulage	kg/m³fub+ bark	Transportation weight and freshness criterion at delivery. To be compared with green density at felling.
Basic density (radial average)	kg/m³	Correlates with all strength properties, thermal properties e.g. Modulus of elasticity (MOE) and modulus of rupture (MOR)
Heartwood diameter	mm	Durability, water uptake, impregnability for preservatives, permeability. Emissions of extractives. Affects conditions when optimising kiln drying.
Juvenile wood diameter	mm	Shape stability, MOE, MOR correlated with spiral grain, basic density and microfibril angle.
Log position in stem		Correlates with all strength properties, e.g. Modulus of elasticity (MOE) and modulus of rupture (MOR)
Mean annual ring width	mm	- " -
Internode length	cm	Length of clearwood
Maximum knot diameter at surface	mm	MOE, MOR, Probability of “critical knots”. Surface properties and aesthetic quality.
Average knot diameter at surface	mm	- " -
Number of knots/whorl	no	- " -
Sound knot length	mm	Surface properties, planeability, paintability, aesthetic quality. (Differences in load carrying capacity related to fibre distortions and stress peaks)
Bark thickness	mm	Dimensions and volumes over and under bark
Debarked % of surface	%	Drying rate - freshness criterion and reduction of bark volume
Bark volume	m³	Energy
Bark dry substance	kg/m³	Energy
Bark moisture content	%	Energy
Radial profiles pith/bark		
Distance from pith	mm	Positioning at sawing
Green density at processing	kg/m³fub	Sawing conditions, kiln drying
Basic density along radius	kg/m³fub	MOE, MOR
Microfibril angle	°	MOE, MOR
Spiral grain	°	Shape stability => twist
Loose/Sound knots distances from pith	mm	Surface properties. Processability MOE, MOR, (Differences in load carrying capacity related to fibre distortions and stress peaks) planeability, paintability.
Knot diameter (largest knot)	mm	Surface properties. Processability MOE, MOR, aesthetic quality
Knot diameter (average knot)	mm	Surface properties. Processability MOE, MOR, Aesthetic quality
Knot index	%	Knot area/Total area on four board surfaces
Chip characterisation		To be used by pulp and paper producers, Energy plants
Chemical characterisation		Chemical extraction procedures. Quality control of undesired extractives
Energy values of components		Specification of energy values of different components, dust, bark, chips = function of lignin and carbohydrate content , basic density, moisture

Table 3. Properties predicted by pre-harvesting measurements and information (Y=Yes)

Property	Case					
Legend	7.1 Setra Norsjö	7.2 Scanpole	7.3 Eidskog	7.4 Raunion	7.5 Ducerf	7.6 Rol Pin
ID of forest object (key for utilisation of stand information)	Y	Y	Y	Y		Y
Coordinates of stem at felling	Y	Y	Y	Y		Y
Cross-sectional diameter along stem	Y	Y	Y	Y	Y	Y*
Stem taper based on breast height diameter (dbh), tree height and tree age	Y	Y	Y	Y	Y	Y*
Length of stem from but to end of last top log (e.g. 50-70 mm o.b.)	Y	Y	Y	Y	Y	Y*

*) The share of logs, harvested by CTL harvester

Table 4. Properties measured and recorded by tree harvesters (CTL) (Y=Yes, ± figures indicate precision in practice.)

Property	Case					
Legend	7.1 Setra Norsjö	7.2 Scanpole	7.3 Eid-skog	7.4 Raunion	7.5** Ducerf	7.6 Rol Pin
ID of harvesting object (key for utilisation of stand information)	Y	Y	Y	Y		Y
Coordinates of stem at felling	± 5-10m*)	± 5-10m	± 5-10m	± 5-10m		Y
Coordinates of log stack	± 5-10m	± 5-10m	± 5-10m	± 5-10m		Y
Log position in stem (longitudinal 1=butt, 2=sec.)	Y	Y	Y	Y	Y	Y
Cross-sectional diameter of logs and log ends	68% within ± 4 mm		Y	Y	Y	Y
Length of logs	82% within ± 2 cm		Y	Y	Y	Y
Cross-sectional diameter along stem	68% within ± 4 mm		Y	Y	Y	Y
Length of stem from but to end of last top log (e.g. 50-70 mm o.b.)	Y		Y	Y	Y	Y

*) Indicate absolute precision of ordinary GPS (Not DGPS!). The distance between subsequently generated coordinates (relative positions) is considerably more accurate.
**) oak trees are too big to be cut by CTL, properties should be manually measured in sawmill

Table 5. Properties possible to predict by models (PG=Primary Goal according to D3.1 Initial analysis of drivers and barriers, + = of possible importance, ++=important, +++=of large importance)

Property	Case					
	7.1[2]	7.2	7.3	7.4	7.5	7.6
Green density at felling	+	++	+	+		
Green density at haulage	+	+	+	+		
Basic density (radial average)	+	++	+	+		
Moisture content at processing, %	++	PG	+	++		
Heartwood diameter	+	++	++	+		
Mean annual ring width	+	+	+		+	
Internode length	PG	+		+		
Maximum knot diameter at surface	+	+		+	+	+++
Average knot diameter at surface	+	+		+	+	+++
Number of knots/whorl	+	++		+		+++
Sound knot length	++		++	+		+++
Log position in stem, recorded by harvester	+	+		PG	+++	PG
Bark thickness	+			+		
Debarked % of surface	+			+		+++
Bark volume	+			+		
Bark dry substance	+			+		
Bark moisture content	+			+		
Radial profiles pith/bark						
Distance from pith	+		+++		+	
Green density and moisture content at processing	+	+++	+++	+		
Basic density along radius	PG[1]			+		
Microfibril angle	+					
Spiral grain	+	++	+	++		
Loose/Sound knots distances from pith	+					
Knot diameter (largest knot)	+			+	++	+++
Knot diameter (average knot)	+			+	++	+++
Knot index	+			+	++	+++
Chip characterisation	+					
Chemical characterisation	+					
Energy values of components	+					

[1] Minimum level required
[2] With primary respect to the Malå-Norsjö window case. If other products from Malå are taken into account, more emphasize (more +) will be put on some of the properties above.

