LICENTIATE THESIS

Computer Simulation in the Forestry-Wood Chain

Magnus Fredriksson

LULEÅ UNIVERSITY OF TECHNOLOGY

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ABSTRACT

The forestry-wood chain today involves many actors, and the decisions taken in the process of making trees into finished products are so many that the effect of each individual decision is difficult to assess, especially if the natural variation of the input material is considered.

This means that a simulation approach to the forestry-wood chain is suitable, since it makes it possible to evaluate the effects of decisions in a short timeframe, while the input material can be kept constant for different production setups. The long term aim is to connect tree and log properties to the quality of a final product through simulation, depending on the various operations involved in making the product.

A part of this is realized through this thesis. It is shown that a simulation model of a cross-cutting and finger-jointing process is representative of a real process. The model is used to evaluate an adaptive strategy for setting the safety zone size between finger-joints and sound knots, a strategy which improves recovery in a finger-jointing operation by 3 %.

Another issue addressed in this thesis is that of simulation input data. The sawing simulation tool used to a large extent in research today, Saw2003, uses the Swedish Pine Stem Bank as input data. This is a very well-documented data source, and computed tomography (CT) scanning of the stem bank logs allows wood features such as knots to be represented in a realistic way in Saw2003. There are limitations to the stem bank, however, mostly due to the fact that CT scanning is a time consuming process, which means that the amount of scanned logs is relatively small. In this thesis, it is shown that it is possible to use a small amount of log features for determining the knot structure in a log, which opens up possibilities for using industrial data from two-directional X-ray scanners. This would increase the amount of logs to be used as simulation input data.

A second set of data used for simulation was also collected in a study of a production process, where the wood raw material was followed from the log yard through all production operations of making finger-jointed furniture components. Each individual piece of wood was traced through the operations, thus ensuring a link between the properties of logs and those of the finished product. This second data set was collected by grey-scale camera scanning of boards prior to cross-cutting and finger-jointing, and was used in the development of cross-cutting and finger-jointing simulation. It contains information on non-clearwood features of the board surfaces such as knots, cracks, and pitch pockets.

It can be concluded from this thesis that it is possible to increase both functionality and the amount of input data in the simulation of the forestry-wood chain, and by doing so production strategies and decisions can be evaluated. Wood quality discussions may be simplified by being able to assess the effects on the production process of decisions being made. Future work involves adding more functionality to the simulation environment as well as evaluating the methods proposed in this thesis industrially. The long term vision is to be able to integrate the forestry-wood chain from log to finished product in one simulation model.

PREFACE

The work of this thesis has been carried out at the Division of Wood Science and Engineering at Luleå University of Technology, Skellefteå. The research work was funded by WoodWisdom-Net and VINNOVA through the project CT-Pro and by the European Union Objective 2, as well as by WoodCenter North. This financial support is acknowledged and highly appreciated.

Scientific work is never done alone. First and foremost, I would like to express my gratitude to my supervisors: Professor Anders Grönlund, Associate Professor Olof Broman, and Associate Professor Micael Öhman, for all their support, suggestions, and interesting discussions in both formal and informal circumstances. Thank you for always taking time to answer my questions and keeping my spirits up, and for your knowledge and ideas; it is a privilege to work alongside all of you.

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I would like to thank the ice-hockey team IF Björklöven for teaching me some life-lessons and to cope with disappointments; it can always get worse…

From being an ice-hockey supporter I have also learned the importance of savouring those precious moments of brief success. You never know when they will return.

Finally, my warm thanks go out to my family and friends for supporting me and teaching me new things every day. Some of you I see much too seldom, unfortunately.

I do not have space to express my gratitude to everyone who deserves it, but thank you to all others who have contributed and advised me in some way, both formally and informally.

Grazie e c'i vediamo!
Skellefteå, April 2012

Magnus Fredriksson

LIST OF PAPERS

Paper I.
Olof Broman, Magnus Fredriksson (2012) Wood Material Features and Technical Defects that Affect Yield in a Finger Joint Production Process. *Wood Material Science and Engineering*, submitted paper.

Paper II.
Magnus Fredriksson (2011) A simulation tool for the finger-jointing of boards. *Proceedings of the 20th International Wood Machining Seminar*, *Skellefteå, Sweden, 7–10 June*.

Paper III.
Magnus Fredriksson, Micael Öhman, Haitong Song (2012) Adaptive cross-cutting safety zone for finger-jointed *Pinus Sylvestris* L. furniture components. *Forest Products Journal*, submitted paper.

Paper IV.
Magnus Fredriksson (2012). Reconstruction of *Pinus Sylvestris* knots using measurable log features in the Swedish Pine Stem Bank. *Scandinavian Journal of Forest Research*, accepted ahead of print, available online from 7 February 2012.

CONTENTS

1. Introduction

1.1 Computer simulation in the forestry-wood chain

In recent years, there has been an increased interest in an integrated approach to the forestry-wood chain. This means that forest and tree characteristics are seen as linked to the end-user requirements for wood products (Houllier et al., 1995; Bengtsson et al., 1998; Nordmark, 2005; Broman et al., 2008). The aim of an integrated approach is to utilize knowledge of both the end-user requirements for different wood products and of the properties of trees and logs in order to control the flow of material from forest to market and to achieve an improved use of the raw material. However, the forestry production chain is complex, due to the nature of the raw material, the various stages of production, various actors, and the decisions taken in harvesting, breakdown, cross-cutting, final processing, and marketing (Bengtsson et al., 1998).

This complexity means that computer simulation is a suitable tool for analysing the forestry-wood chain, as it allows for experimentation with complex systems without disrupting the system itself, achieving better control over experimental conditions, and studying a system with a long time frame (Law, 2007).

Simulation efforts so far in wood research have focused mainly on the early parts of the forestry-wood chain, resulting in the log breakdown recovery simulation tools described by Nordmark (2005) and Usenius (2007) or the numerous commercial programs on the market. They model the recovery and board quality in sawmills. Another area of interest is discrete event simulation and other simulation tools used for both sawmills and secondary wood processing (Adams, 1984; Kline et al., 1992; Reeb, 2003). Lundahl (2009) relied on both discrete event simulation and log breakdown simulation in his doctoral thesis work. There are also tools available for the simulation of traditional cross cutting (Giese & Danielson, 1983; Thomas, 1998). Cross cutting and finger jointing of wood with unwanted defects have been described by Åstrand (1996). Eliasson and Kifetew (2010) studied the impact of raw material quality on finger-jointed Scots pine boards by using a scanner with the optimization algorithm described by Åstrand (1996).

The log breakdown recovery simulation software Saw2003 described by Nordmark (2005), which is used as an important research tool today, uses the Swedish pine stem bank (SPSB) as the source of input data. The SPSB consists of data for 198 Scots pine trees which have been felled and bucked into 628 logs. The stem bank logs have been scanned with a medical computed tomography (CT) scanner in order to record internal properties such as knots, pith location, and sapwood/heartwood border (Grönlund et al., 1995). These properties are used to predict the quality of sawn boards when simulating breakdown of the SPSB logs (Nordmark 2005), and is the sole source of input data to Saw2003.

Computer simulation in the forestry-wood chain will contain the areas outlined in Figure 1. Some of the work has already been done, either in the shape of previous research or in the work presented in this thesis.

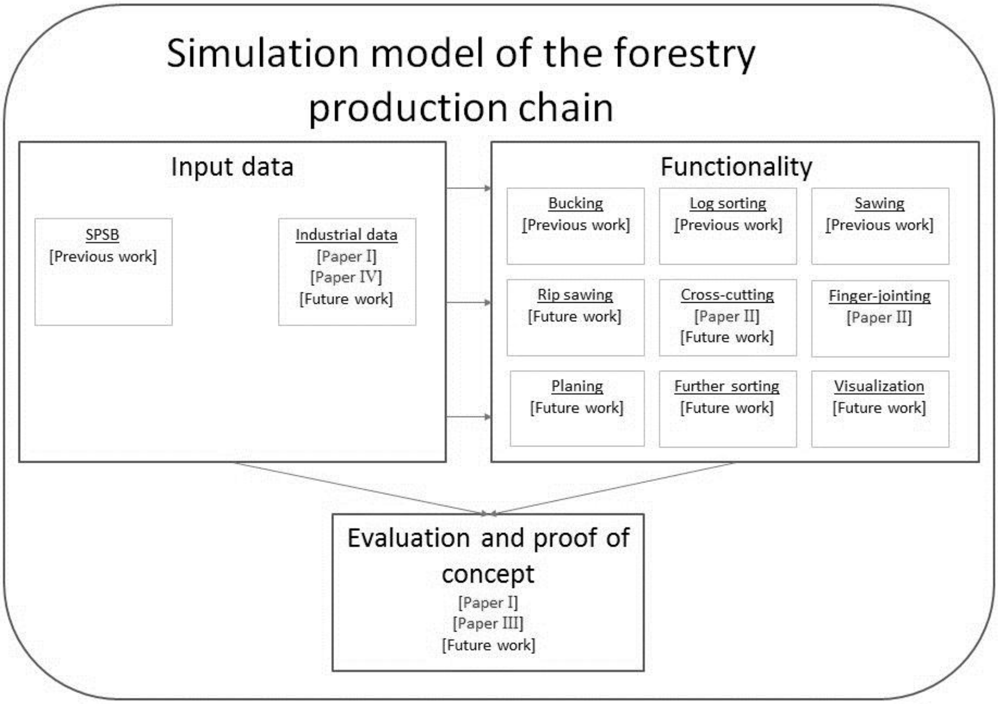

Figure 1. Outline of a simulation model for the entire forestry production chain. It involves past, present and future work.

The possibility of performing sawing simulation on the SPSB material has been beneficial for the wood technology research (Chiorescu and Grönlund, 1999, 2001; Nordmark, 2005; Moberg and Nordmark, 2006), in large part due to the thorough documentation of the stem bank trees. An extension of the earlier work will be to be able to predict the effects of further processing, such as planing, cross-cutting, and rip sawing, on the quality of the sawn timber. A first step is to enable cross-cutting and finger-jointing simulation of simulated boards based on the SPSB. This is presented in Paper II, and is part of developing simulation *functionality* (Figure 1).

In Paper I, a study of a production process is described in detail, and it is also presented to some extent in the *Materials and methods* section. This paper provided input data for other parts of this thesis, and is thus a part of *Input data* and *Evaluation and proof of concept* (Figure 1).

1.2 Wood quality

In the field of recovery simulation, it is almost inevitable that wood quality will be concerned in one way or the other. Wood quality is a concept which varies across time and place. A few definitions have been put forth, like that of Mitchell (1961): “Quality is the resultant of physical and chemical characteristics possessed by a tree or a part of a tree that enable it to meet the property requirements for different end products”. This definition conforms well to the more general definitions of product quality, such as the simply phrased one proposed by Juran (1951): “Fitness for use”, or the definition by Deming (1986): “Quality should be aimed at the needs of the customer, present and future”.

One important differentiation in definitions of wood quality is that which separates the quality of logs from that of sawn timber. Logs are scaled in order to decide the price for each log in the seller/buyer relationship of sawmills and forest owners; however they can be quality graded and sorted as well. Sawn timber, on the other hand, is quality graded in order to put a price on the boards in the relationship between sawmill and customer. The quality of sawn timber is normally defined from either a construction perspective (strength grading) or an appearance perspective (visual grading), or both. One visual grading definition for sawn timber is the Nordic Timber Grading Rules (Anon., 1994) or the older “Green Book” (Anon., 1980). These grading rules define certain levels of size and frequency of wood features, which, in turn, define the quality class of sawn timber. The Nordic Timber Grading Rules are used by sawmillers throughout the Nordic countries as the basis for quality sorting. There are also other rules such as those defined in several European standards: EN 942:2007 (European Committee for Standardization, 2007) for joinery, and EN 1611-1 (European Committee for Standardization, 2000) for sawn timber, are two examples. Nylinder (1959) claims that knottiness is probably the most important quality feature of a tree. This suggests that the board feature which is most important to model in recovery simulation is knots.

The difficulty of quality grading boards manually by grading rules is shown by Grundberg and Grönlund (1997) as well as Grönlund (1994). Their studies show that different persons grade the same boards differently to a large degree, which is to a large extent due to differences in judging the size of knots.

Current secondary processing of wood is characterized by a high degree of automation. This has increased both production speed and volume. However, discrepancies can occur between the desired and actual quality of the finished product. There are many factors contributing to this problem, which will not be elaborated upon here, but the effect is that some products are rejected during the latter stages of production, which can be a costly waste of resources. Due to the biological nature of the material, the rejection of some products due to wood features cannot be totally avoided, but it is therefore important to utilize knowledge of the biological features of boards in order to handle them appropriately in the production process and minimize this loss.

1.3 Chipped finger-joints and cross-cutting safety zone

In the case of vertically finger-jointed furniture components, one important defect causing rejection is chipped finger-joints. This is shown in Paper I. This defect is caused when milling a finger-joint where fibres at an angle to the board surface have a lower strength in the vertical direction than the fibres parallel to the surface, and are more easily chipped away. This can be described by a Hankinson-type formula, which relates the elastic strength of wood to the angle of the fibre direction:

$$N = \frac{PQ}{P \sin^n A + Q \cos^n A} \tag{1}$$

where:
N = strength at grain angle *A* from the longitudinal fibre direction
Q = strength perpendicular to the fibre direction
P = strength parallel to the fibre direction
n = an empirically determined constant

At grain angle $A = 0$, *N* will be equal to *P*. With an increased *A*, *N* will approach *Q*, and since *Q* is usually significantly smaller than *P*, and *n* is in most cases set to values around 2, the strength will be significantly reduced even for relatively small values of *A* (Bodig and Jayne, 1982).

Currently, a common strategy to deal with this problem is to use a safety zone between finger-joints and non-clearwood features, such as knots, which has the downside that a larger amount of material is cut away in the cross-cutting process prior to finger-jointing. It is common practice that the size of this safety zone is set to a fixed value regardless of type and/or size of the feature.

Öhman and Chernykh (2011) describe a model to predict the size of the so-called diving grain-area (Figure 2), based on knot size and location. This area is almost exclusively located around sound knots, whose fibres are inter-grown with the wood fibres of the stem, in contrast to dead knots, which are not connected to the normal wood in the same fashion. Their model is supposedly useful for reduction of chipping in finger-joints, but they do not elaborate on how this may be achieved.

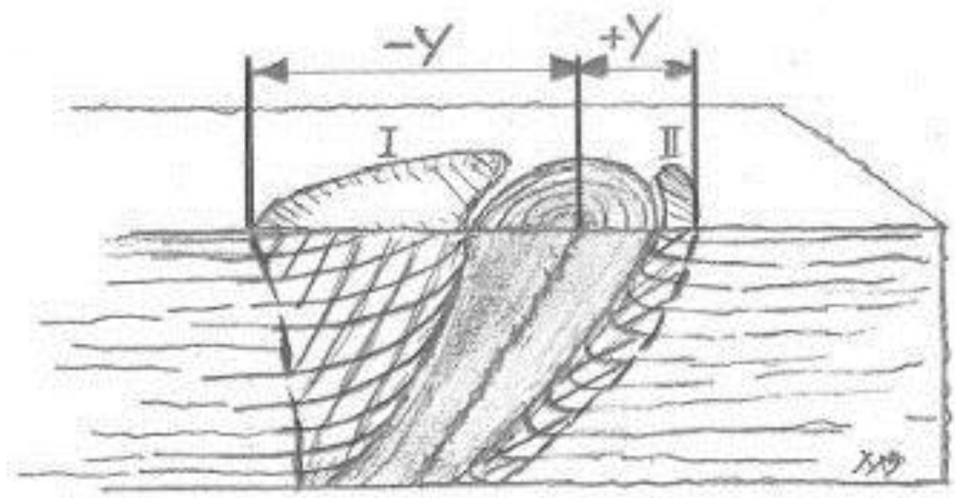

Figure 2. Principal sketch of the diving grain area around a knot. I and II correspond to the regions surrounding the knot where the fibres deviate substantially from the longitudinal direction. Image from Öhman & Chernykh (2011).

One hypothesis presented in this thesis is that a suitable strategy for production of finger-jointed furniture components is to use a flexible safety zone around sound knots, based on the size of the knot. Such a strategy has potential benefits, since it will not cut away more material than is needed as a safety measure. The testing of this strategy is part of the *Evaluation and proof of concept* (Figure 1) and is further described in Paper III.

1.4 Simulation input data

An issue with using sawing simulation for research purposes or production planning is the relatively small amount of data available today. Since the SPSB is limited to 198 trees, it is problematic to evaluate the validity of results of sawing simulation based on this material. It is thus desirable to be able to increase the amount of input data for simulation.

A knot reconstruction method using two-directional X-ray could provide a source which would allow a significant number of new virtual logs to be used in simulations. The reason for this is that a large number of logs are scanned in sawmills on a daily basis. This requires a novel method of reconstructing knots from log features that can be detected by a two-directional X-ray scanner. These features are far scarcer than features extracted from CT scanning. The reconstructed knots should be represented in the same parametric fashion as in the stem bank, to allow sawing simulation. The shape of the logs, which is also necessary for creating logs for sawing simulation, can be obtained from optical 3D-measurements at sawmills, an issue which is not addressed here. The knot reconstruction study will be part of developing *input data* (Figure 1), and is presented in Paper IV. It is based not on actual X-ray images at this stage but on a few internal log features of the SPSB.

1.5 Objectives

The long term vision is to be able to integrate the forestry-wood chain from forest to market in a simulation environment. A portion of this vision is being realized through the work of this thesis. This is formulated in the following objectives:

- To develop a simulation method to model cross-cutting and finger-jointing of boards with surface wood features, using the SPSB as input data.
- To show the potential of simulating further processing of wood in order to develop novel production strategies, by testing an adaptive safety zone strategy for cross-cutting and finger-jointing.
- To study the possibility of enlarging the amount of data available for sawing simulation by using a small number of log features in the SPSB, representing discrete X-ray scanning of logs.

2. Material and methods

2.1 An industrial case

A central part of the studies presented here is a case study of a wood furniture component production process, which is presented in detail in Paper I. The finger-jointed components (e.g. bedsides) of final dimensions 25 × 110 × 2018 mm were made from 177 Scots pine (*Pinus sylvestris* L.) logs. The logs were each sawn into two 33 × 120 mm center boards, green size, and kiln dried to 14% moisture content. The nominal dimensions after drying were 31 × 115 mm with varying lengths.

The secondary processing of the boards is described by a flow chart in Figure 3. The boards were scanned using a WoodEye (Innovativ Vision AB, 2012) industrial scanner which was equipped with four greyscale line cameras for wood feature detection and a laser for measuring board dimensions and grain direction. The scanning equipment also included cross-cut optimizing software. Unwanted features such as large knots, wane, or cracks were cut away from the boards, and the resulting pieces were finger-jointed together and cross-cut to a final length of 2018 mm. Planing operations took place both during and after the finger-jointing process. In the final steps of the production process, the boards went through a quality inspection where rejected components were sorted out before the final processing of the product.

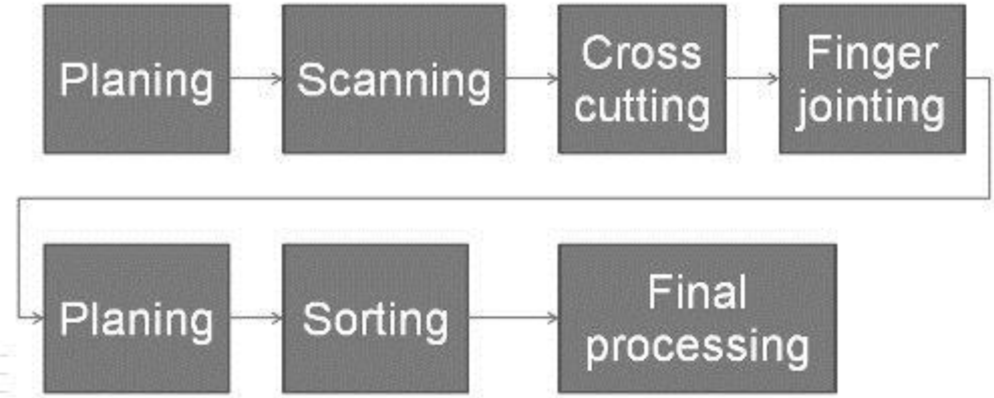

Figure 3. Description of the later part of the furniture production process, from boards to furniture components. The scanning and cross-cutting operations are closely connected, since large non-clearwood features detected in the scanner are cut away in the cross-cutting operation. The final sorting is done in order to find features not visible before planing, and was in this case done manually. A further description of the process is provided in Paper I.

2.2 Material

The development and study of simulation in the forestry-wood chain was mainly based on two sets of input data. One is the SPSB, based on CT scanning of logs, and the other is based on scanning of sawn and planed timber in the process described above.

The SPSB knot database is based on 11 parameters named A to K, derived from CT-images of logs (Grundberg et al., 1995). The geometry of each knot is described by these parameters and the parametric description makes it possible to describe knots in a tree with a minimal amount of data. A further description of the knot parameters is included in Grönlund et al. (1995) and in Paper IV. The SPSB was used in Paper II to validate the finger-jointing simulation tool as well as in Paper IV as a basis for a knot reconstruction method from internal log features.

The other set of input data used was collected at the finger-joint mill in the production process described, where sawn and planed boards were scanned using the industrial scanning equipment WoodEye (Innovativ Vision AB, 2012).

Information was collected on non-clearwood features (type, position, size) and the length of every cross-cut piece in addition to the board from which the piece was cut. This was the dataset used in the development of the finger-jointing simulation program, and it contained data for 354 boards. It was used in Papers II and III.

2.3 Simulation program for cross-cutting and finger-jointing

A computer program imitating a cross-cutting and finger-jointing process was developed in the programming language C++. The program uses board and surface feature data which are a result of Saw2003 (Nordmark 2005) or a WoodEye scanner, with information regarding board dimension, feature position, type, and size. It is also subject to various process settings, including product dimensions, maximum and minimum acceptable length of cross cut pieces, length losses in finger joints, quality requirements regarding the maximum size of surface features on the product, minimum acceptable distance between feature and cutting position, and so forth.

The simulation result is a length recovery figure for every board, taking into account all losses generated in the finger jointing process. Total length recovery, number of components, number of cross cut pieces, and all cutting positions for each board are also recorded. Length recovery is defined as the total length of the finger-jointed products divided by the total length of the boards that are cut and jointed.

A comparison was made of simulation results using two sets of input data: the data from the SPSB and the data from the industrial scanner. In this comparison only knot features were taken into consideration. This was done because the SPSB does not contain any data regarding other types of features. From the dataset taken from the SPSB, two subsets were also tested: one with trees taken from high site index (SI) (T28) plots and one with trees from low SI (T16) plots. In order to facilitate comparison, the same products as in the case study were used for the simulations: finger-jointed boards with the dimensions 31 × 115 × 2018 mm.

2.4 Adaptive safety zone strategy

An adaptive strategy for setting the safety zone size when cross-cutting and finger-jointing boards of Scots pine was developed, based on measurements of sound knots.

All sound knots within 30 mm of the tip of the teeth of each finger-joint were measured using a carpenter's rule. The measurement principle is described in Figure 4. The following features were measured and registered (the unit of measurement is given in square brackets):

- *D* = Distance from finger-joint to sound knot (from tip of tooth to knot edge, lengthwise direction of board). This was set to 0 if the knot was within the finger-joint [mm]
- *L* = Length of sound knot (lengthwise direction of board) [mm]
- Whether the finger-joint is chipped or not [yes, no]. Figure 5 shows an example of a chipped finger-joint due to a nearby sound knot.

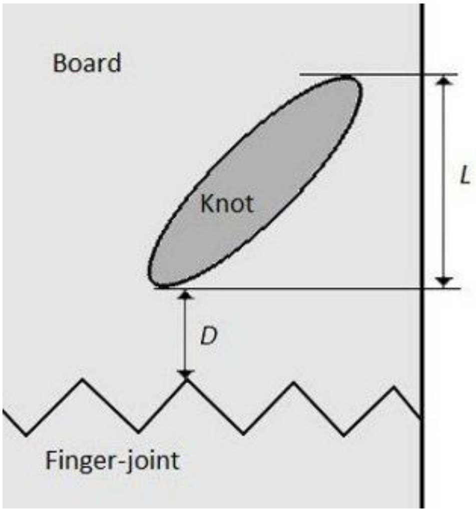

Figure 4. Principle of measurement. *L* = Length of sound knot in the lengthwise direction of the board, *D* = Distance from finger-joint to sound knot.

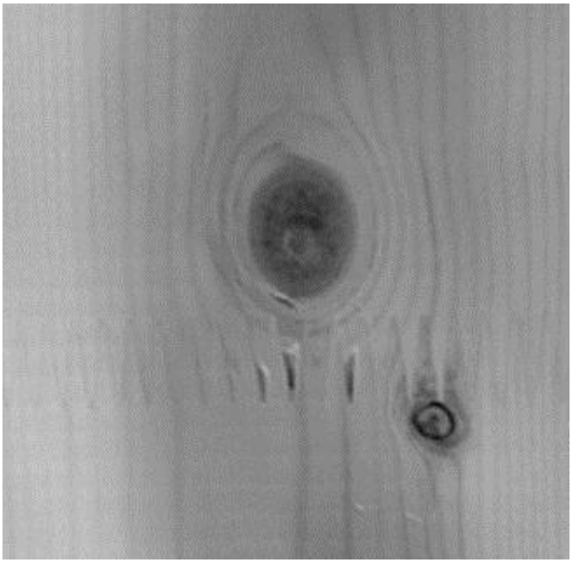

Figure 5. One example of a chipped finger-joint caused by a sound knot. Note that the small black knot does not cause chipping.

Overall, 1173 knots were measured.

From the measured knot data, a linear regression model was constructed to predict the risk of chipping in the finger-joint depending on two variables: size of sound knot in the longitudinal direction *L* and distance between knot and finger-joint *D*.

Using the results from the analysis of the knot measurements, a strategy for deciding the safety zone length between sound knot and finger-joint was developed.

The adaptive safety zone was decided for each sound knot in order to minimize the expected loss resulting from the decision. The expected loss of length was calculated according to:

$$E_L = risk_{fjD} \cdot length_{comp} + D \qquad (2)$$

where:
E_L = expected loss
$risk_{fjD}$ = risk of chipped finger-joint, between zero and one, modelled from knot features
$length_{comp}$ = length of finger-jointed component in millimetres
D = safety zone length in millimetres (Figure 3)
The variable $risk_{fjD}$ was calculated using the linear regression model relating $risk_{fjD}$ to L and D, and since $risk_{fjD}$ depends on D, values of D between 1 mm and

150 mm were tested for each sound knot. The distance which resulted in the lowest expected loss was chosen for that particular knot.

This adaptive strategy was tested using the simulation tool developed in Paper II.

Several cases of a fixed safety zone were tested through simulation and compared with the strategy of using an adaptive zone based on sound knot size.

2.5 Knot reconstruction from two-directional X-ray

The development of a knot reconstruction method from internal log features followed the structure presented in Figure 6. The left-hand side of the structure represents work already done within the development of the SPSB (Grönlund et al., 1995), while the right hand side is the contribution of this study.

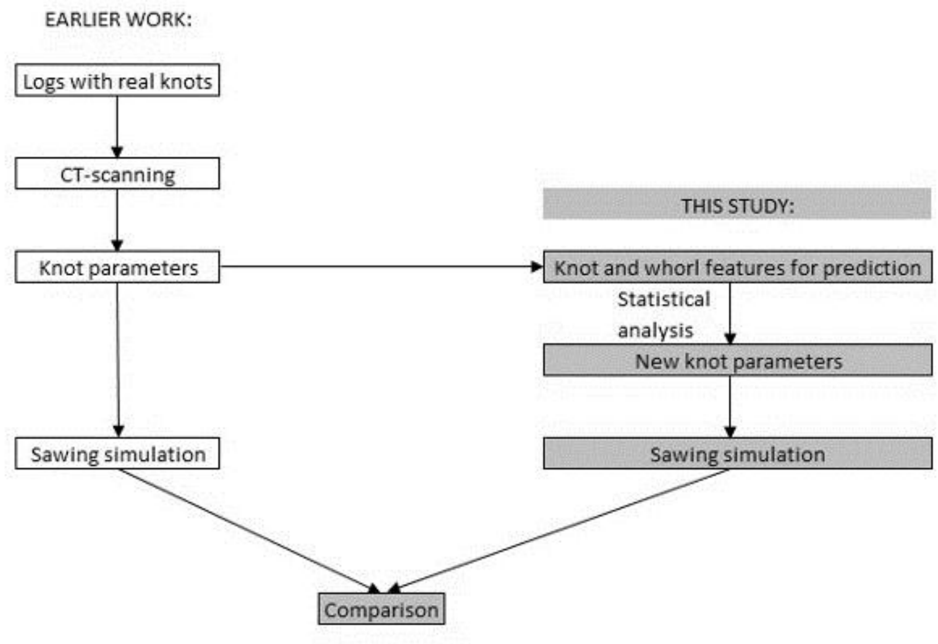

Figure 6. Description of the main structure of the knot reconstruction study. At the last step the sawing simulation is made on the same set of physical knots, but reconstructed in two separate ways. The original SPSB knots (left) are considered ground truth and are also the foundation for the new parameterization of the SPSB knots (right).

The knot reconstruction method is based on four log features, presented in Table 1. In a first step, these features are calculated from the parameterized SPSB knot data, which is a substitute for detecting these features from two-directional X-ray images.

Table 1. Features used for reconstructing knots. These features are possible to extract using two-directional X-ray scanning, and in this study were calculated for the SPSB knots.

Feature	Description	Unit
WhorlHeight	Height of whorl in log	cm
ΔHeight	Distance from one whorl to the nearest whorl in the downwards direction (intercept)	cm
Whorl volume	Total volume of all knots in the whorl	mm^3
SurfaceDist	Distance from the pith to the surface of the log	mm

A method was developed to predict the structure of whorls in a log from these features. The whorl structure was defined by the number of knots in the whorl and the azimuthal distribution of knots. Together with the total volume of the whorl, knot parameters for the knots in the whorl was predicted, and thus the knot structure in a log was reconstructed from a small number of features.

The method was tested by sawing simulation, comparing the resulting board quality with the board quality when using the original SPSB parameterized knots, obtained from CT scanning.

2.6 Simulation

The development of functionality has been focused on recovery simulation, which is not focused mainly on the economic matters of the production process. The recovery simulation models can generally be described as discrete, deterministic, and static. The problem is solved on the board level, where each board is handled as a discrete object. The model is for the most part deterministic; however some stochastic parts are introduced for validation and sensitivity analyses. In the normal case, no stochastic elements are used. The model is static in terms of time; it is not a matter of flow simulation where certain time-dependent quantities are used.

The approach to performing simulations with a stochastic element differed depending on the objective. If the objective was to compare different input data or variations in input data, for instance in sensitivity analysis, the random algorithm was seeded with the same number each time according to the principle of common random numbers (Law, 2007). The seed was not the same each time when testing a method, that is, without variance in input data.

3. Results

3.1 Simulation program for cross-cutting and finger-jointing

The developed software resulted in a length recovery of 81.8% for the simulated cross-cutting and finger-jointing process, compared to 82.8% in the real process. This recovery number was the result when using the data from the industrial scanner as input, thus comparing the industrial case with simulation on the industrial data. Figure 7 presents the cross-cutting decisions made for a few example boards.