5 Traceability and models

In a practical log sorting process, companies can achieve benefits by developing a sorting strategy based on the tree-stem-log sources and desired end products as shown below.

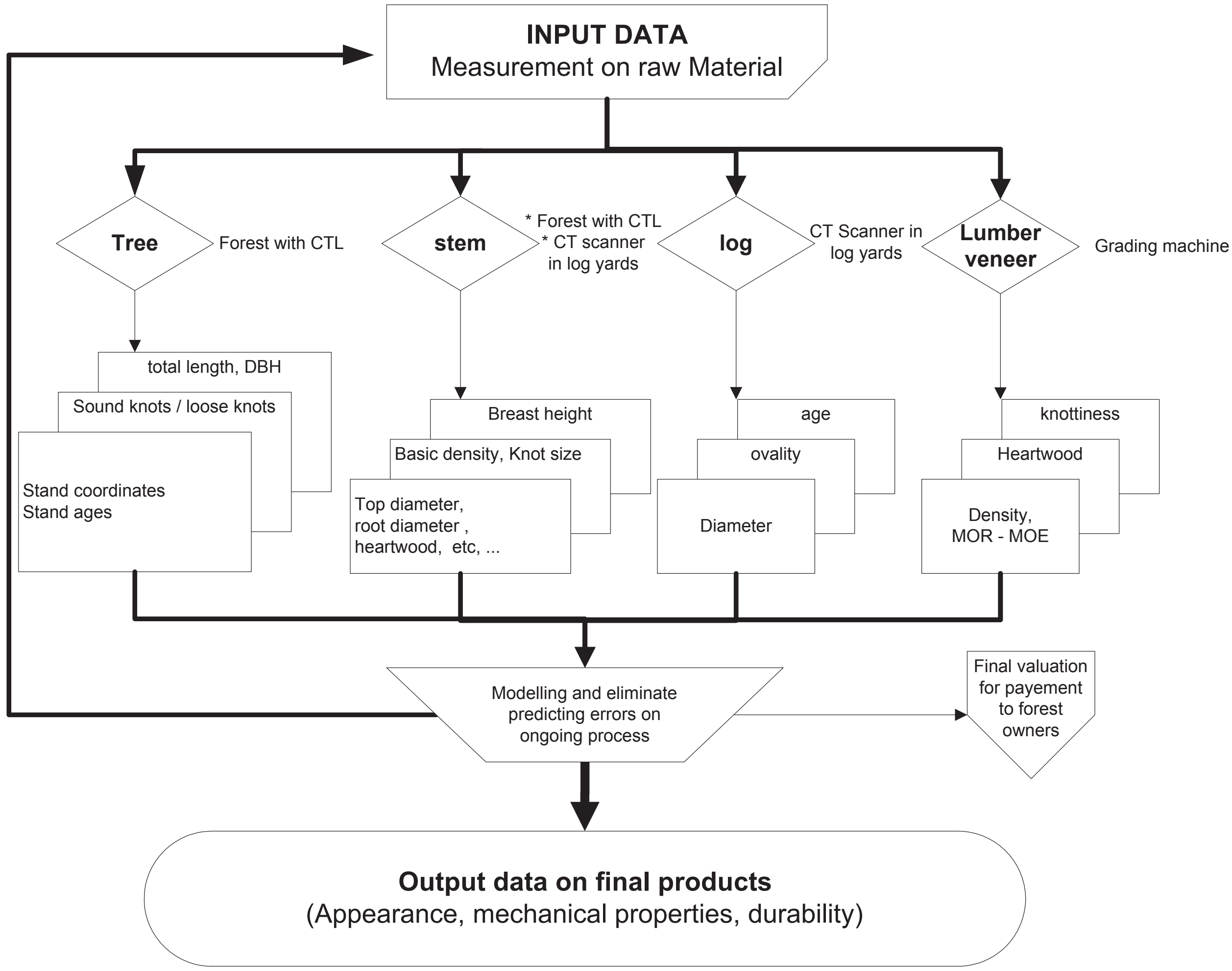

Figure 16. Examples of interactions between models (predicted) and output data. Input data on a log is e.g. age, ovality and diameter. From the collected input data, other wood properties of the object and/or on the final product can be calculated by the use of wood property models. The acquired information can be used for e.g. valuation for payment to forest owners and enhanced sorting of raw material before further processing in the sawmill.

The accuracy of different “models” is not yet validated in most IK cases. Depending on the situation the minimum required precision to justify the use of models should be further analyzed. Generally, prediction errors SE (RMSE) of models are important information to calculate possible selection effects.

On the other hand, IK project should establish traceability of products and evaluate the benefits of characterizing the initial “quality” of raw material, the primary product coming from models at the beginning of the process. The challenge of this project is to check if the input information is closed to the received output. A link with IK task WP2 should be done in order to define the accessibility of information connected by different marking strategies (Marking of each individual, sample of individuals, pile, assortment/object etc.).

However, models could be currently adjusted and improved to fit specific value chain benefits if individual log traceability is employed (at least statistically). For example following table 1, saw millers could install equipment to detect defects and “sort” raw material products to improve the utilization of delivered logs. In this case, IAD information coming from forest measurements and models should be read at the phase when the primary product (adapted raw material) is sorted and production control decisions are made at the sawmill.

All input data for models to use in the traceability system as well as the model results themselves need to be included in the list of properties for IAD objects (Appendix C in D2.8). The list of properties will be revised during the course of the project.

6 Discussion

This document shows that there are gaps between wood property information desired by the industry and wood properties possible to predict by statistical models. Part of the problem might have its origin in different ways to express wood properties along the value chains.