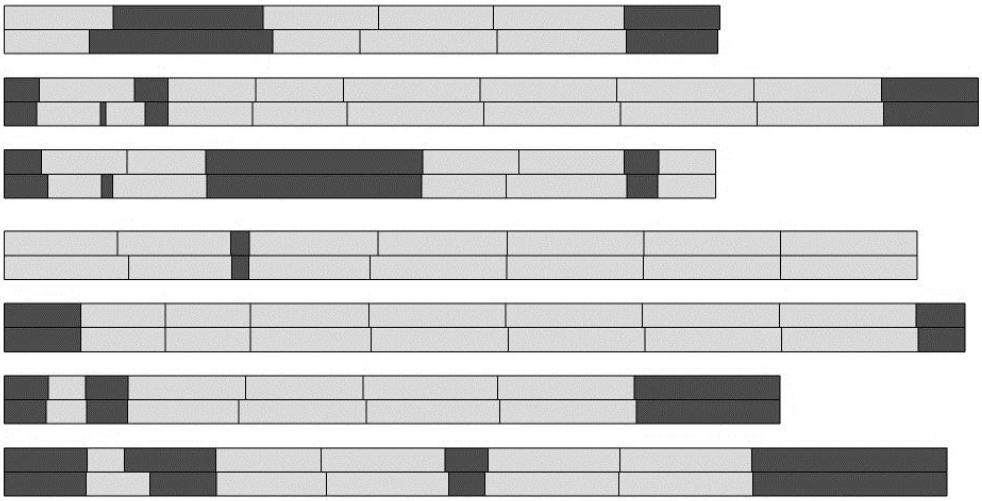

Figure 7. Six boards, with simulated (top) and real (bottom) cut positions. Dark areas are rejected, light accepted. In many cases, the small differences are a result of minor differences in optimization strategies employed by the simulation program and the industrial cross-cutting optimizer.

As another illustration of the similarities in cross-cutting strategy, the frequencies of different lengths of cross-cut pieces are compared in Figure 8. This comparison was made using the data from the industrial scanner.

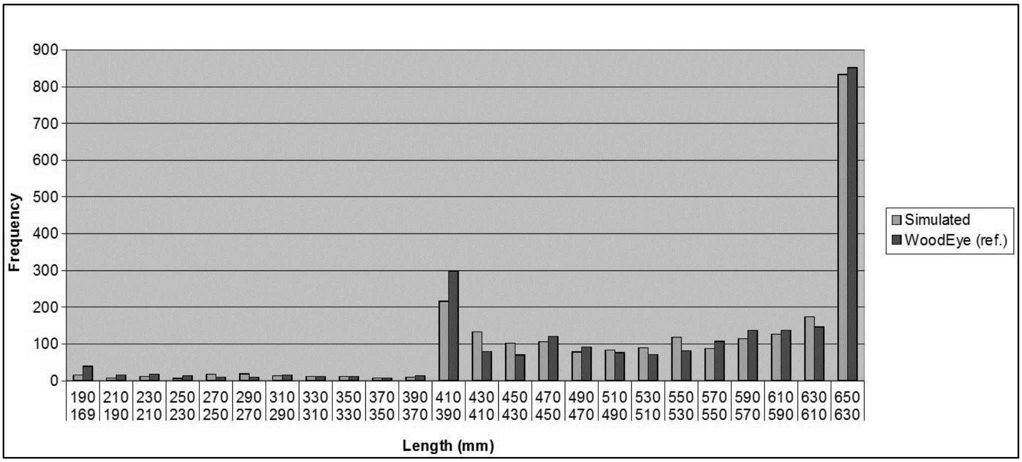

Figure 8. Number of pieces produced in different length classes: comparison of simulation with the empirical results. The simulation was made on the same dataset that yielded the correct lengths (WoodEye). Long pieces are preferable in order to reduce the amount of cuts on each board.

An application of finger-jointing simulation on the SPSB is presented in Figure 9. Here, the quality requirements for sound knots and dead knots were varied, and the length recovery for different input data is shown in the figure. The quality requirements used in the real process are shown as well.

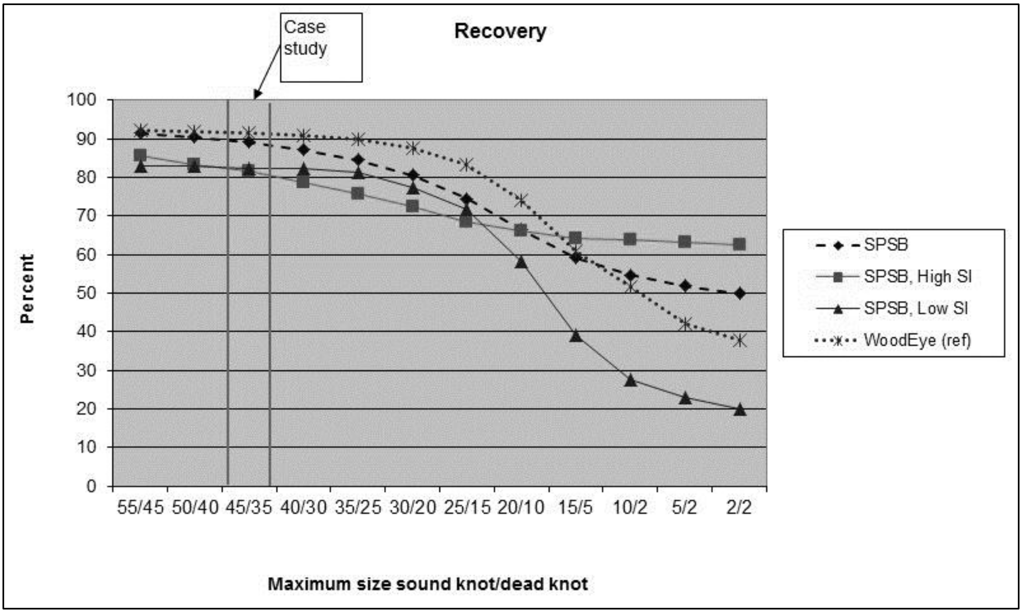

Figure 9. Recovery comparison between industrial data and the SPSB. Both the results for the Stem Bank as a whole and for the two high and low SI sets are plotted. These are compared with the empirical reference data from the industrial scanner (WoodEye). The quality rules of the case study are indicated in the chart: 45 mm maximum acceptable diameter for sound knots and 35 mm for dead knots.

Figure 10 presents the values of boards produced by sawing simulation, for each log in the SPSB, for the first simulation run. The horizontal axis shows the values obtained when using the original SPSB knots and the vertical axis the values when using reconstructed knots.

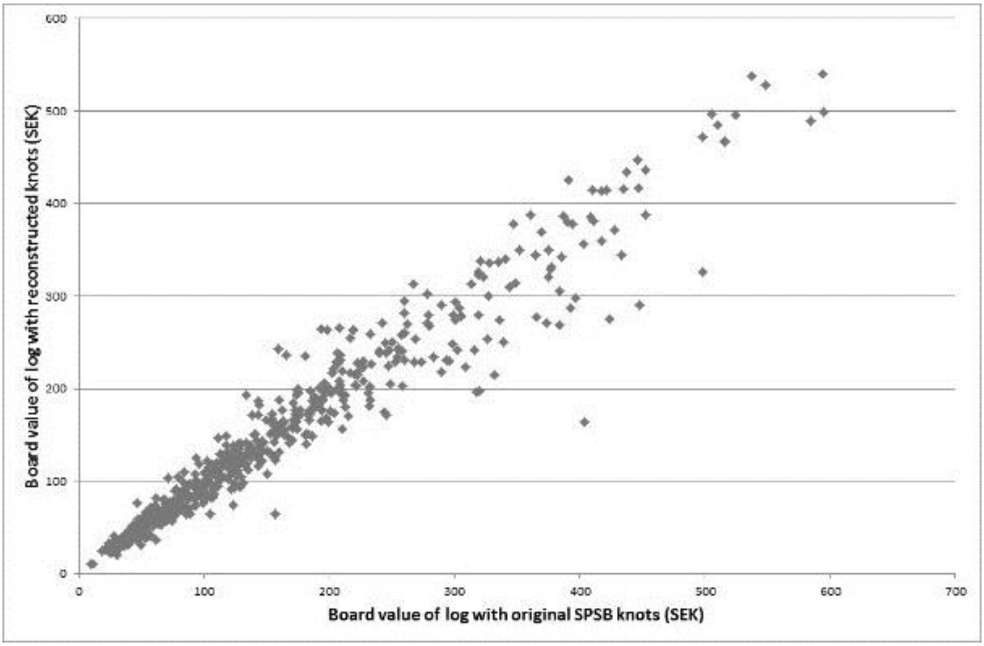

Figure 10. Simulated values of logs with reconstructed knots, plotted against the simulated values of logs with the original SPSB knots; values in Swedish Crowns (SEK).

3.2 Adaptive safety zone strategy

The results of finger-jointing simulation using two strategies, one with a fixed safety zone size and one with an adaptive safety zone size, are shown in Table 2. The results are represented by overall length recovery, recovery for the finger-jointing process alone, average piece length, and average risk of chipping finger-joints. Average piece length is the length of the cross-cut pieces that are to be joined, which should be as long as possible for an efficient finger-jointing process.

Table 2. Strategy of using an adaptive safety distance based on knot size compared to using several values for a fixed distance.

Strategy	Overall recovery (%)	Recovery, finger-joint process (%)	Average piece length (mm)	Chipping risk (%)
10 mm fixed distance	**70.7**	83.1	533.9	14.9
20 mm fixed distance	**79.9**	80.8	531.2	1.2
30 mm fixed distance	**78.3**	78.3	524.5	0.0
Adaptive distance	**83.1**	83.1	533.7	0.0

3.3 Knot reconstruction from two-directional X-ray

The method of reconstructing knots from data that can be extracted from two-directional X-ray was tested by simulation. Sawing simulation using Saw2003 was done on logs with the original knots, obtained from a medical CT-scanner, as well as logs with the reconstructed knots. This was done on all 628 logs of the SPSB. The result shows that the resulting boards with reconstructed knots had the same grade as the boards with the original knots in 63.5% of the cases.

The average numbers of boards in each grade, A, B, and C, for the reconstructed and original knots, respectively, are presented in Table 3. The grading is done according to the Nordic Timber Grading Rules (Anon., 1994), and is further described in Paper IV.

Table 3. Comparison of the grades assigned to boards which have knots reconstructed by the method described and the original SPSB knots.

		Original			
		A	B	C	Percentage correct
Reconstructed	A	**918**	117	150	77.5
	B	248	**584**	248	54.1
	C	214	302	**718**	58.2
	Percentage correct	66.5	58.2	64.3	

4. Discussion

4.1 Wood quality

Several definitions of wood quality exist, each more or less suited for its own purpose. The question is how these definitions correspond to the real situation. In this study, the quality of sawn timber has been in focus, with most attention paid to knots.

Measurement of knot size is a difficult task, no matter whether the measurements are made on images or on physical boards. The border between knot and clear wood is uncertain, especially in sound knots where the knot itself is intergrown with the stem of the tree. This was shown by Grundberg and Grönlund (1997) as well as Grönlund (1994). Nor is the discussion settled on what the ground truth really is concerning knot sizes or whether it is possible to determine such a truth at all. This difficulty means that the results of simulation should not be interpreted as the ground truth for a real production system; however simulation is very suitable for comparative studies since it treats wood features such as knots in a consistent way.

The Nordic Timber Grading Rules (Anon., 1994) were created in order to define quality rules more precisely compared with the older “Green Book” (Anon., 1980). The newer quality definitions made automatic grading of sawn timber easier, especially at the time they were written, when computational capacity was more limited than it is today. Handling one feature at a time is easier for a computer based system compared with a holistic view of visual board “quality”. Furthermore, limits on feature sizes are set to discrete values within the millimetre range, which can be seen in contrast to the fact that the feature size is difficult to determine, especially for knots. Similar quality definitions are often found in industrial scanners for sorting or cross-cutting in the further processing industry as well. In summary, this means that many of the grading rules and criteria used today in parts of the production chain can have an arbitrary effect on both recovery and quality of the final product, something which should be further investigated in future studies.

The way a scanner interprets a wood surface is fundamentally different from the way a human does. Whereas a human in most cases considers the holistic quality perception of a wooden surface, while still taking into account single features, a machine or scanner is nowadays normally programmed to consider one feature at a time, or at best feature clusters.

This means that it is difficult or sometimes impossible to translate customer needs in terms of visual quality of a wood product into parameters controlling scanning and cross-cut optimization equipment, for instance. In many cases, the amount of quality parameters together with process parameters is so vast that it is very difficult to judge how one small change in the settings will affect recovery and the appearance of the final product. Lycken and Oja (2006) showed that it is possible to grade boards by using multivariate statistics, thus obtaining a more holistic view of board surfaces. Such an approach makes it easier to change quality settings and works in a way which is more similar to how an end-user views the sawn timber. However, they do not include the effects of such a grading system on recovery in, for instance, a cross-cutting operation.

This is where a simulation tool connecting tree and log properties to a finished product can contribute. Together with preference studies and improved scanning technology, this can enable improved process control, hopefully up to the point where a large degree of customization of products is made possible. The vision is to keep the consistency of machine scanners while being able to define quality not in a "feature-by-feature" manner but as a holistic interpretation of entire board surfaces. The question of whether this is desirable is important to keep in mind, but since most end-users view sawn timber in a holistic way it is probably so.

4.2 Simulation input data

The SPSB contains almost 200 trees from different geographical locations in Sweden. Although not representative of Swedish pine forests in their entirety, the differences in silvicultural treatment, geographical location, site fertility, and so forth makes this sample sufficiently large and diverse to provide a cross-section of Swedish pine forests which contains good examples of Swedish pine. In a wider perspective, this material is limited geographically to Sweden and by species to Scots pine. Any conclusions drawn here should be drawn in the light of this fact.

The other source of data used, from the industrial scanner, is even more restricted in terms of growth location to the north of Sweden. One should also bear in mind that the collection of these data was done with a different method than for the SPSB and on a different physical material. Whereas the SPSB data are collected by CT scanning of entire logs in green condition, the industrial data are collected by scanning planed boards in dry condition. This needs to be kept in mind when comparing results obtained using different input data.

The possibility of increasing the amount of input data is important, since the SPSB is of limited size. Even though the diversity of the SPSB trees and logs is probably sufficient, it is desirable to be able to use industrial data for simulation. Since a vast amount of logs are scanned in sawmills on a daily basis, the amount of simulation input data will grow rapidly if those data can be utilized. In this study it has been shown that this is possible, provided that a few log features are available.

4.3 Results in context and limitations

In the evaluation of the finger-jointing simulation tool, there is a difference in results between the two sets of input data in terms of length recovery. This can be explained by two main factors: the raw materials are different, and the scanning and image analysis techniques are different. This is further elaborated upon in Paper II. In Figure 9, it can be noted that the input material from low SI sites responds differently to changes in quality definitions compared to the input material from high SI sites. In some cases the change in recovery is quite large even for small quality definition changes, which is important to bear in mind when making decisions about the latter.

It has been shown that it is possible to model the risk of chipping in finger-joints and to account for this in a strategy for cross-cutting and finger-jointing in a robust way by using an adaptive safety zone between sound knots and finger-joints. This is an approach that promises higher recovery in a finger-joint production process than a strategy using a fixed safety zone. However, there are some limitations regarding the strategy’s applicability, mainly in terms of the species, which is limited to Scots pine, and the geographical location, which is limited to the north of Sweden. The adaptive strategy which is tested is viable for this particular process, but it is not shown whether this is true for other production processes with different setups. The study demonstrates the possibility of using a simulation model for production strategy evaluation, however.

In the selection of safety zone length *D*, values for *D* up to 150 mm are tested although measurements were only made up to 30 mm. This means that the model is extrapolated for *D* values of 30–150 mm. However, values of *D* over 30 mm are very rarely chosen since at this point the predicted risk of finger-joint chipping is reduced to zero for most knots. This was also the case when the measurements were made and is the reason why no knots further away than 30 mm were measured; there were no chipped finger-joints caused by such knots.