The literature contains a large number of investigations, but in many cases the statistics produced are descriptive, and models predicting properties are missing. However, a lot of models predicting some of the wood properties of interest for industry have been published and a number of models are closely related to the demanded but are not yet applied in wood industries. However, the principal benefit of “Models” is that they help companies to understand their operations and to improve their profits.

Before implementation a model for wood quality predicting the cost and benefit must be investigated. The realization of the system will be justified if revenues exceed costs considerably.

IK project is a new chance for saw miller to take into account new technologies in order to assess customer order based on available raw material resources and increase benefits with ordered products quality specifications.

This report shows one state of the art because scientists can make new investigation on this field and create new models during IK time project. A review of this report should be done periodically.

7 Conclusion

Part of the most relevant information about wood properties of saw logs is possible to predict by existing models. By combining measurements from ordinary Cut-To-Length harvesters, for some properties with information of tree (stand) age information and geographic positions stands a number of properties can be predicted. In some cases the accuracy of predicted properties of individual logs may justify use of statistical distributions and marking of individual piles rather than individual logs. In other cases and for some of the properties, measured (e.g. diameter (shape) and length) or predicted properties (e.g. sound knots, heartwood diameter) of individual logs may justify traceability of individual logs. In any case all model results from Pri-analyses (or simular tools) will fit into IAD-structures when requested to gain economy or reduce the environmental load. Further ahead in the production chains IAD can be used to analyse interrelationships between information from logs measured by 3D-frames and CT-scanning and the wood products. There is also a potential in accumulating information from the forest inventory and harvester measurements and property characterisation into such tools. To make the selection, sorting and bucking in a Cut To Length system more efficient, backtracking from final products and production processes may be analysed by from IAD. A closer communication forestry ⇔primary transformation industry ⇔ secondary transformation industry concerning implementation is necessary. Further validation of existing models will also be required.

Tables 6-8 show the general perspectives to take advantage of models predicting different properties into the case studies. These tables should be interpreted as the broad sense possibilities and the further work within Indisputable Key will give us better possibilities to decide what models and combination of models to be utilized in the different case studies. This work should be done in close cooperation between the industrial partners, WP3 task 3.3 (Saw mill processing) and the other WP's of Indisputable Key.

System analyses including the importance of information accuracy and precision may put light on the possible benefits. Cost of information in relation to possible benefits should also be further analysed in WP3.

Table 6 Models currently introduced in the Pri-analyses (Skogforsk). These could be utilized in all cases served by CTL harvesters. (Here cases 7.1 and 7.4 are considered, other cases presented below) Input data based on production files from harvesters and general stand information. **PG=Primary Goal, ++ = of large relevance**, + = of some/or potential relevance. Models available, Y=Yes, or ± figures indicating Standard Error (SE) at the single log level when relevant and estimated (unit given in column "Property").

Property	**Case study 7.1 Setra Malå Norsjö windows**	**Case study 7.4 Raunion**	**Models available ±SE**	**x=Model not available or more investigations needed**
Green density at felling, kg/m³fub	+	+	Spruce ± 70, Pine ± 50	
Green density at haulage	+	+	Y	
Basic density (radial average), kg/m³fub	**++**	++	Spruce and pine ± 26	
Moisture content, %	**++**	**++**	Y	
Heartwood diameter (mm)	++	++	Pine ± 17 Spruce ± 20	
MOE	+	++		x
MOR	+	++		x
Mean annual ring width	+	+	Y	
Internode length	**PG**	+	Y	
Maximum knot diameter at surface, (mm)	+	+	Spruce and Pine ± 6	
Average knot diameter at surface, (mm)	+	+	Spruce and Pine ± 5	
Number of knots/whorl	+	+	Y	
Sound knot length	**++**	+	Y	
Log position in stem	**++**	**PG**	**Measured**	
Bark thickness	+	+	Y	
Debarked % of surface	+	+		x
Bark volume	+	+	Y	
Bark dry substance	+	+	Y	Not validated
Bark moisture content	+	+	Y	Not validated
Radial profiles pith/bark				
Distance from pith	+	+	Y	
Green density at processing	+	+	Y	
Basic density along radius	**PG**	+		x
Microfibril angle	+	+		x
Spiral grain	+	+		x
Loose/Sound knots distances from pith	+	+	Y	
Knot diameter (largest knot), mm	+	+	Y	
Knot diameter (average knot), mm	+	+	Y	
Knot index	+	+		x e.g. based on knot models
Chip characterisation	+		Y	
Chemical characterisation	+		Y	x
Energy values of components	+		Y	

Table 7. Models of specific interest for implementation or further development in the Norwegian cases. **PG=Primary Goal, +++ of very large relevance**, ++ = of large relevance, + = of some relevance.

Property	**Case study 7.2 Scanpole (pine) (Pole production)**	**Case study 7.3 ESAS (spruce) (Eidskogkledning)**	**Models available (suggested origin indicated)**	**x=Model not available or more investigations needed**
Mean annual ring width	+	++	Sweden	
Annual ring width along radius		**PG**	Norway, more analyses necessary	x
Basic density, log average	+	++	Sweden	
Basic density along radius		**PG**	Norway, more analyses necessary	x
MOR stems	**PG**		Finland	
MOE stems	+		Finland	x
Moisture content of stem	**PG**		Sweden	x
Heartwood diameter	++		Sweden	
Resin pockets		**PG**	Only descriptive statistics available	x
Sound-knot cylinder		**PG**	Norway, Øyen 1999	
Knot diameter		**PG**	Sweden and Norway Øyen 1999	
Reaction wood		**+++**	Only descriptive statistics available	x

Table 8. Models currently introduced in the Pri-analyses (Skogforsk). Input data based on production files from harvesters and general stand information. **(+++ of very large relevance**, ++ = of large relevance, + = of some relevance, ,).

Property	**Case study 7.5 DUCERF (oak) (boules; squared timber &squared edged timber)**	**Case study 7.6 ROL PIN (veneer Pinus pinaster)**	**Modelling**	**Model not available or more investigations needed**
Log position in stem	+	+	Done for mechanical properties	should be more useful and fit back with experiments
Knot diameter (largest knot)		**+++**		
Knot diameter (average knot)		**+++**		
Knot index		**+++**		
Mean annual ring width	+			Aesthetics grades should be developed
Maximum knot diameter at surface	+	**+++**		
Average knot diameter at surface	+	**+++**		
Number of knots/whorl		**+++**		
Knot diameter (largest knot)	++			
Knot diameter (average knot)	+			
Knot index	+			
Distance from pith	+			
Quality of veneer		**Just a prediction of raw characteristics**	**Daily used**	No model available for the quality of final products (aspect, mechanical properties)

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9 Appendix – descriptions of models

This appendix is a detailed compilation of models of interest for characterisation of log properties. Model output, list of input variables needed, degree of explanation (when applicable), and prediction error (precision) are presented for each model.

Along the progress of the IK project, new or modified model descriptions may be added to this appendix.

9.1 Models for predicting softwood properties

Number of annual rings General information.	
Model description supplied by	*Skogforsk*
Model	*Number of annual rings*
Objective and description	*This model provide the number of rings of any cross-section of the stem from breast height and above. This model is useful when models predicting other wood properties (e.g. densities, heartwood, internode length etc.) do require the number of rings at breast height as an input (independent) variable.* *This model may also be used to predict the approximate number of branch whorls of pine (and major branch whorls on spruce) by subtracting the number of rings in the top end from the number of rings in the but end of a log.*
Reference	*The model is published in Wilhelmsson, L. 2006. Two models for predicting the number of annual rings in cross-sections of tree stems. Scand. J. For. Res. 21 (supplement 7):37-47.*
Algorithm	*Multiplicative function, see below.*
Calculation steps	*The function is based on the diameter (over bark) at the considered cross-section and the diameter (over bark) at breast height.. Prediction of the number of annul rings will preferably be done for cross sections in which age-dependent wood properties are to be predicted.*
Program code	*Model exist as a dll (Delphi-code), programmed by Skogforsk (Arlinger, J.).*

$$AGE_k = AGE_{BH}^{\left(\frac{D_{k\,pb}}{DBH}\right)^{a_1 + m\frac{Dk\,pb}{DBH}}}$$

$m = b_1$ $\quad l < b_1$
$m = l$ $\quad b_1 \le l \le b_2$
$m = b_2$ $\quad b_2 < l$

$$l = c_0 + c_1\,LATITUD + c_2 \ln AGE_{BH} + c_3\left(\ln AGE_{BH}\right)^2 + c_4\left(\ln AGE_{BH}\right)^3 + c_5\left(\ln AGE_{BH}\right)^2 \ln DBH + c_6\left(\ln AGE_{BH}\right)^3 \ln DBH + c_7\,DBH^{-1/2} + c_8\frac{DBH}{AGE_{BH}}$$

Model results. Number of annual rings				
Variable	Unit	Integer or floating	Max/Min	Description
AGE_k	*rings*	*Integer*	*Max=AGE_{BH}*	Number of annual rings in a cross-section at height k (m) from ground to cross-section. Corresponds with diameter at the same height ($D_{k\,pb}$) below.

Model variables. Number of annual rings						
Variable	Unit	Integer or floating	Max/Min	Description	National forest inventory Sweden	
					Variable	Table
$D_{k\,pb}$	*mm*	*Integer*	*DBH/30*	Diameter over bark at height k (m) from ground (or stem butt-end+0,2m) to cross-section		
AGE_{BH}	*year*	*Integer*	*150/18*	Number of rings at breast height	BRHAL-DER	KLAV-BER
DBH	*mm*	*Integer*	*500/50*	Diameter at breast height over bark	DIAMETER	KLAV-TRAD
LATITUD	°	*Floating*	*66/56*	Latitude	BREDGR/10	TRAKT

Number of annual rings Functions applied to	
Function 1	Function 2
Scots pine	*Norway spruce*

Number of annual rings Function coefficients		
Variable	Coefficient Function 1	Coefficient Function 2
a_1	0.3392	0.2921
b_1	-0.23	-0.19
b_2	1.0	1.2
c_0	3.271	
c_1		$8.9\ 10^{-3}$
c_2	-1.799	
c_3	0.4434	
c_4		0.02043
c_5		-0.02117
c_6	-0.00737	
c_7	-7.554	
c_8		0.04026
R^2	0.92	0.91
RMSE	7.7	5.9
Bias	-	-

SAS-code Number of annual rings

Function 1

```
l = 3.2711 - 1.7991*LOG(AGEbh) + 0.4434*LOG(AGEbh)**2
      - 0.00737*(LOG(AGEbh)**3)*LOG(DBH) - 7.5538*(1/(DBH **0.5));
IF l <-0.23 OR l >1 then do;
  IF l <-0.23 then m = -0.23;
  ELSE m = 1;
END;
ELSE DO;
  m = l;
END;

AGEk =  AGEbh ** ((MIN(Dkpb, DBH)/ DBH)
        **(0.3392 + m*MIN(Dkpb, DBH)/ DBH));
```

Function 2

```
l = 0.008905*LATITUD + 0.02043*(LOG(AGEbh)**3)
      - 02117*(LOG(AGEbh)**2)*LOG(DBH) + 0.04026*(DBH/AGEbh);
IF l <-0.19 OR l >1.2 then do;
  IF l <-0.19 then m = -0.19;
  ELSE m = 1.2;
END;
ELSE DO;
  m = l;
END;

AGEk =  AGEbh ** ((MIN(Dkpb, DBH)/ DBH)
        **(0.2921 + m*MIN(Dkpb, DBH)/ DBH));
```