The results of the knot reconstruction method are promising, with a prediction rate (the amount of boards which were given a correct grade using the reconstructed knots) of almost 64%. Several assumptions and simplifications have been made in this method, which limits its use, until shown otherwise, to Scots pine logs from Sweden. Future work could also improve some other aspects of the method, as is pointed out in Paper IV. The prediction rate of 64% is better than that achieved by earlier methods, but this figure must be improved for an online application. However, Figure 10 shows that the value of a log is predicted quite accurately, if somewhat underestimated in general. This can also be seen in Table 3: more boards are assigned a lower grade than a higher one compared to the case when the original knots are used. Furthermore, the method seems to be poorer for large logs than for small ones, but that is in absolute terms, which means that errors are larger simply because the values are larger.

4.4 Development of a simulation model

One possible integrated approach to the forestry-wood chain is to be able to model and simulate the complete process of making trees into finished products and how the growth of the living tree affects the product properties. This is to some extent possible today, by using existing sawing simulators to predict board quality from the properties of saw logs. It is, however, of interest to be able to predict the effect of secondary processing activities on the wood quality. Thus, there is great motivation for improving functionality in a simulation environment. One of the truly interesting possibilities is to be able to combine recovery simulation such as the one described here with discrete event production simulation, making it possible to assess the production costs involved with making particular decisions.

Another aspect is the communication between buyers and sellers in the forestry-wood chain. A simulation tool, together with visualization of the finished products and the ability to calculate production costs, would aid these discussions.

When discussing simulation, there are a couple of things which need to be emphasized: the distinction of simulation from optimization, and the distinction of simulation from the real system. It must be stressed that a simulation model is merely an attempt to model the real system. It does not necessarily imply that the results of simulation studies are by any means optimal in a true mathematical sense. Neither is it usually possible to draw any absolute conclusions from a simulation study. Most of the time, results should be interpreted in a relative sense, that is by performing comparative studies between different cases.

5. Conclusions

A simulation model of the forestry-wood chain can contribute in several ways: in wood quality discussions the limits and rules, and their effect on recovery, can be evaluated. Such a model can be used to evaluate the raw material properties and how they affect the end result. Production planning is another possible area of utilization. The main advantage of simulation is the possibility of carrying out studies in a short timeframe, as well as keeping the input material consistent in comparative studies. In this thesis it has been shown that increasing both the functionality and the amount of input data for a model of the forestry-wood chain is achievable, and a part of this work has been done and presented here.

- A simulation model has been developed whose results are comparable to those of the real process. Changes in input data result in plausible changes in simulation results.
- An adaptive safety zone for cross-cutting and finger-jointing can increase recovery in the process by at least 3%, which is shown by simulation.
- With access to a few log features, possibly but not necessarily retrieved from two-directional X-ray images, the knot structure in a log can be predicted for sawing simulation purposes.

6. Future work

In the shorter perspective, the main aim of future work is to develop the further processing simulation further, possibly integrating it with sawing simulation. Furthermore, the method of reconstructing knots by using industrial data will be verified, and methods for calculating the necessary data from two-directional X-ray images will be developed.

In the longer perspective, the aim should be to complete the integration of the forestry-wood chain by being able to simulate all production stages from forest to finished product, and to be able to use industrial input data extensively.

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Paper I

Wood Material Features and Technical Defects that Affect Yield in a Finger Joint Production Process

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ABSTRACT

A cost efficient process is the goal of all production, and each manufacturing step affects the material utilization and cost efficiency. There is high diversity in the inherent features of wood, and manufacturing steps must be able to handle this. The overall objective was to study the potential and problems in manufacturing production processes in terms of material utilization efficiency. The production of finger jointed bed sides was chosen as a study case, where the chain of production units are the sawmill, finger joint plant, and furniture plant. This article describes the impact of raw material and wood defects that could affect the total yield. A total of 177 logs of three types were tested: butt, intermediate, and fresh knot logs. The test material quality was detected and measured through all steps in the manufacturing chain. The results show differences between log types in down-grade causes, reject volume, and final yield. Also, the test material showed high levels of defective components with process related defects, which suggested the need for technical improvement in the manufacturing process. The intermediate log group showed the overall best result.

Keywords: *Finger joint, Furniture, Log quality, Scots pine, Process analysis*

1. INTRODUCTION

A cost efficient process is the goal of every production process. In most end products, the proportion of the raw material cost is high (Bergqvist *et al*. 1989). In wood manufacturing, each processing step affects the material utilization and the cost efficiency. Wood as a material has a high diversity in its inherent wood features and the different manufacturing steps must be able to handle this. Thus, material utilization and cost efficient processes are of great importance.

A lot of research has been done on how to measure, grade, and process wood material, focusing on the first part of the wood processing chain (Jäppinen 2000, Oja *et al*. 2003, Nordmark 2005, Lycken 2006). Different technologies to achieve improved results in the value chain have been described (Pinto *et al*. 2002, Usenius 2002, Grönlund 2003, Grönlund *et al*. 2005, Oja 2007). Also the last part of the chain has to some extent been described and evaluated by consumer preference studies (Broman 2001, Broman *et al*. 2008, Nyrud *et al*. 2008). However, few studies have focused on describing whole wood product chains together with collecting empirical data about the process and raw material (Grönlund *et al*. 2004, Pinto *et al*. 2005). Such data can be used not only for describing the complexity of the raw material allocation during a process but also for improving or building simulation models for future use and studies. Oja *et al*. (2008) studied how to optimize a solid flooring manufacturing process. The study was based on 177 logs that produced 708 floor boards. The results showed that X-ray scanning of logs in combination with preference studies and optimization of the whole chain made it possible to minimize down-grading and to increase the volume of raw material for wood flooring by 27%.

The overall objective of this project was to study the potential and problems in manufacturing production processes in terms of material utilization efficiency. The production of finger jointed bed sides for IKEA was chosen as the study case. The motive for choosing this example product is that it is a large volume product and the finger jointed bed sides have high requirements for final quality. The chain of production units is as follows: a sawmill for plank production, a company producing components, and finally a furniture company that produces the end product. The research approach was to follow the raw material and its yield and quality issues through the whole production process with full traceability of the material.

The aim of this article was to describe the impact of using different raw materials (here log types) and wood defects that could affect the total yield of the manufactured products. Defects that were not directly associated with the raw material were studied as well. In relation to the whole project the results presented here focus on the later part of the production chain: the finger joint production line and the furniture manufacturing process.

2. MATERIAL AND METHODS

This study was designed to follow the quality of the wood material of Scots pine (*Pinus sylvestris* L) through the long chain of operations, from the log yard to the final finger jointed bed side product. Three different log types were used: butt logs, intermediate logs, and fresh knot logs (often top logs). The different log types were seen as representing the input of different raw material qualities into the wood processing chain. The quality of the logs was detected and measured using 3D and X-ray scanning, while at the sawmill the green planks were scanned with a FinScan BoardMaster. At the finger joint plant, the quality of the planks was scanned and managed by a WoodEye CrossCut system for the production of bed side components. Finally at the furniture plant a manual quality inspection of the final products was done. All measured data were documented. The flow of operations is described in Table 1.

Table 1. Flow of operations and some details of the wood material studied in the project

Place	Action	Details	Dimensions
Log yard	Selection of logs Scanning	Three log Q.-types 3D and X-ray	Ø 134–147 mm
Sawmill	Sawing Scanning Kiln drying [1)]	2x-log FinScan BoardMaster to 14% MC	33 × 120 mm 31 × 115 mm
Finger joint plant	Planing Scanning Optimization Finger jointing	Symmetric WoodEye greyscale WoodEye cross-cut to component length	30 × 114 mm 30 × 114 × 2018 mm
Furniture plant	Planing Quality inspection Cutting	Symmetric Manually Both ends	25 × 110 × 2018 mm 25 × 110 × 2005 mm

[1)] *The final bed side product reached an MC of 8–10% thanks to a cold and dry mid winter climate.*

In the study all process parameters were chosen to be similar to those commonly used at the time of the test. The focus of the study was to show how the raw material input affects the yield and quality of the final product.

2.1 Test sawing of three groups of log qualities

In total 180 logs were selected from the appropriate sawing class with top diameters of 137–174 mm. By manual inspection at the log yard, three equally sized groups of butt, intermediate, and fresh knot logs were selected. These three types of log qualities represent the normal range of variety in input material quality at the present sawmill. During the 3D and X-ray scanning, this first manual log type classification was verified and some logs were moved from one log type group to another. Each group of logs was sawn with a 2X-log pattern into two 33 × 120 mm centre planks. The side boards were not incorporated in this study. Due to uncertainty associated with the identity of the planks from three logs after sawing, it was decided not to process those planks any further. Thus, the test set of logs comprised a total of 177 logs and the results of sawing can be seen in Fig. 1.

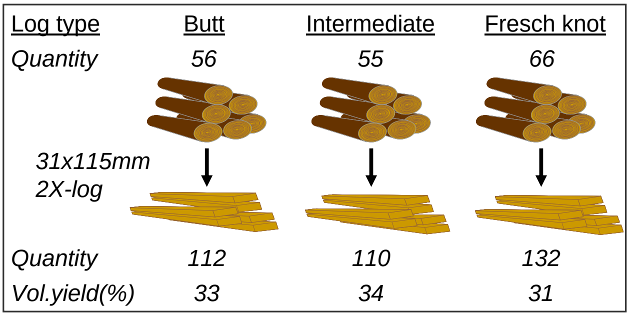

Fig. 1. Three groups of logs with different log qualities were selected from top diameters of 137–174 mm. The figure shows the amount of planks in each group together with the yield expressed as the dried centre plank volume as a percentage of the log volume.

Immediately after sawing, the planks were marked with an ID number, then scanned (green) using a FinScan BoardMaster, and kiln dried to 14% moisture content (MC). Since it was wintertime (cold and dry), the final bed side product reached a final MC of 8–10% without any further drying. Normally at the sawmill, all planks are cut at both ends to eliminate drying cracks from log ends. Also, visible (big) defects such as cracks, rot, discoloured wood, and breakage are cut away at the sawmill. In this study, no such operation was done because of the risk of losing the traceability of the input raw material.

The data collected from the log scanners and the FinScan board scanner are not used or analysed in this article. This report focuses on the later part of the product line starting with the finger joint component (FJC) production.

2.2. Finger jointing for component production

The finger joint production line comprises the following operations, in sequence: (1) planing, (2) scanning, (3) optimization, (4) cross-cutting, (5) trim cutting of short lengths, (6) finger joint cutting, (7) glueing, (8) pressing, (9) trimming to final component lengths, and (10) packaging and final delivery.

The order of incoming planks was documented and all short length blocks (after the cross-cutting operation) were marked with an ID number to make it possible to trace the accepted raw material back to its origin. In the study, the three groups of planks (log types) were processed separately.

First, 0.5 mm was planed from all sides of each plank (op1) to secure steady feeding during the scanning operation (op2). For this scanning and cross-cut optimization, a WoodEye CrossCut system (www.ivab.se) was used. This system had grey scale cameras that scanned all four sides and a laser-profile detector. It scans and tests the scanned planks against the current customer defined product quality grades and makes a cut optimization (op3) to maximize the yield from the input material.

This particular bed side product was produced at only one quality level. The quality requirement setup was the same for all sides of the planks. The quality grade and settings used were the same as those used in the typical daily production of the bed sides for the furniture producer. Thus, the furniture company quality requirements had earlier been translated into product-specific settings for the WoodEye CrossCut system. The settings were formulated as maximum sizes allowed for each wood defect. These settings are given in Table 3. Also in op3, the maximum and minimum lengths were 650 mm and 170 mm, respectively. A clear end-cut (1 mm) of each incoming plank was adopted. The safety distance for cross-cutting close to knots was set to 10 mm. According to the company, the precision of the length measurement was ± 5 mm in the cross-cutting operation (op4).

A trim cut of 1 mm at both ends of each short length (op5) was automatically made before the finger joint cutting to ensure a good result. The finger joint profile (op6) had a depth of 10–11 mm. The glueing (op7) was done in this case in batches of seven short cut items which were simultaneously pressed together. The raw bed side components were finally cross-cut to specific lengths, packed, and delivered. The dimensions of the delivered components were 30 × 114 × 2018 mm and finger joints were visible on the flat sides. Every final component was labelled at its cross-section.

2.3. Manufacture of bed sides and quality inspection

Each log type group of components was planed on all sides to the final cross-section dimensions of 25 × 110 mm. All components were then removed from the production line for quality inspection. This manual inspection was done more strictly than usual to identify differences between the input materials (here log quality types). A single small defect that in typical daily production could be used in non-visual parts of the bed was considered as a reject and noted as such in order to avoid grey areas and uncertainty and to achieve the greatest degree of objectivity possible.

2.4. Analysis

With a focus on differences between log type quality groups, the yield and causes of rejection were analysed and compared. The amount of waste material in the finger joint production was summarized to show the impact of raw material quality. The same was done for the summation of the causes of rejection of the final bed side product.

3. RESULTS AND DISCUSSION

In this study, the impact of the input raw material on yield and quality issues was evaluated for the example product, finger jointed bed sides. The material was studied by following it through the three production lines: sawmilling, finger joint component production, and finally furniture component production. Compared with the normal production of this bed side product, the production speed was relatively slower in the finger joint plant. All production parameters were typical of what was normally used except for one significant difference: In normal production, visible cracks, rot, and discoloured wood are cut away at the sawmill to improve the performance at the finger joint production line. This was not done in this study, to enable traceability of the raw material and also to test the ability of the WoodEye CrossCut system to cope with this new situation.

3.1 The sawmill step

The input material groups did affect the yield, which may have an impact on the selection of raw material for this product. In Figure 1, the centre plank volume is shown as a percentage of the log volume and was as follows: 33% for butt logs, 34% for intermediate logs, and 31% for fresh knot logs. These differences can be explained by the outer shape characteristics. Commonly, fresh knot logs are associated with high top-taper while butt logs are associated with high butt-taper (and are also often crooked). Intermediate logs, however, are associated with low taper and high straightness. Thus, from the point of view of the sawmill, intermediate logs should be preferred for this bed side product if the cost per volume is the same for the different kinds of logs.

3.2 The production of finger jointed components

The results from the production of finger jointed components with dimensions of 30 × 114 × 2018 mm are given in Table 2. The yield is expressed as the total length of finger jointed components divided by the total input plank length. Again the intermediate log group exhibited the highest yield (86%) followed by the butt log group (81%) while the fresh knot group had the lowest yield (79%).

Table 2. Yield and waste of the FJC production.

C. dim.: 30 × 114 × 2018mm	**Input material/Log type group**			
Resulting parameter	**Butt**	**Intermediate**	**Fresh knot**	**Units**
Input total plank length	502	489	538	Metres
Total length of FJC	408	422	426	Metres
Yield of FJC	81	86	79	Percentage of length
Total waste	19	14	21	Percentage of length
WoodEye cut waste	15	10	17	Percentage of length
Short pieces mean length	541	545	529	Millimetres
Produced components	202	209	211	Pieces
Delivered components [1)]	196	204	202	Pieces

[1)] *Due to slow production speed and special requirements within the research project a few produced components were not fully glued. These were lifted out and not delivered to the furniture plant.*

The causes of these differences are further demonstrated in Table 3, where the share of defects that were cut away is given. Table 3 also provides the settings (the maximum limits for each defect type) that were used for daily production of this bed side product. Inspecting the effect of knots, it can be observed that the fresh knot log type group had the highest waste caused by knots. Surprisingly, this group had the same level of waste caused by black knots as the butt log group. In the table, the *Fibre knot* defect represents sound knots that are very bright and are measured by the laser detector. *Pitch pockets* are frequent causes of waste in all three log type groups even if the intermediate logs had fewer defects than the others. The defect *Bark* was not frequent but *Cracks* occurred more often. In our study, no crack elimination was done at the sawmill. Therefore, our test material was expected to have a relatively high amount of cracks. Fresh knot logs seemed to have the lowest frequency of *Cracks*. The biggest difference between the groups was in the detection of *Wane* and *Dimension* errors. Only a third of the amount of *Wane* was detected in intermediate logs compared to the other two groups. This can be explained by differences in the outer shapes of the log types and also by how well the sawing class (log dimension) fits the sawing pattern. The defect type *Dimension* is a measure that checks the nominal width and thickness. An error at the plank edge may also fall into this category. *Dimension* errors are the most frequent cause of waste with the types of settings used. Fresh knot log and butt log groups had a higher degree of dimension errors compared to the intermediate group. This again may be explained by differences in outer shape and the fact that the *Dimension* measure also covers areas with wane and other edge related problems like breakage.

Table 3. Share of defects cut away as waste in the WoodEye CrossCut optimization step

	Log type group			Settings for max limits of
Defect type	**Butt**	**Intermediate**	**Fresh knot**	**width/length/depth (mm)**
Sound knot	0.4	1.2	2.0	45 / 45
Fibre knot	0.6	4.5	8.9	50 / 50
Black knot	8.2	4.1	7.4	35 / 35
Pitch pocket	20.5	15.5	19.1	1.5 / 15
Bark	1.2	0.4	1.1	30 / 30
Cracks	9.6	7.4	5.4	0.3 / 100
Wane	31.7	10.8	27.5	14 / 14 / 14
Dimension	31.9	21.7	41.6	2 / 5
Profile	0.4	0.0	0.0	0 / 30 / 0
Total:	104.4	65.6	113.2	

Note: The share is calculated as the amount of defects cut away divided by the input plank length × 100.

When analysing the material efficiency for the finger joint component production line independently from the other production steps, it seems that the intermediate log group resulted in less waste but also exhibited the highest average length of the glued short blocks (Table 2).

3.2 The production of the furniture (bed sides)

In this project, the most interesting part was the last part, the furniture production step. The goal was to adopt an extra strict and precise quality control procedure to map what defects showed up as vital in the furniture production. This bed side product is particularly sensitive to the shapes of the edges. There are very high requirements for the edges, to avoid potential injury to users (scratches or laceration damage) during service. Every component with one or more defects was put aside as a reject and the causes were documented.

The proportion of final bed side products found to have one or more defects at the manual inspection is given in Table 4. Normally the total reject rate is between 8 and 12% according to the furniture company. The very high amount of waste shown in the study can be attributed partly to the extra strict quality control procedure but also to the details shown in

Figures 2 and 3. Focusing on the differences between the three log type groups and the wood related defects in Table 4, we see that butt logs result in approximately 11–12% more waste compared with the other log types. Even at the furniture company, the intermediate log type group resulted in the highest yield.

Table 4. Proportion of produced component length that had one or more defects.

(Percentage)	**Butt**	**Intermediate**	**Fresh knot**
Wood material defects	35	24	23
Technical factor related defects	14	8	12
Total waste	49	32	35

The different causes of rejection that were found in the test material are given in Table 5. The very high levels of waste caused by wood related features are further analysed in Figure 2. The most obvious result is that butt logs are associated with detached black knots after planing. Another finding is that the fresh knot group is associated with the presence of big cracks in the centre of the knots and also drying cracks outside the knot (at the component edge). The intermediate log type group did not have any typical defects.

Table 5. Causes of rejection at the quality inspection with corresponding abbreviations

Abbreviation	**Wood material defects**	**Criteria**	**Assessment**
K-size	Knot size too big	Size	Measure
K-crack1	Crack in knot-centre	Size	Hand
K-crack2	Crack outside knot (black, sound)	Size	Hand
K-loss	Detached knot (black, sound)	Size	Hand
K-bark	Bark-ringed knot	N.A.	Size
Top rupture	Top rupture (forest)	Size	Eye
Discolour	Rot/discolouration	N.A.	Eye
Scar	Bole scar or bark pocket	N.A.	Size
Resin pocket	Resin pocket	N.A.	Size
Abbreviation	**Technical defects**	**Criteria**	**Assessment**
Finger joint	Finger joint with defect	N.A.	Eye/hand
Wane	Wane	N.A.	Eye
Wood loss	Wood material loss (at edge)	N.A.	Eye/hand
Planer miss-edge	Planer miss at the edge side	N.A.	Eye/hand
Planer miss-flat	Planer miss at the flat side	N.A.	Eye/hand
Cracks	Cracks in clear wood area	N.A.	Eye
Twist	Twisted component	Size	Eye
Bow	Bowed component	Size	Eye
Roller mark	Feed-roller marks (sawmill)	N.A.	Eye/hand
Mech.-dam.	Mechanical damage (sawmill)	N.A.	Eye/hand

Note: Criterion "N.A." stands for not accepted and criterion "size" for size limited.

Knots that reach the edge of the bed side component cause problems and a high risk of rejection (from the left side in Figure 2, defect nos. 2–6). This qualitative information may be used for changing the criteria and settings of the WoodEye CrossCut system with the aim of meeting stricter requirements close to the edge zone. Another possible improvement may be to set stricter limits for bark. With the current settings, very few bark defect areas were cut away (see Table 3). If stricter limits were set some of the bark-ringed knots (*K-bark*) and bole scars (*Scar*) may have been cut away during the previous WoodEye CrossCut operation.

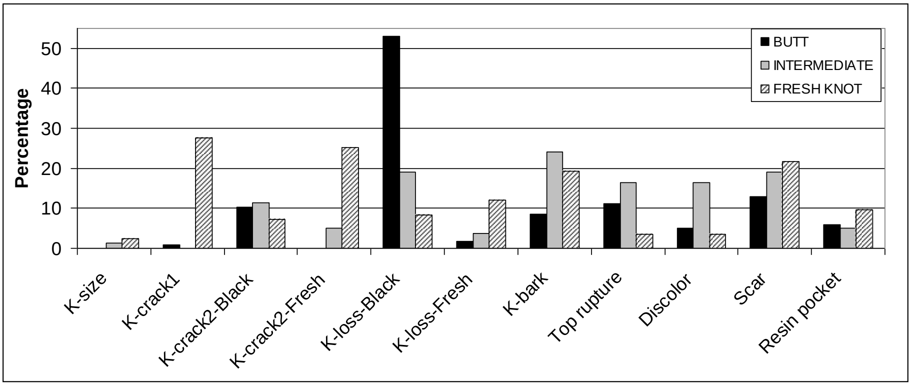

Fig. 2. The proportional impact of wood material related defects found. Metrics: the number of defects divided by the number of rejected components in the corresponding log type group.

When analysing Figure 3, the very high amount of waste caused by defects related to technical factors listed in Table 4 can be explained. Due to the fact that no quality-increasing cross-cut operation was done at the sawmill, the planks proceeded to the finger joint production line with a higher proportion of cracks, breakage in plank ends, wane, and even rot than normal. The figure shows how sensitive the WoodEye CrossCut system, together with the settings of the finger joint glueing line, is to changes in input material characteristics. The very high proportion of incorrect finger joints is partly due to the too small clear end-cut of each incoming plank (a 1 mm criterion was used). This resulted in finger joints that did not reach the bottom. Also the problem with cracks can be explained similarly. A lot of log end cracks followed the input material and caused unusually high levels of waste. Also, with current settings (*Dimension* and *Profile* in Table 3), a large amount of edge related problems already initiated at the sawmill were noted as causes of defects. Even roller marks from the harvester and breakage from the debarking machine were visible at the edges of the bed sides. This problem may also indicate that the cross-section dimensions of the input planks should be increased. The planing operation at the furniture company was badly centred for butt logs (*PlanerMiss-edge*) and showed high sensitivity to positioning, supporting such a conclusion. Thus, the results shown in Figure 3 emphasize that the current settings of the WoodEye system need to be adjusted if similar input raw material is to be processed.

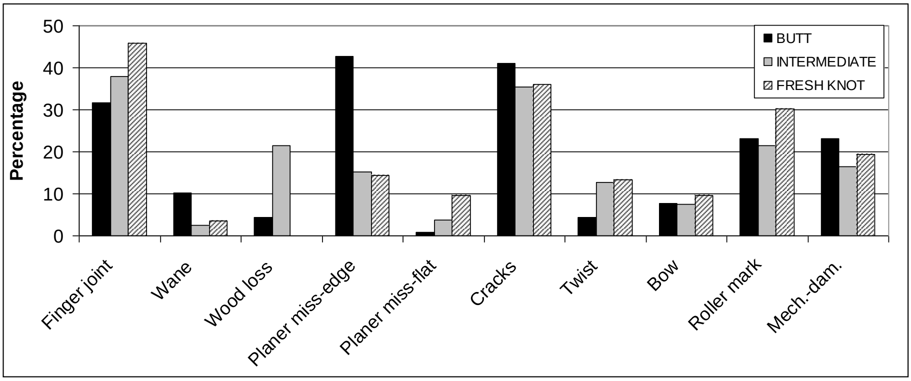

Fig. 3. The proportional impact of the technical factor related defects found. Metrics: the number of defects divided by the number of rejected components in the corresponding log type group.

In this study the safety distance for cross-cutting close to knots was set to 10 mm. Still, a high proportion of the finger joints were defective because knots were too close to the joint. Therefore a special inspection was made of all finger joints for all bed side components that were classified as defective (all causes). All knots closer than 25 mm to the nearest finger tip were described by the following parameters: knot size, type, shape, side of the plank, distance to the finger joint, and finally, whether the knot gave rise to a defective finger joint. The results are given in Table 6.

Table 6. Share of knots causing defective finger joints in different categories. ("FJ" denotes finger joint)

	Number of knots [1)]	Causing defective FJs	Share of defective FJs (%)
Sapwood side	234	67	29
Pith side	124	14	11
Sound knots	274	71	26
Black knots	115	10	9
Round knots	223	37	17
Oval knots	113	23	20
Splay knots	40	10	25

[1)] The sum of knots differs between the three parts, due to difficulties in classification of the knots.

In analysing the table, it is possible to observe that knots on the *Sapwood side* more often cause problems when they are close to the finger joint compared to *Pith side* knots. The knots on the sapwood side were on average larger than the pith side knots. Also, *Sound knots* cause more problems than *Black knots*, which can be explained by their larger average size and the fact that the wood around a sound knot has more fibre irregularities than a black knot. Concerning the shape of knots, *Oval* and *Splay knots* close to the finger joint cause problems more frequently than *Round knots*. The data also showed that with increased knot size, the risk of defective finger joints increases. Also, a strong dependency between the distance from the knot to the finger joint and the risk of defective joints was found (see Figure 4).

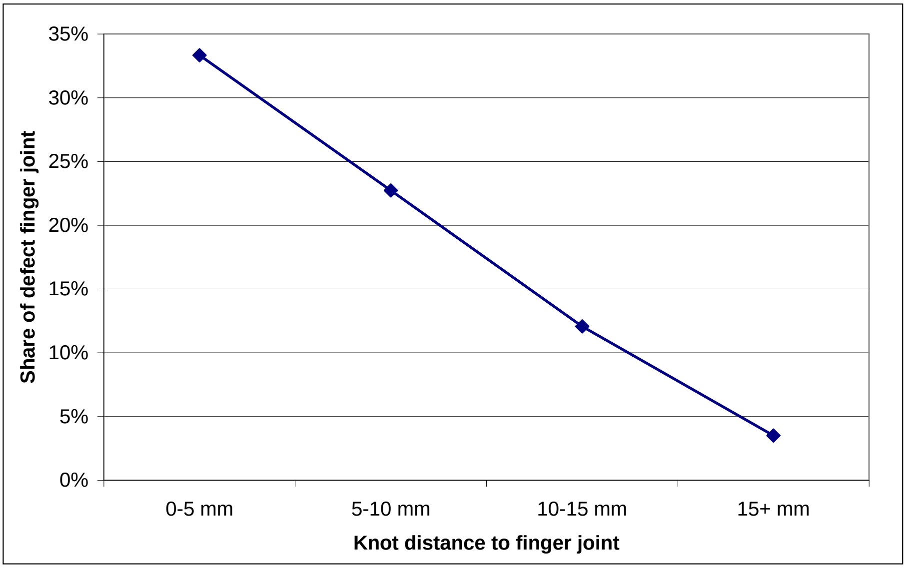

Fig. 4. Share of defect finger joints depending on the distance from the knot to the finger joint (round knots). *Note: For each distance interval, the share is calculated by dividing the number of defective finger joints (caused by round knots) by the total number of finger joints in the respective interval.*

According to information from the finger joint company, a safety zone of 10 mm is normally applied between defect and finger joint. This setting may need to be increased due to the fact that the length measurement precision is ± 5 mm in the cross-cutting operation. The empirical data however showed too many knots right in the centre or close to the finger joints.

4. CONCLUSIONS

Choosing the right input material and processing it in a way that minimizes the final rejected volume at the end of the processing chain is important due to the fact that reject costs are high for such a production type (2005 mm). A very high proportion of defects were found within the final bed side product. The extra strict quality control procedure together with the fully traceable material data showed results which indicated weaknesses in the process chain and areas that can be improved. Below are some interesting findings based on this study:

- For the current log dimensions, the intermediate log group gave the highest yield and fewer problems at all three production plants studied. Butt logs showed the lowest yield and the largest amount of rejects, mostly due to black knots that detached after the final planing.
- Knots (all types and sizes) did cause problems but only when they extended to the edges of the component and when they were too close to the finger joint. Knots also caused more problems on the sapwood side of the plank. Both these results indicated that some kinds of zone-related settings for the WoodEye optimization step may decrease the reject volume of the finished bed side products.
- Very few bark defects were cut away at the finger joint plant but many causes of rejection related to bark were found in the end product. A higher sensitivity for bark may reduce the amount of wane, bark-ringed knots, bole scars, and, to some extent, top breakage, which often has bark inclusion.
- A surprisingly high level of technical causes of defects was found in this study. These problems originated from the sawmill step and the chosen research strategy of not carrying out any pre-cutting of obvious defects such as cracks, rot, discoloured wood, and breakage at component ends. The results show how sensitive an existing wood processing chain can be to changes in input material characteristics. Also, it shows that the used (current) settings of the WoodEye CrossCut system did not cope well with the new situation. Adjustment of the settings may, to some extent, solve some of the problems. The test also indicated the need to have the right dimensions and high precision in each process to avoid rejection of the final product.

This study shows similar results to those of Oja *et al.* (2008). Having access to all data for a whole production chain is of great importance for the optimization of the raw material utilization and hence the volume and value revenue. The present study resulted in a revision of the settings of the WoodEye CrossCut system and changes were made in line with the findings presented here. A dialogue between the companies about the material dimensions required in each production step was started. The reason was to decrease the high rate of rejection of components due to defects related to technical factors.

This study contains process and material data for a whole wood product chain. The complexity of material allocation through a wood product process has been described and some results are of general interest while others are product- or process-specific. Questions always arise about what the consequences will be if some parameters are changed. The collected data will be a good base for development and validation of simulation models that can be used for answering some of those questions.

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Paper II

A simulation tool for the finger jointing of boards

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ABSTRACT

Knowledge about how tree properties affect the final product is necessary to utilise each log and tree in the forestry production chain fully. So far, the Swedish Pine Stem Bank (SPSB) has been used extensively for sawing simulation, but not for simulation further down the production process. Hence, it is desirable to model the further processing of sawn timber using the SPSB. In this study, a simulation tool for cross cutting and finger jointing of boards has been developed and tested. The simulation program utilises the SPSB and the results from a sawmill simulation program to simulate a cross-cutting and finger-jointing process. The tool has been tested against an empirical material consisting of defect data from an industrial scanner, used at a producer of finger-jointed furniture products. To illustrate the potential use of the finger-jointing simulation program, two investigations have also been carried out. The first deals with comparing the recovery for finger jointing and cutting of solid boards for different products. The second investigation is an attempt to estimate the impact of process-related defects on the recovery of finger-jointed products. The results show that the simulation tool produces similar results as the real process, and the use of the SPSB provides adequate predictions of the real system's behaviour. The first of the investigations shows that finger jointing generally has a better recovery than cutting of solid boards, but for short products, the latter might be a viable option. The second investigation suggests that process-related defects reduce recovery by up to 5% units in the finger-joint process studied. Thus, there is future potential for using the finger-jointing simulation tool to investigate production strategies and/or raw material selection in the forestry production chain.