Basic density General information.	
Model description supplied by	*Skogforsk*
Model	*Basic density (Scots pine and Norway spruce)*
Objective and description	*The models provide a mean value for a cross-section of the stem. To get aggregated mean values for a log a stem a stand etc. predicted values should be volume weighted. The functions are valid above breast height only. Calculation is done by predicted number of annual rings (see model predicting number of rings) in actual cross section.*
Reference	*Model (slightly different parameters) described in: Wilhelmsson, L. Arlinger, J. Spångberg, K. Lundqvist, S-O. Grahn, T. Hedenberg, Ö. Olsson, L. 2002. Models for predicting wood properties in stems of Picea abies and Pinus sylvestris in Sweden. Scand. J. For. Res. 17(4):330-350.*
Algorithm	*Additive function, see below.*
Calculation steps	*The function is based on input: diameter breast height (u.b.), number of rings (age) at breast height, diameter (u.b.) of regarded cross-section and number of rings and bark thickness of regarded cross-section. Number of rings of cross-sections above breast height can be predicted by function e.g. Wilhelmsson (2005). Bark thickness and bark thickness. Volume weight of the property can be calculated by the following expression (Wilhelmsson et al 2000) (1=but end cross-section, 2=top end cross-section):* $L50 = \left[4.25^{\left(1-\frac{D2}{D1}\right)} + 0.63^{\left(1-\frac{D2}{D1}\right)} \right]^{-1}$ *Density = Density*$_1$ *+ L50 (Density*$_2$ *- Density*$_1$*)*
Program code	*The model exist as dll, programmed in Delphi-code.*

$$\textit{Basic density} = C + a_1 (\ln AGE_k)^{0.5} + a_2 (\ln AGE_{bh})^3 + a_3 \frac{0.5 \cdot D_{k\,ub}}{AGE_k}$$

$$+ a_4 \frac{D_{k\,ub}^{1.5}}{AGE_k \cdot T_{sum}} + a_5 T_{sum} \cdot \left(\frac{0.5 \cdot D_{k\,ub}}{AGE_k} + m \right)^{-1} + a_6 (\ln AGE_{bh})^3 \cdot e^{\left(\frac{D_{k\,ub}}{DBH_{ub}}\right)^7}$$

$$+ a_7 T_{sum}$$

Model result. Basic density				
Variable	Unit	Expressed as integer or floating	Max/Min	Description
BASIC DENSITY	*kg m^{-3}*		*550/250. Fix at max. and min*	Basic density of a specified (arbitrary) cross-section along the stem.

Variables of the model. Basic density				
Variable	Unit	Integer or floating	Max/Min	Description
C		*Floating*		Intercept
$D_{k\ ub}$	*mm*	*Integer*		Diameter under bark at height k, = $D_{k\ pb}$ - $BARK_k$
$BARK_k$	*mm*	*Integer*		Double bark thickness under bark at height k (may be predicted by function e.g. Hannrup, 2005)
$D_{k\ pb}$	*mm*	*Integer*	*DBH/30*	Diameter over bark at height k
AGE_k	*year*	*Integer*	*200/3*	Number of annual rings (age) at height k (may be predicted by functions e.g. Wilhelmsson, 2005)
DBH_{ub}	*mm*	*Integer*		Diameter at breast height = $DBH - BARK_{DBH}$
DBH	*mm*	*Integer*	*500/50*	Diameter at breast height (bh) over bark
$BARK_{DBH}$	*mm*	*Integer*		Double bark thickness under bark at height k (may be predicted by function e.g Hannrup, 2005)
AGE_{BH}	*year*	*Integer*	*180/15*	Number of annual rings (bh)
T_{sum}	*°C-days*	*Integer*	*1500/700*	Temperature sum ≈ 4922.1 - 60.367**LATITUD* - 0.837**ALTITUD* (Moren & Perttu 1994). Valid in Sweden

Basic density Function applied to	
Function 1	Function 2
Scots pine	*Norway spruce*

Basic density Coefficients functions		
Variable	Coefficient Function 1	Coefficient Function 2
C	365.08	306.86
a_1		14
a_2	-0.6041	
a_3	-17.468	
a_4		- 492.27
a_5		0.273
a_6	0.4176	
a_7	0.05886	
m		2.3
R^2	0.59	0.5
RMSE	25.5	26.3
Bias	-	-

SAS-code Basic density

Function 1

```
DENSITY =    365.08 - 0.6041*(LOG(AGEbh))**3
             - 17.468*(0.5*(Dkpb - BARKk)/AGEk)
             + 0.4176*(LOG(AGEbh))**3*EXP(((Dkpb-BARKk)/(DBH-BARKbh))**7)
             + 0.05886*Tsum;
DENSITY = MIN(MAX(DENSITY, 300), 550);
```

Function 2

```
DENSITY =    306.86 + 14*(LOG(AGEk))**0.5
             + 0.273* Tsum /((0.5*(Dkpb-BARKk)/AGEk) + 2.3)
          -  492.27*((Dkpb-BARKk)**1.5)/(AGEk*Tsum);
DENSITY = MIN(MAX(DENSITY, 250), 550);
```

Heartwood diameter. General information.	
Model description supplied by	*Skogforsk*
Model	*Heartwood diameter*
Purpose and description	*The model gives a mean value for a cross-section in the stem. To aggregate this to a mean value per stem or stand, estimated values should be volume-weighted. The functions are only valid at and above breast height. The calculation is done after estimating age at the relevant cross-section.*
Reference	*The model (although with other parameter estimations) is described in:* *Wilhelmsson, L. et al. 2002. Models for predicting wood properties in stems of* Picea abies *and* Pinus sylvestris *in Sweden. Scand. J. For. Res. 17(4):330-350.*
Algorithm	*Additive function, see below.*
Calculation procedure	*The function requires information about actual diameter and age (as well as bark thickness, if the diameter is stated over bark) at the cross-section. It is suggested that the calculation is done at DBH, the size boundary between lumber and pulpwood, as well as at the smallest pulpwood diameter. It can also be done at both log ends, together with a more accurate yield calculation. Age and bark thickness can be calculated with separate functions. Volume weighting can be done with the following expression (1=root cross-section, 2=top cross-section):* $L50 = \left[4.25^{\left(1-\frac{D_2}{D_1}\right)} + 0.63^{\left(1-\frac{D_2}{D_1}\right)} \right]^{-1}$ $KVED = KVED_1 + L50\,(KVED_2 - KVED_1)$
Program code	*The model is in the form of a dll programmed in Delphi code.*

$$KVED = C + a_1 D_{k\,ub} \ln AGE_k + a_2 D_{k\,ub} (\ln AGE_k)^3$$

Results of the model, Heartwood diameter				
Variable	Unit	Integer or floating number	Max/Min	Description
KVED	*mm*	*Floating*	*$D_{k\ ub}$/9.* *Fix at max. and min.*	Diameter of the heartwood.