INTRODUCTION

In recent years, there has been an increased interest in an integrated approach to the forestry production chain. This means that forest and tree characteristics are seen as linked with end-user requirements on wood products [1, 2, 3, 4]. The aim of an integrated approach is to utilise knowledge of the end-user requirements for different wood products and knowledge of the properties of timber to control the flow of material from the forest to market, thus achieving a more optimised use of the raw material. However, the forestry production chain is complex in its nature as a result of the complexity of the raw material, as well as the various production stages, actors, and decisions involved, such as in harvesting, breakdown, crosscutting, final processing, and marketing [1].

Simulation is the use of various techniques to imitate the operations of real-world facilities or processes, often to study it in a scientific way in order to understand its behaviour. It is one of the most common operations-research and management-science techniques employed. Among the advantages of simulation are that it allows for experimentation with complex systems without disrupting the system itself, achieving better control over experimental conditions, and studying a system with a long timeframe in compressed time [5]. This makes simulation an excellent tool for studying the forestry production chain, which is both complex and has a long timeframe.

Simulation efforts in wood research have focused mainly on the early parts of the forestry production chain, such as the different log breakdown simulation tools described by [6, 7], or the numerous commercial programs on the market. Another area of interest is production flow simulation for both sawmills and the secondary wood industry [8, 9, 10]. There are also tools available for the simulation of traditional cross cutting [11, 12]. In the area of finger jointing, cross cutting and finger jointing of wood with unwanted defects have been described by Åstrand [13]. Eliasson and Kifetew [14] have studied the impact of raw material quality on finger-jointed Scots pine boards. In their study, knot-free finger-jointed boards were produced together with solid knot-free boards in a production line using an industrial scanner, with a recovery of 55–62% depending on which sawmill the boards came from. Clément et al [15] studied the impact of process-induced defects on lumber volume recovery, finding an average recovery reduction of 10% resulting from manufacturing defects.

There is a need for a simulation tool that focuses on the secondary wood industry and the process of converting lumber to a final product, especially finger-jointed products. If such a tool can use the Swedish Pine Stem Bank (SPSB) [16], or other databases of real but virtual logs, it would provide means to test different production strategies and raw material choices for different products without the need for time-consuming and expensive test sawing. The in-data will be constant, which is an advantage for comparison purposes. It would also mean that the whole production chain can be studied, as well as the impact of various decisions on the entire system.

Based on a case study with empirically collected data, the main objective of this study was to develop a flexible computer model of a finger-joint production process, resulting in a simulation tool. It was intended that this simulation program would use the SPSB as in-data. The study had two subordinate objectives designed to show the potential usability of the simulation tool:

1. To compare the simulated length recovery from finger jointing and cutting of solid boards for three wooden furniture products. This aimed to show the feasibility of finger jointing these three products.
2. To compare the simulated length recovery in the finger-joint process considering only biological defects, with the simulated recovery considering both biological and process-related defects in order to highlight the potential for recovery by reducing process defects.

MATERIAL AND METHODS

The material

The study was based on two datasets; the first set was obtained from a case study where the material was followed through a process of manufacturing a finger-jointed furniture component, from the forest to final product. The raw material consisted of 178 Scots pine (*Pinus Sylvestris L.*) logs from the north of Sweden. Within the finger-joint mill, the sawn boards were scanned using industrial scanning equipment, WoodEye [17]. The sawn boards were then cross cut and finger jointed. The WoodEye in this study was equipped with four grey-scale cameras (one for each side of the board) and laser equipment to indicate fibre deviations. The components produced in the finger-jointing process were sent to a furniture manufacturer for processing, final sorting, and packaging.

WoodEye generated data for the length and defects (type, position, size) of every cross-cut piece in addition to the board from which the piece was cut. This made up the first dataset used in the development of the finger-jointing simulation program, which contained data from 354 boards. Because the WoodEye data were based on optical scanning of boards, they included defect types such as bark, cracks, pitch pockets, and dimensional errors, in addition to knots and wane. The board dimensions were 31 × 115 mm, of various lengths. The final finger-jointed components were 2,018 mm long, with the same cross section. The quality requirements for knots were that if both the longitudinal and tangential diameter of the knot exceeded 35 mm for dead knots and 45 mm for sound knots, then the knot was considered unaccepted. Similar quality rules, with various limits, existed for other kinds of defects. There were also other limits, for instance, a minimum acceptable distance between cutting positions and defects. Another important criterion was the maximum and minimum length of the cut pieces. In this case, technical considerations in the production process limited the length to between 170 and 650 mm. Additionally, piece lengths greater than 400 mm were more desirable than those below 400 mm.

The second dataset was obtained from the SPSB, which is a database consisting of properties of 246 Scots pine trees. The trees, from 41 well-documented sites at different locations in Sweden, have been documented thoroughly both in terms of tree properties and silvicultural treatments. They have also been CT scanned in order to record internal properties such as knots, pith location, and heartwood border. This gives a parametric description of each tree in terms of these properties, as well as for surface structure [16].

A sawmill breakdown simulation tool developed by Nordmark [6] was used to simulate the breakdown of the SPSB logs into boards, providing board and defect data for the cross-cutting and finger-jointing simulations. This resulted in 1,257 boards, with information regarding dimensions and defects (type, size, position). At the time of this study, the defects included in the sawing simulation results were dead knots, sound knots, and wane. Hence, these were the only defect types studied here. The boards were of the same dimensions as in the first dataset, 31 × 115 mm, and all boards of these dimensions were used, regardless of quality and length.

Development of the simulation tool

A computer program imitating the cross-cutting and finger-jointing process was developed in the programming language C++. The program reads board and defect data from plain text files, with information regarding board dimension, defect position, type, and size. It also reads a second file containing various settings, including product dimensions, maximum and minimum acceptable length of cross cut pieces, length losses in finger joints, quality requirements regarding maximum size of defects on the product, minimum acceptable distance between defect and cutting position, and so forth. This arrangement makes it convenient to change the parameters of the simulation.

The program generates a list of cutting positions for each board according to the settings, thereby generating pieces that are considered either rejected or accepted depending on quality requirements. Pieces longer than the specified maximum length are cut into several maximum-length pieces if possible. If not, for instance, if the remaining piece will be too short, the long piece is cut in half, and the algorithm is repeated on the two resulting pieces. The program also includes a function for avoiding cutting within defects.

The above procedure results in a length recovery for every board, taking into account various losses such as those generated in the finger jointing. The defect data from the accepted pieces are carried over into finger-jointed components, and these data are stored in plain text files. Total length recovery, number of components, number of cross cut pieces and all cutting positions for each board are also recorded. Length recovery is defined as the total length of the finger-jointed products divided by the total length of the boards that are cut and jointed.

A comparison was made of simulation results using the two datasets, and then only knot defects were taken into consideration. This was because the SPSB does not contain any data regarding other types of biological defects, and the non-biological defects are not simulated in the sawmill breakdown simulation. From the dataset taken from the SPSB, two subsets were also tested; one with trees taken from high site index (SI) (T28) plots, and one from low SI (T16) plots. In order to facilitate comparison, the same products as in the case study were used for the simulations; finger-jointed boards with the dimensions 31 × 115 × 2,018 mm.

To show the potential use of the simulation tool, two production strategies were tested, finger jointing and cutting of solid products, for three different product lengths, comprising a total of six different scenarios. Simulation was made on each one using the SPSB data and testing different quality rules. The recovery was compared for the six cases. One of the products was the original length of 2,018 mm, one was 1,400 mm, and one was 900 mm, but with the same cross section dimensions of 31 × 115 mm. All products were produced by the same furniture manufacturer as the case study.

The study of the effect of process-related defects was made using the WoodEye data. One simulation run was made where all defects were taken into account, and one where only biological defects such as knots and pitch pockets were accounted for. The results were then compared in terms of recovery.

RESULTS AND DISCUSSION

Choosing industrial scanning equipment to provide the first dataset had both advantages and disadvantages. The equipment was not designed to provide a true picture of the boards and defects, but rather to make production decisions as fast as possible given the information available. On the other hand, the simulation model was designed to imitate the behaviour of a real production system. As such, using a real-world production system for comparison and as a reference can be deemed acceptable.

The SPSB contains almost 250 trees from different geographical locations in Sweden. Although not representative of Swedish pine forests in their entirety, the differences in silvicultural treatment, geographical location, site fertility, and so forth makes this sample sufficiently large to provide a representational cross-section of Swedish pine forests.

Validating the simulation model

The aim of the present study was to compare the simulations with the empirical data in order to validate the model. The simulation used the data obtained from the WoodEye equipment, taking into account all types of defects, with the same product and quality rules as the case study. This resulted in a simulated length recovery (length of products divided by length of boards) of 82.8%, compared to the real length recovery of 81.8%. A review of the cutting positions chosen by the simulation program compared with the positions chosen by the WoodEye algorithm shows a large degree of conformity. Figure 1 shows some typical examples.

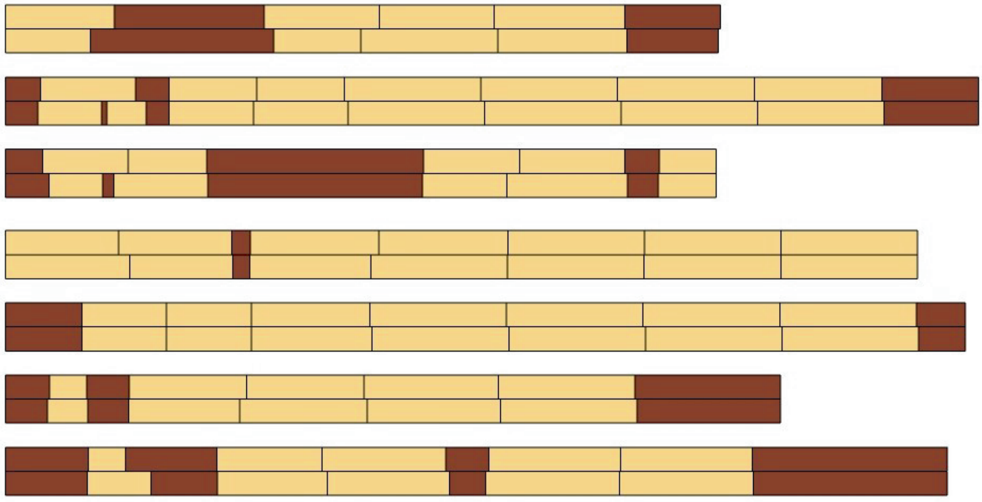

Figure 1. Six boards, with simulated (top) and real (bottom) cut positions. Dark areas are rejected, light accepted. In many cases, the small differences are a result of minor differences in optimisation strategies employed by the simulation program and the WoodEye equipment.

Another analysis was made on the empirical WoodEye data, where the number of pieces produced of various lengths was counted (Figure 2). The same analysis performed on simulated data shows that the cutting decisions are similar. The high number of pieces between 400 and 410 mm long is a result of a setting that is designed to avoid pieces less than 400 mm in length. This is performed by the simulation tool by using some of the neighbouring piece (if it is long enough to be accepted).

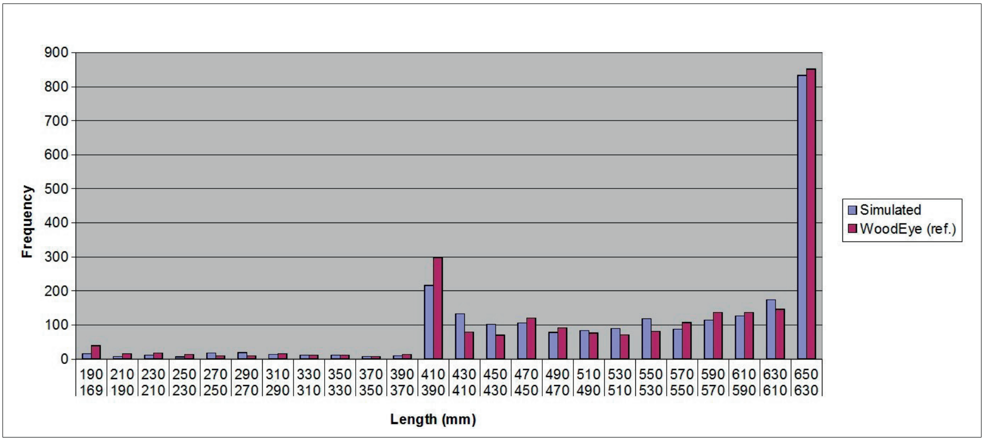

Figure 2. Number of pieces produced in different length classes, simulation compared with the empirical results. The simulation was made on the same dataset that yielded the correct lengths (WoodEye). Long pieces are preferable in order to reduce the amount of cuts on each board.

The comparison between the simulated data and the results of the case study shows some differences between the two. In some cases, these differences can be explained by the different strategies employed when cutting up a long, accepted piece into small enough pieces. WoodEye uses a value optimisation procedure, while the strategy employed in the developed simulation tool is more oriented towards minimising the amount of cuts (i.e. making pieces as long as possible). Other minor discrepancies are more difficult to explain. In some cases, the WoodEye system rejected a piece even though there is no apparent reason for this label. No 'non-accepted' defects can be found on the piece, and if it was to be joined with the neighbouring accepted piece, then it would still be shorter than the maximum acceptable length for the piece. These cases make up the majority of the 1% difference between the simulation and the WoodEye data. However, the total recovery and the vast majority of the cutting positions are very similar, or in most cases identical, to the WoodEye system. This is a good indication that the simulation is representative of reality.

Applying the simulation program on the Stem Bank

When the SPSB was used as data for the simulation, it was compared with a simulation on the WoodEye data. The whole stem bank was used, as well as two subsets, one containing high SI trees and one containing low SI trees. The WoodEye material originates from the north of Sweden, so it is probable that it originates from a low SI location. Differences were found between the two main datasets, and between the SPSB data and the two subsets (Figure 3). The WoodEye data show a pattern similar to the low SI subset, but with a higher recovery in the whole interval. The low SI subset results in relatively high recovery when the acceptable knot size is high, with a dramatic decrease in recovery when the requirements are stricter. The high SI subset, on the other hand, has a relatively low recovery when only large knots are cut away, but the recovery decrease is much less substantial than for the low SI subset when the maximum acceptable knot size is lowered.

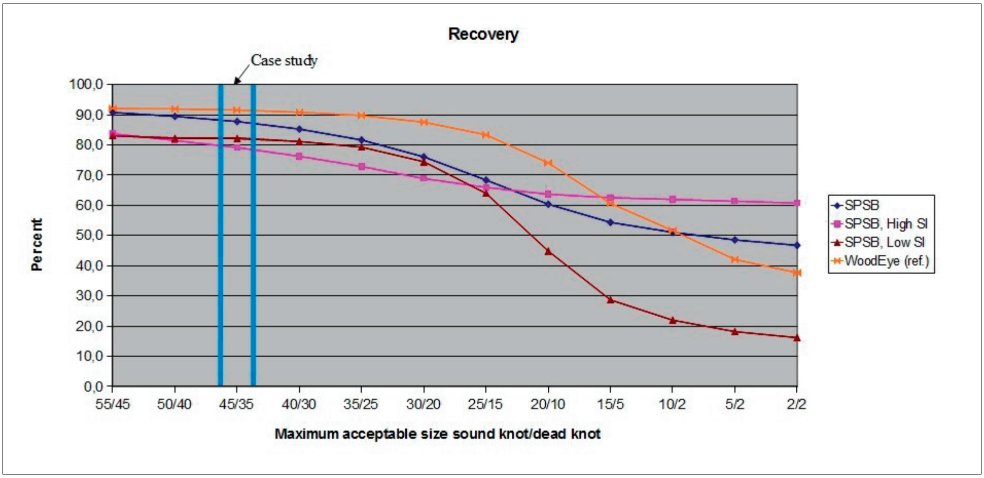

Figure 3. Recovery comparison between the case study and the SPSB. Both the results for the Stem Bank as a whole and for the two high and low SI sets are plotted. These are compared with the empirical reference data, from WoodEye. The quality rules of the case study are indicated in the chart, 45 mm maximum acceptable diameter for sound knots and 35 mm for dead knots.

The difference in results between the two datasets in terms of length recovery can perhaps be explained by three factors: the raw material is different, and the scanning and image analysis techniques are different. These factors are discussed below.

Raw material

The SPSB contains information about trees from very different sites all over Sweden. That is probably why the full SPSB recovery curve is in between the low and high SI curves. The WoodEye data, however, came from trees in the north of Sweden, which explains why the plot looks similar to the low SI one, albeit at a constantly higher recovery level. Unfortunately, all we know about the site from which the trees were harvested is that it is located somewhere in the northern part of Sweden. For instance, no information regarding SI or silviculture was available.

Scanning technique

Grönlund [18] compared the results of CT scanning and image analysis with manual measurements of knots. The comparison showed that CT scanning overestimates the knot size by an average of 5 mm. Grundberg's [19] validation of a sawmill simulation program using the SPSB showed that the simulated knot diameter on the boards was an average of 2.3 mm larger than a manual measurement.

In order to investigate this further, a new simulation decreasing the knot sizes in the SPSB data by 3 mm was carried out. Similar to Figure 3, Figure 4 shows the recovery with the changes mentioned above. From these changes, we can see that the WoodEye data and the SPSB data align to a much higher degree.

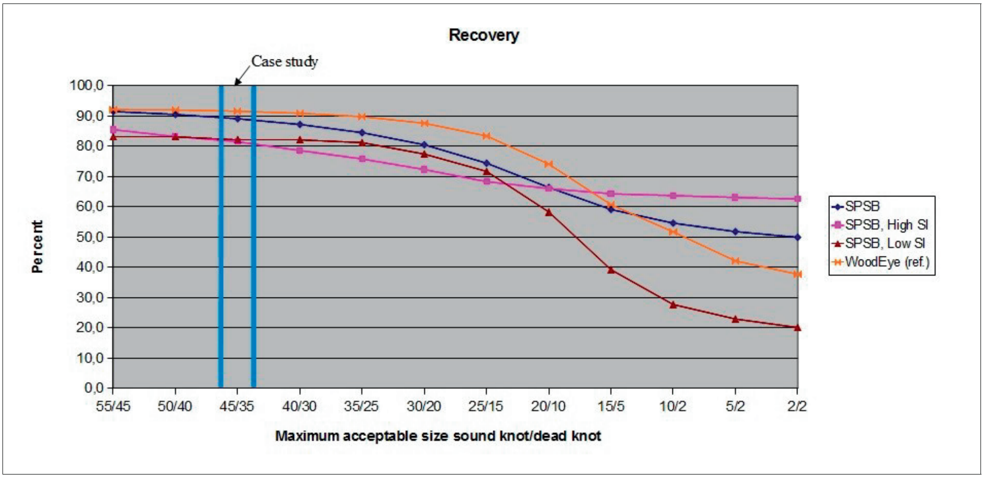

Figure 4. Recovery plot with the knot size of the SPSB data, both as a whole and the two subsets, decreased by 3 mm. The reference data remain unchanged. The quality rules of the case study are indicated in the chart, 45 mm maximum acceptable diameter for sound knots and 35 mm for dead knots.

The fact that the recovery for the low fertility site is high with large acceptable knots, and decreases dramatically when the requirements are hardened, is not surprising considering that low fertility sites usually result in trees with smaller knots than do high fertility sites [20]. The opposite is true for the high fertility site. Another factor that influences the recovery is the shorter distance between whorls for low fertility sites. This means that if one considers all knots as unwanted defects, it is usually impossible to fit even a minimum length piece between whorls, thus, the recovery decreases dramatically.

Finger jointing and cutting of solid products

The aim of this investigation was to compare the recovery between finger jointing and cutting of solid products for three different product lengths. The dataset used is from the SPSB.

As can be seen in Figure 5, the length recovery for the 2,018 mm product is significantly higher for finger jointing compared with cutting of a solid product. This is especially true when the knot size limits are more restricted than in the case study. For the other two products, which are shorter, the difference is less significant. In addition, the finger-jointing curve is almost the same regardless of product length. It is important to bear in mind that these results are based on simulation on the whole SPSB, and only knots are considered as defects.

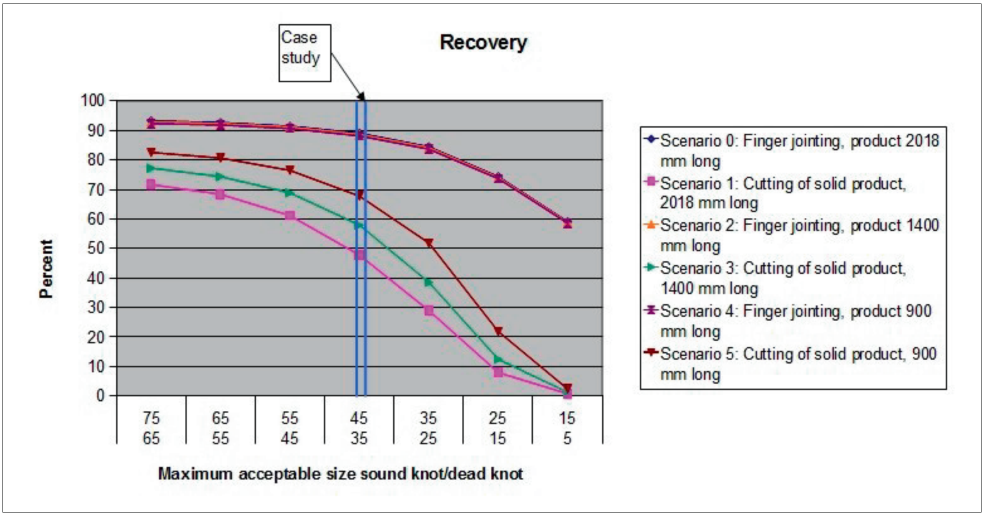

Figure 5. Length recovery for the six scenarios based on different products and production strategies. Note that the scale on the x-axis is different from that in earlier plots, and that the three finger-jointing scenario curves are almost identical, at least in this scale. The quality rules of the case study are indicated in the chart, 45 mm maximum acceptable diameter for sound knots and 35 mm for dead knots.

The results suggest that solid board cutting may yield a recovery of almost the same magnitude as finger jointing, provided that the product is short enough. Thus, if one considers the production cost of finger jointing together with the difference in recovery, it may be feasible to produce shorter products with traditional cross cutting, as opposed to finger jointing. This may also increase the visual quality of the final product given that the finger joints are absent. However, if the product length is large enough, then the difference in recovery makes finger jointing the most profitable choice. The finger-jointing recovery is not as affected by product length as it is by the minimum and maximum length of the cut pieces. In a real-world application, a mixture of the different products would probably be employed, resulting in better optimisation possibilities and thus better production economy.

The impact of manufacturing defects

The present investigation was an attempt to estimate the effect of process-induced defects on the recovery in the finger-joint process. This was conducted using simulation on the WoodEye dataset.

Figure 6 shows that the difference in recovery in the finger-jointing process is around 5% between data with only biological defects and data with all defects included, in the category of quality rules used at the present day (45/35 mm).

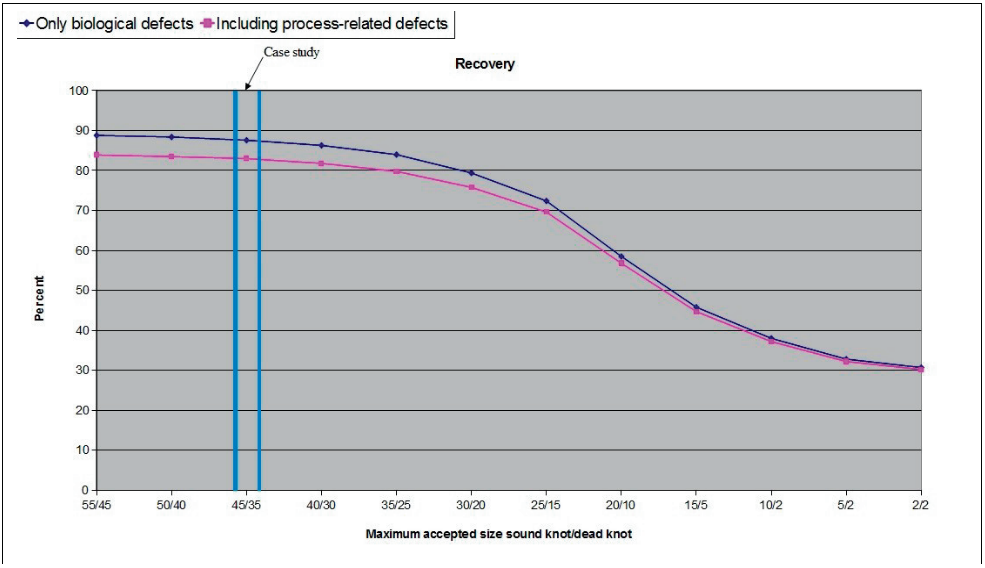

Figure 6. Length recovery using the WoodEye data, considering only biological defects and considering all defects, respectively. The quality rules of the case study are indicated in the chart, 45 mm maximum acceptable diameter for sound knots and 35 mm for dead knots. The potential recovery gain in the process studied, if all process-related defects could be eliminated, is around 5% units.

As Figure 6 indicates, there is room for improvement in terms of damage to the wood induced by the manufacturing process. If spike and conveyor marks were reduced, measurement and control in the sawmill was improved, along with improved planing operations resulting in less wane, bark, dimension errors, and so forth, then this could result in a potential recovery increase of up to 5% in the finger-jointing process studied alone. This is in 5% less potential improvement than the results obtained by Clément et al [15]. An improved process would also obviously result in an improved visual quality of the final product, resulting from a reduction of the defects that are accepted or perhaps even missed by the WoodEye, but still visible to the final customer.

CONCLUSIONS

The developed cross-cutting and finger-jointing simulation program produces results that closely represents the real-world system.

The differences between the results obtained when using the SPSB as data source and the empirical data can be explained and largely accounted for using reasonable assumptions. The simulation results seem to behave in a manner that is expected for different raw material.

This study also shows that cutting of solid boards is a viable option for producing relatively short wood-furniture components when the correct strategies are utilised. If the product length is too high, then finger jointing is a better choice.

The simulation also shows that there is potential for an improved recovery of up to 5% units in the finger-jointing process studied, if defects resulting from manufacturing errors could be completely eliminated.

The simulation tool provides ample scope for future research. For instance, sawmill breakdown simulation using the SPSB together with this simulation program would allow investigation of the impact of different sawing patterns, other breakdown strategies, and raw material on the whole forestry production chain, including the further processing. Future research using data from X-ray log scanners installed at sawmills to increase the size of the SPSB would vastly increase the amount of available data, thus improving simulation results.

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Paper III

Adaptive cross-cutting safety zone for finger-jointed *Pinus Sylvestris* L. furniture components

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Abstract

In finger-jointed wood furniture components, a common problem is chipping in the finger-joints due to fiber deviations around sound knots. The common strategy for avoiding this is to employ a safety zone of a fixed size between defects and cross-cuts. The downside of this is that excess material is cut away in the cross-cutting process. An adaptive strategy was thus developed, for setting the safety zone size between sound knots and the finger-joints in Scots pine furniture components. This strategy was based on measurements of knots, assessment of the risk of chipping the finger-joint, and modeling the risk depending on the knot measurements. The model was used in the strategy in order to minimize the expected loss due to cutting away material around knots, compared with the risk of sorting out components in later stages due to chipped finger-joints. Each knot is therefore assigned a unique safety zone. This strategy was tested using computer simulation of the finger-jointing process, and a sensitivity analysis was performed in order to quantify the effect of variations in in-data. The results show that such a strategy improves recovery in the overall process of turning lumber to finger-jointed furniture components by at least three percent units, and is very robust towards variations in knot size measurements by for instance scanning equipment, but less robust towards variations in cross cutting precision.

Key words: Wood component production, further processing of wood, production simulation

Introduction

In recent years, there has been an increased interest in an integrated approach to the forestry production chain. This means that forest and tree characteristics are seen as linked to the end-user requirements on wood products (Houllier et al. 1995, Bengtsson et al. 1998, Broman et al. 2008). The aim of an integrated approach is to utilize knowledge of both the end-user requirements for different wood products, and of the properties of timber, in order to control the flow of material from the forest to market, and achieve an improved use of the raw material. However, the forestry production chain is complex, due to the nature of the raw material, the various stages of production, various actors, and the decisions they take in harvesting, breakdown, cross-cutting, final processing, and marketing (Bengtsson et al. 1998).

This means that computer simulation is a suitable tool for analyzing the forestry production chain, as it allows for experimentation with complex systems without disrupting the system itself, achieving better control over experimental conditions, and studying a system with a long time frame (Law 2007).

Current secondary processing of wood is characterized by a high degree of automation. This has increased both production speed and volume. However, discrepancies can occur between the desired and actual quality of the finished product. This means that some products are rejected during the latter stages of production which can be a costly waste of resources. Due to the biological nature of the material, the rejection of some products due to wood features cannot be totally avoided, but it is therefore important to utilize knowledge of the biological features of boards, in order to handle them appropriately in the production process, to minimize this loss. In the case of vertically finger-jointed furniture components, one important defect causing rejection is chipped finger-joints (Broman and Fredriksson 2011). This defect is caused when milling a finger-joint where fibers at an angle to the board surface have a lower elastic strength in the vertical direction, than the fibers parallel to the surface, and are more easily chipped away. This can be described by a Hankinson-type formula, which relates the elastic strength of wood, to the angle of the fiber direction:

$$N = \frac{PQ}{P\sin^n A + Q\cos^n A} \tag{1}$$

Where:
N = strength at grain angle A from longitudinal fiber direction
Q = strength perpendicular to the fiber direction
P = strength parallel to the fiber direction

n = empirically determined constant

At grain angle $A = 0$, N will be equal to P. With an increased A, N will approach Q, and since Q is usually significantly smaller than P, and n is in most cases set to values around 2, the strength will be significantly reduced even for relatively small values of A (Bodig and Jayne 1982).
Currently, a common strategy to deal with this problem is to use a safety zone between finger-joints and defects, such as knots, which has the downside that a larger amount of material is cut away in the finger-jointing process. It is common practice that the size of this safety zone is set to a fixed value regardless of type, and/or size of the defect.
Öhman & Chernykh (2011) describe a model to predict the size of the so called diving grain-area (Figure 1), based on knot size and location. This area is almost exclusively located around sound knots, whose fibers are inter-grown with the wood fibers of the stem, compared with a dead knot, which is not connected to the normal wood in the same fashion. Their model is supposedly useful for reduction of chipping in finger-joints, but they do not elaborate on how this may be achieved.

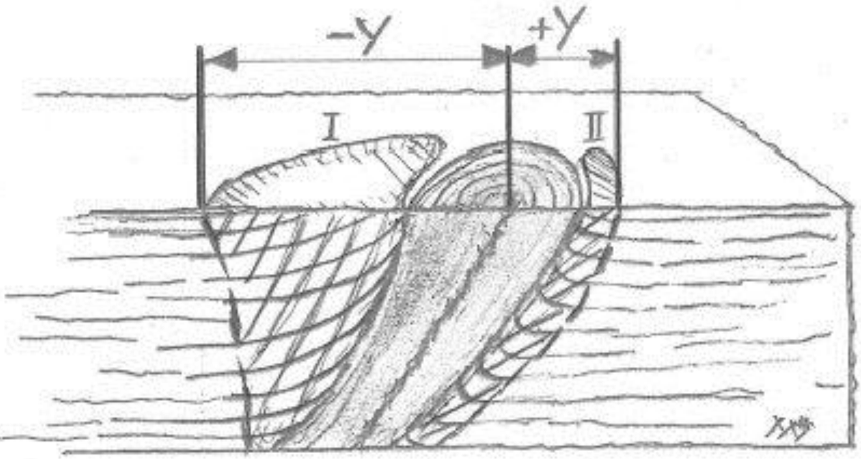

Figure 1. Principal sketch of the diving grain area around a knot. I and II correspond to the regions surrounding the knot where the fibers deviate substantially from the longitudinal direction. Image from Öhman & Chernykh 2011.