Variables of the model, Heartwood diameter						
Variable	Unit	Integer or floating number	Max/Min	Description	Rikstax reference	
					Variable	Table
$D_{k\ ub}$	*mm*	*Integer*		Diameter under bark at height k, = $D_{k\ pb}$ - $BARK_k$		
$BARK_k$	*mm*	*Integer*		Double bark thickness under bark at height k (can be calculated, see function)		
$D_{k\ pb}$	*mm*	*Integer*	*DBH/30*	Diameter on bark at height k		
AGE_k	*years*	*Integer*	*200/3*	Age at height k (can be calculated, see function)		

Applicability of the functions Heartwood diameter	
Function 1	Function 2
Pine	*Spruce*

Function coefficients, Heartwood diameter		
Variable	Coefficient Function 1	Coefficient Function 2
C	-15.4	-15.6
a_1	0.158	0.2149
a_2		$-1.24\ 10^{-3}$
R^2	0.88	0.91
RMSE	16.9	20.1
Bias	-	-

SAS code, Heartwood diameter

Function 1

$KVED = -15.4 + 0.158*(D_{kpb}-BARK_k)*LOG(AGE_k);$

Function 2

$KVED = -15.6 + 0.2149*(D_{kpb}-BARK_k)*LOG(AGE_k)$
$- 0.00124*(D_{kpb}-BARK_k)*(LOG(AGE_k))**3;$

Knot diameter, individual knots. General information.	
Model description supplied by	*Skogforsk*
Model	*Knot diameter*
Purpose and description	*The model generates a value for an individual knot. It is based partly on random variation around the mean diameter and partly on the knot direction. The knot diameter is used, amongst other things, to model sound-knot and loose-knot lengths.*
Reference	*The model form and model description (although with slightly different variables and parameter values) can be found in:* *Moberg, L. 2000. Models of internal knot diameter for* Pinus sylvestris. *Scand. J. For. Res. 15:177-187.* *Moberg, L. 2001. Models of internal knot properties for Norway spruce. Forest Ecology and Management 147:123-138.*
Algorithm	*Multiplicative function.*
Calculation procedure	*To be calculated from mean and max knot diameter, knot direction and directional dependence of the diameter. To be calculated before knot length.*
Program code	*See SAS code below.*

$$KD_l = KD_{k\,mean}\; e^{AMP_k\, COS(V_{k\max} - V_l)}\; e^{\varepsilon_{ijkl}}$$

Knot diameter. Results of the model.				
Variable	Unit	Integer or floating number	Max/Min	Description
KD_k	*mm*	*decimal*	*70/1 (fix at max/min)*	Internal knot diameter at sound knot boundary or cylindrical surface (living branches). Maximum and mean diameter for knot whorl at height k.

Variables of the model, Knot diameter						
Variable	Unit	Integer or floating number	Max/Min	Description	Rikstax reference	
					Variable	Table
$KD_{k\ mean}$	*mm*	*Floating*		Mean knot diameter in the knot whorl (see separate function).		
AMP		*Floating*		Magnitude of the directional dependence of the knot for the knot whorl (see separate function)		
$V_{k\ max}$	°	*Integer*		The direction where the effect on individual knot diameter in a knot whorl is greatest (see separate function).		
V_j	°	*Integer*	*360/0*	Radial angle of the knot. Random 0-360. Knots within a knot whorl should be equidistant. (E=0, N=90, W=180, S=270)		

Applicability of the functions, Knot diameter	
Function 1	Function 2
Pine	*Spruce*

Function coefficients, knot diameter		
Variable	Coefficient Function 1	Coefficient Function 2
R^2		
ε_{ijkl} (RMSE)	0.2814	0.365
Bias	-	-

Knot diameter, one per whorl. General information.	
Model description supplied by	*Skogforsk*
Model	*Knot diameter*
Purpose and description	*The model generates one value per knot whorl. The model is limited to give zero knot diameters at ground height and at overall height.* *The calculated value is used as input data to the knot length model.*
Reference	*The model form and model description (although with slightly different variables and parameter values) can be found in:* *Moberg, L. 2000. Models of internal knot diameter for* Pinus sylvestris. *Scand. J. For. Res. 15:177-187.* *Moberg, L. 2001. Models of internal knot properties for Norway spruce. Forest Ecology and Management 147:123-138.*
Algorithm	*Additive function, see function expressions below. This is a segmented non-linear model consisting of three parts (hyperbolic-quadratic-quadratic) in the vertical direction.*
Calculation procedure	*The model requires information about the stem for each knot whorl, which can be generated by a height development function (e.g. Elfving & Kiviste 1997 for pine). Alternatively, the knot whorls are disregarded and, for example, one value per 10 cm from stump height (1% of total height) to total height is generated. To be calculated before knot length.*
Program code	*See SAS code in below.*

$$KD_k = \begin{cases} a\dfrac{H_k}{b_1 + H_k} & (H_k \le h_1), \\ a\dfrac{h_1}{b_1 + h_1} + \left(c(h_2 - H_t) + d(h_2 - H_t)^2 - a\dfrac{h_1}{b_1 + h_1} \right)\left(\dfrac{H_k - h_1}{h_2 - h_1} \right)^2 & (h_1 < H_k < h_2), \\ c(H_k - H_t) + d(H_k - H_t)^2 & (H_k \ge h_2), \end{cases} \tag{1}$$

$a = a_1\, T_{sum} + a_2\, DBH_{rel} + a_3\, RW_{1\text{-}20}$ (1.1)

$c = c_1\, DBH + c_2\, AGE + c_3\, CL + c_4\, DBH\, CL$ (1.2)

$$d = \left(\left(c(H_t - h_2) + a\frac{h_1}{b_1 + h_1} \right)(h_2 - h_1)^{-1} + \frac{c}{2} \right)\left((H_t - h_2) + \frac{(H_t - h_2)^2}{h_2 - h_1} \right)^{-1} \tag{1.3}$$

$h_1 = \mathrm{MIN}\{h_{11}\, SI,\ h_2 - h_3\}$ (1.4)

$h_2 = H_t - h_{21}\, CL$ (1.5)

Results of the model				
Variable	Unit	Integer or floating number	Max/Min	Description
KD_k	*mm*	*decimal*	*70/1 (fix at max/min)*	Internal knot diameter at sound knot boundary or cylindrical surface.

Variables of the model						
Variable	Unit	Integer or floating number	Max/Min	Description	Rikstax reference	
					Variable	Table
H_k	*m*	*Floating*	*$0.99\ H_t$/ $0.01\ H_t$*	Height in the stem (possibly from height development function)		
T_{sum}	°C-days	*Integer*		Temperature sum = 4922.1 - 60.367*latitude - 0.837*altitude (Moren & Perttu 1994)	TSUMMA? BREDGR HOJDOH	AREAL TRAKT AREAL
DBH_{rel}		*Floating*		Relative breast height diameter = DBH / DBH_{mean}		
RW_{1-20}	*mm*	*Integer*		Year-ring width, pith – year 20 (can be calculated)		
DBH	*cm*	*Floating*	*50/5*	Breast height diameter on bark	DIAMETER	KLAV-TRAD
DBH_{mean}	*cm*	*Floating*		Basal area weighted mean diameter	MDITALL MDIGRAN	AR-BERF AR-BERF
AGE	*years*	*Integer*	*160/20*	Total age	BRHAL-DER? BESTALD?	KLAV-BER AREAL-SKM
H_t	*m*	*Floating*	*-/5*	Overall height	HOJD?	PROV-TRAD
CL	*m*	*Floating*		Crown length = $H_t - H_{llb}$		
H_{llb}	*m*	*Floating*	*$0.9\ H_t/0$*	Crown limit (can be calculated, see Pettersson, H.) 1997. Scand. J. For. Res. 12(2):179-188).		
SI	*m*	*Floating*	*38/12*	Site index, H100	SITALL SIGRAN	AREAL-BON

Area of application of the functions			
Function 1	Function 2	Function 3	Function 4
Max diameter per knot whorl Pine	*Mean diameter per knot whorl Pine*	*Max diameter per knot whorl Spruce*	*Mean diameter per knot whorl Spruce*

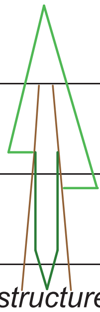
Function coefficients				
Parameter	Coefficient Function 1	Coefficient Function 2	Coefficient Function 3	Coefficient Function 4
a_1	0.00936	0.00576	0.0180	0.00139
a_2	4.49	5.95	1.1602	1.9016
a_3	0.241	0.14	0.9036	0.5838
b_1	0.239	0.199	0.3180	0.3083
c_1	-0.28	-0.116	-0.2464	-0.2009
c_2	-0.0347	-0.0279	-0.005	-0.00326
c_3	0.266	0.105	0.1380	0.0710
c_4	0.0106	0.00485	0.00191	0.00289
h_{11}	0.172	0.277	0.2232	0.2488
h_{21}	1.078	1.1408	0.9477	0.9178
h_3	0.75	0.75	0.5	0.5
R^2			0.618	0.557
RMSE			5.43	4.38

SAS-kod

```
d = ((((c1*DBH + c2*AGE + c3*(Ht-HIIb) + c4*DBH*(Ht-HIIb))
        * (h21*(Ht-HIIb))
        + (a1*TSUM  + a2*DBH/DBHm + a3*RW1_20)
        * (MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3))
        / (b1 + (MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3))))
        / (Ht - h21*(Ht-HIIb) - MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3)))
        + 0.5*(c1*DBH + c2*AGE + c3*(Ht-HIIb) + c4*DBH*(Ht-HIIb)))
        * 1/(h21*(Ht-HIIb) + ((h21*(Ht-HIIb))**2) / (Ht - h21*(Ht-HIIb)
        - MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3)));

IF Hk < MIN(h11*SI, Ht-h21*(Ht-HIIb)-h3) then do;
  KDk = (a1*TSUM  + a2*DBH/DBHm + a3*RW1_20) * Hk / (b1 + Hk);
end;
else do;
  if Hk < (Ht - h21*(Ht-HIIb)) then do;
    KDk = (a1*TSUM  + a2*DBH/DBHm + a3*RW1_20)
                 * (MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3))/(b1 + (MIN(h11*SI,Ht-h21
                   *(Ht-HIIb)-h3)))
                 + (((c1*DBH + c2*AGE + c3*(Ht-HIIb) + c4*DBH*(Ht-HIIb))
                   *(-h21*(Ht-HIIb))
                 + (d)*(-h21*(Ht-HIIb))**2
                 - (a1*TSUM  + a2*DBH/DBHm + a3*RW1_20)
         * (MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3)) / (b1 + (MIN(h11*SI,
                   Ht-h21*(Ht-HIIb)-h3))))
         * (Hk- (MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3)))**2
         / (Ht - h21*(Ht-HIIb) - MIN(h11*SI,Ht-h21*(Ht-HIIb)-h3))**2);
  end;
  else do;
    KDk = (c1*DBH + c2*AGE + c3*(Ht-HIIb) + c4*DBH*(Ht-HIIb)) * (Hk-Ht)
                 + d * (Hk-Ht)**2;
  end;
end;
```

Sound knot cylinder. General information.	
Model description supplied by	*NTI*
Model	*Sound knot cylinder*
Objective and description	*The models describes an internal sound-knot structure in individual standing trees from old even aged stands of Norway spruce (Picea abies). The sound-knot cylinder is defined from 10 % of the tree height and up to the live crown.*
Reference	*Øyen, Ola. 1999. Wood quality in Old Stands of Norway Spruce (Picea abies (L.) Karst.) (Virkeskvalitet i skog av gammel gran (Picea abies (L.) Karst.)). Department of forest Sciences. Agricultural University of Norway.*
Modelling method	*Multiple Linear regression*
Estimated value	*85%SKCi*



Parameter definitions, Sound knot cylinder		
Variable	Unit	Definition
R85%	*mm*	*85 % quantile based on a normal distribution assumption for the sound-knot length.*
85%SKCi	*mm*	*85%SKCi =2 x R85%*
DBH_u	*mm*	*Diameter at breast height under bark (mm)*
Age	*year*	*Age at breast height*
LCP	*dm*	*Height to the lower crown point (180°)*
RC	*%*	*The difference between tree height and lower crown point relative to tree height*
LLW	*dm*	*Height to lowest living branch-wreat (at least ¾ of the branches are alive)*
Site index	*None*	*H40*

Model results, Sound knot cylinder	
Model number	Model
1	*35,8+0,389* DBH_u
2	*47,9+0,434* DBH_u *-0,254 Age*
3	*66,1+0,449* DBH_u *-0,301 Age – 0,018 LCP*
4	*74,3+0,466* DBH_u*-0,243 Age -0,028 LLW*
5	*-21,2+0,57* DBH_u*+0,464 RC+2,226 Site index*

Model accuracy, Sound knot cylinder					
Model number	F-ratio	Pr>F	RMSE	R^2	DF
1	150,8	<0,0001	20,9	0,631	1,88
2	88,2	<0,0001	19,9	0,670	2,87
3	69,7	<0,0001	18,8	0,709	3,86
4	78,8	<0,0001	18,4	0,720	3,85
5	59,8	<0,0001	19,8	0,676	3,86

Bending strength on round small-diameter timber General information.	
Model description supplied by	*NTI*
Model	*Bending strength on timber*
Objective and description	*Bending strength on small-diameter timber of Scots pine in Finland.*
Reference	*Alpo, Ranta-Maunus. 1999. Round small-diameter timber for construction: Final report of project FAIR CT 95-0091 / Edited by Alpo Ranta-Maunus, VTT Building Technology.*
Modelling method	*Multiple Linear regression*
Estimated value	f_m

Parameter definitions, bending strength on round small-diameter timber		
Variable	Unit	Definition
f_m	*N/mm²*	*Bending strength of round small-diameter timber*
B	*None*	*81,9 (constant)*
d	*mm*	*Diameter of the specimen measured at or close to the failure point*
ks	*mm*	*Knot sum measured at or close to the failure point*
r	*mm*	*Ring width measured at or close to the failure point*
u	*%*	*Moisture content measured at or close to the failure point*

Model results, bending strength on round small-diameter timber
$\mathrm{f_m} = B - 0{,}104\frac{ks}{d} - 30{,}51\lg r - 0{,}63u$

Model accuracy, bending strength on round small-diameter timber			
F-Value	Pr>F	Standard error	R^2
222,5	<0,0001	9,826	0,6

Annual ring width and basic density - Variation from pith to bark General information about model	
Investigation	*Physical and mechanical properties in Norwegian spruce and pine- An activity in the SSFF project.*
Objective and description	*The variation in wood properties has been investigated in the x- and y-direction of standing trees and between trees from stands in southern Norway*
Reference	*Bramming, Jan. 2006. Fysiske og mekaniske egenskaper hos norsk gran og furu – en aktivitet I SSFF-prosjektet. Treteknisk rapport nr. 65.*
Modelling	*Multiple Linear regression*
Limitations	*No thorough statistic analysis on variation in x and y-direction has been done yet*

9.2 Models for predicting softwood veneers

Species: Pinus Pinaster

❶ Model of size and shape of stem

Input needs	**Stand data**: **Tree data:** CBH (cm): circumference at breast height (bh) over bark Ht (m): total height Hr (m): Relative height (h/Ht)
Output	**Circumference on bark at height h:** C_h=CBH*A+(-13.964 + 0.5996 CBH + 0.6281 Ht) ((1-Hr^3)- A*(1-$(1.3/Ht)^3$)+ 2.668(1-A) With A = Log Hr / log (1.3/Ht) **Bark Thickness at height h:** E_h=1,3 + 0.075 C_h - 0.85 $(DBH)^{1/2}$ Log Hr
Possible applications within IK	Inputs for wood properties models
References	Najar M. (1998). Modèle de croissance et qualité pour le pin maritime. 30 pp.

❷ Model of growth pattern of stem

Input needs	**Stand data**: Age **Tree data:** Dbh Height
Output	Mechanical behaviour of maritime pine
Possible applications within Ikey	Include laws into CTL
References	**Reuling D., Castera P. (2005)** “Increase Maritime Pine used in housing with PP3 growth model“ Master Research Report in Wood Science (in French), Bordeaux I, juin 2005

❸ Model of wood properties

Input needs	**Stand data**: Age (years) Mean volume of the stand (m^3) Height of first dead branch (or first dead whorl) **Tree data / Logs data:**
Output	**Wood density** Mechanical properties Veneers quality Model that gives the veneers quality (aspect) potential of the mean trees of a stand Paper Properties Model that gives Fiber length and paper properties based on logs diameter and growth rate of the stand
Possible applications within Ikey	Already used into processes
References	Veneers quality Moreau J., 2000. Confidential study for Smurfit Kappa Rol Pin

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