Another way to approach this problem is to detect and measure the diving grain area around a knot, by using, for example, laser and the tracheid effect. This type of measurement is good, but not perfect; because it is in some cases difficult to separate diving grain from other features. This is due to surface unevenness, dirt, or compression wood, pith or bark (Zhou and Shen 2003).
An adaptive strategy for choosing a safety zone around sound knots based on their size, instead of a fixed zone, has potential to reduce chipping in finger-joints, whilst maintaining a recovery in the finger-jointing process which is almost as high as the one obtained when using a fixed zone. The effect of this is that the overall recovery for the production process is improved. Such a strategy has other benefits. For example, depending on the needs of the specific component manufacturer, there may be no need for expensive laser equipment to measure diving grain area, since the measurement of the size of sound knots can be achieved by using grey-scale cameras.
The decisions made in the processing of wood should be aimed at minimizing overall material loss, as this is the primary source of costs in sawmills, and one of the most important budget considerations in secondary processing operations. Thus, a strategy for setting an adaptive safety zone should not only reduce chipping, or improve recovery in one part of the production process, but minimize the loss in the entire value-chain. In decision analysis (von Neumann and Morgenstern 1953, Howard 1966), when making decisions under uncertainty, it is advocated that the decision leading to the maximum expected utility is made (Bernoulli 1738, Laplace 1814), or in some cases, the minimum expected loss.
A suitable measurement of the efficiency in a cross-cutting process is length recovery, which is calculated as length of material output from the process, divided by length of material input. This

measurement does not take into account planing of the boards, as volume recovery would do, and is thus a better measurement of how good the cross-cutting process is.
Based on previous research, a model of the risk of chipping, relative to sound knot size and distance to finger-joint is a hypothetically beneficial approach. Since it is not certain whether a knot near a finger-joint will lead to chipping or not, this risk must be quantified prior to modeling. Such a model can be used in a strategy where the aim is to minimize the expected loss of material in the process, through an adaptive safety zone between the sound knot and finger-joint. It is acceptable to quantify the outcome of the strategy in terms of length recovery.
The objective of the study was to evaluate an adaptive strategy to decide the safety zone between knot and finger-joint. This strategy was based on measurements of knots in finger-jointed furniture components, and used sound knot size to predict the risk of chipping a finger-joint. An evaluation was made by computer simulation of the cross-cutting and finger-jointing process. The aim of the strategy should be to improve length recovery in the production process from board, to finger-jointed component, compared with a fixed safety zone approach, and its robustness towards variations in input data will be assessed and quantified.

Material and methods

The study was based on wood furniture components, made from 177 Scots Pine (*Pinus sylvestris* L.) logs. The studied components were of a type currently produced in the Swedish wood industry, finger-jointed bedsides with final product dimensions of 25 × 110 × 2018 mm. The logs were taken from different parts of the tree, i.e. butt-, intermediate- and top logs, and from the same geographical region. This region was in Sweden between latitudes of 64–66° N. The logs had a top diameter ranging between 134–147 mm. They were each sawn into two 33 × 120 mm center boards, and kiln dried to 14% moisture content. The nominal dimensions after drying were 31 × 115 mm with varying lengths.
The secondary processing is described by a flow chart in Figure 2. The boards were scanned using a WoodEye (Innovativ vision AB 2012) industrial scanner which was equipped with four greyscale line cameras for defect detection, and a laser for measuring board dimensions and grain direction. Unwanted defects such as: large knots, wane, or cracks were cut away from the boards, and the resulting pieces finger-jointed together and cross-cut to a final length of 2018 mm. In the cross-cutting operation, a safety zone of 10 mm from the cross-cut positions to all defects was employed in order to avoid chippings in the finger-joints and to account for errors in cutting position. No cross-cutting in any defects was allowed, regardless of whether they had been classified as accepted, or rejected. A planing operation took place both during, and after the finger-jointing process, planing the boards first to a 30 × 114 mm cross section, and then to the final dimensions of 25 × 110 mm. At the final steps of the production process, the boards went through a quality inspection where defect components were sorted out, before the final processing of the product.

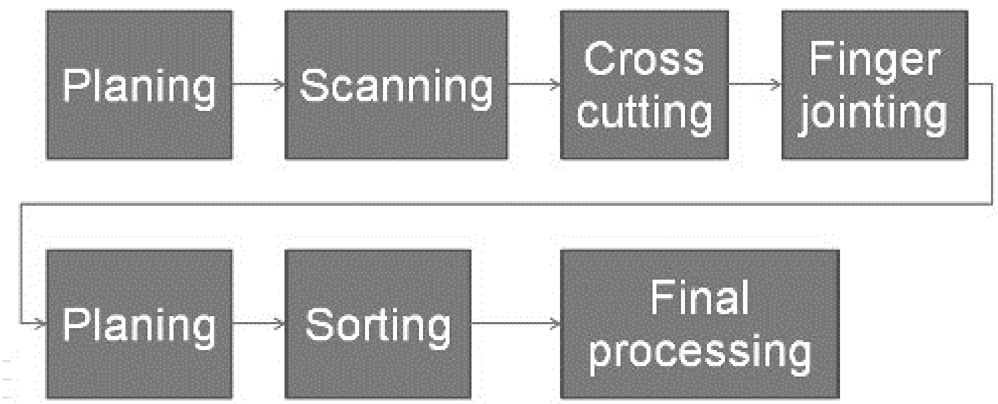

Figure 2. Description of the furniture production process, from boards to furniture components.

In the final product, data on knots in the proximity of the finger-joints was collected. This was done using manual measurements on all components, regardless of whether they had been judged as acceptable or not in the quality inspection.

Measurement of knots

All sound knots within 30 mm of the tip of the teeth of each finger-joint were measured using a carpenter's rule. However, knots with a diameter smaller than 2 mm in all directions were disregarded. The measurement principle is described in Figure 3. The following features were measured and registered (the unit of measurement in square brackets):

- *D* = Distance from finger-joint to sound knot (from tip of tooth to knot edge, lengthwise direction of board). This was set to 0 if the knot was within the finger-joint [mm]
- *L* = Length of sound knot (lengthwise direction of board) [mm]
- Whether the finger-joint is chipped or not [yes, no]

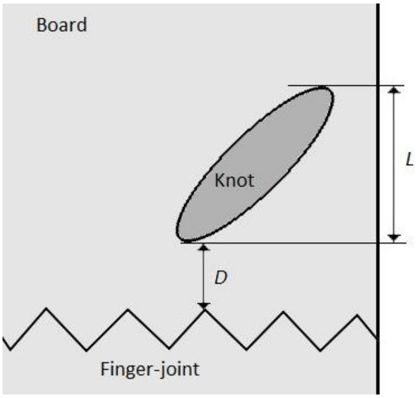

Figure 3. Typical damage to finger-joint due to the vicinity of a sound knot. Note that the area around the dead knot is not affected.

Overall, 1173 knots were measured. Some types of knots, such as splay knots were disregarded, as they do not cause any damage to the finger-joints in this material, i.e. they were measured, but not included in the final analysis. Furthermore, splay knots account for less than 10% of the total knot population in this material. Dead knots and bark-ringed knots were also disregarded since the diving grain area around these knots is very small, or non-existent (Tyvand 1991, Buksnowitz et al. 2010).

Figure 4 shows an example of a chipped finger-joint within the diving grain area of a sound knot.

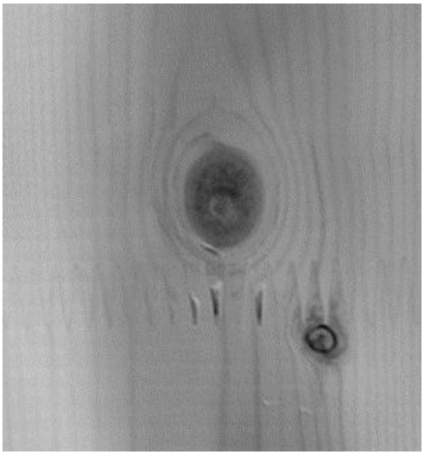

Figure 4. Principle of measurement. ***L*** **= Length of sound knot in the lengthwise direction of board,** ***D*** **= Distance from finger-joint to sound knot.**

In Figure 5, some examples of the types of sound knots that were measured are presented.

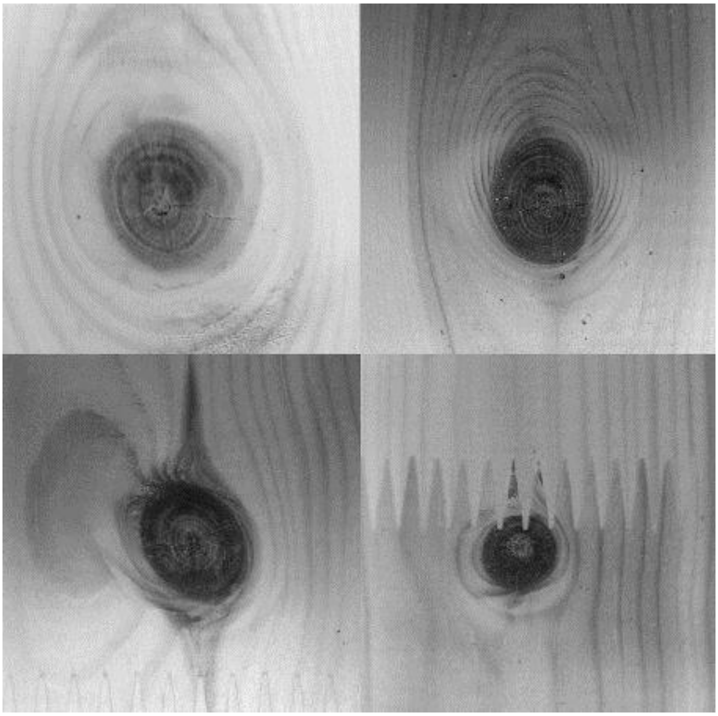

Figure 5. Typical examples of the types of knots that were measured.

Data analysis

From the measured knot data, a linear regression model was constructed to predict the risk of chipping in the finger-joint depending on two variables: size of sound knot in the longitudinal direction *L*, and distance between knot and finger-joint *D*. A prerequisite for this is that the variables are both normally distributed and independent. However, the variable *L* was not normally distributed, but followed a log-

normal distribution. Therefore the logarithm of base ten of the knot length was chosen as a predictor for the finger-joint chipping risk.
In order to calculate the risk of chipping, the knots were divided into 16 classes based on *L* and *D*, according to Table 1, each class having between 12 and 312 knots. The risk of chipping for each class was calculated as the number of knots causing chipping, divided by the number of knots.

Table 1. Classification of sound knots with regard to knot length *L* and distance to finger-joint *D*.

L D	0-8 mm	8-16 mm	16-24 mm	24+ mm
0-3 mm	Class 1	Class 2	Class 3	Class 4
3-6 mm	Class 5	Class 6	Class 7	Class 8
6-9 mm	Class 9	Class 10	Class 11	Class 12
9+ mm	Class 13	Class 14	Class 15	Class 16

When fitting the prediction model, the class center values were used for both *L* and *D*: (class upper limit + class lower limit) / 2. For the classes containing all knots above a certain size, and/or distance to finger-joint, the lower limit plus one half of an interval width was chosen.
Furthermore, the risk is strictly decreasing towards zero with increasing distance from the sound knot, and decreasing size of the knot, and thereafter continues at a constant zero. Thus, only values of risk above zero are used for the linear model, and cases where modeled risk is predicted to be below zero, will be set to zero. This is shown schematically in Figure 6.

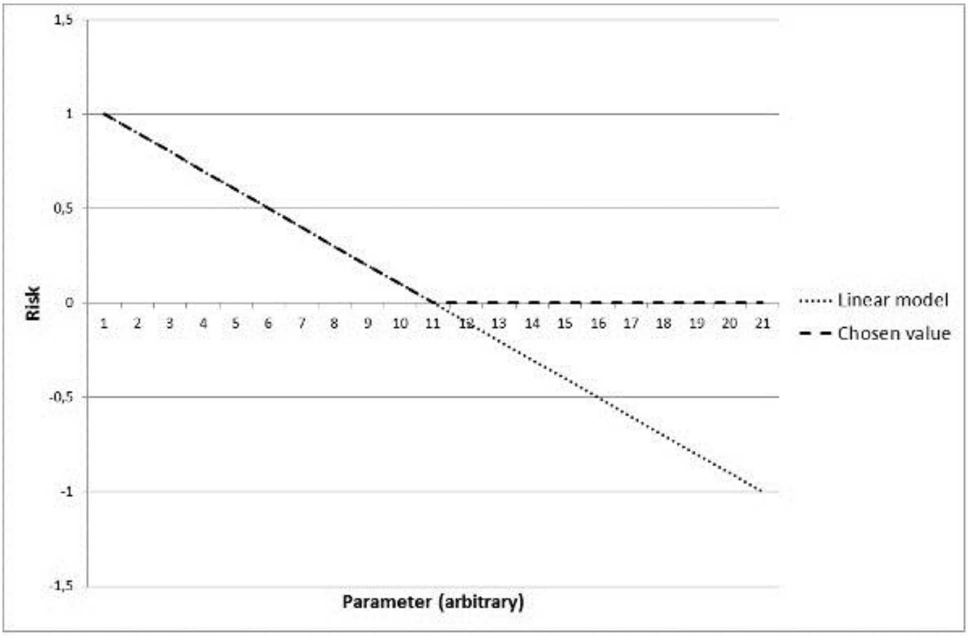

Figure 6. Principle of using a linear model to predict the risk of chipping finger-joint due to a sound knot. When the model predict values below zero, the risk is set to zero. Note that this is not the actual model, but an illustration of the principle.

New safety zone strategy

Using the results from the analysis of the knot measurements, a strategy for deciding the safety zone length between sound knots and finger-joint was developed.

The adaptive safety zone was decided for each sound knot in order to minimize the expected loss resulting from the decision. This is based on game theory and decision making under uncertainty, albeit in one of its simplest forms. The expected length loss was calculated according to:

Expected loss $E_L = risk_{fjD} \cdot length_{comp} + L,$ (2)

Where:
$risk_{fjD}$ = risk of chipped finger-joint, between zero and one, modeled from knot features
$length_{comp}$ = length of finger-jointed component in mm
D = safety zone length in mm (Figure 3)

The variable $risk_{fjD}$ was calculated using the linear regression model relating $risk_{fjD}$ to L and D, and since $risk_{fjD}$ depends on D, values of D between 0.1 cm and 15 cm were tested for each sound knot. The distance which resulted in the lowest expected loss was chosen for that particular knot.

Simulation

The new strategy was tested using a computer simulation program described by Fredriksson (2011). This software uses data from industrial scanners in order to predict the outcome of a cross-cutting and finger-jointing operation on boards. Defects such as: sound knots, dead knots, cracks, and wane etc., are represented. The output from the program includes length recovery, which is defined as length of finger-jointed components divided by length of boards, and average length of the cross-cut pieces. For this application, a module for calculating the chipping risk, according to the model above was added. The input data to the simulation described in this paper were the results from the scanning of the boards, with all identified defects included.

The overall length recovery was calculated as the length recovery in the finger-jointing process multiplied by 1 - $risk_{fjD}$. It is assumed that each chipped finger-joint will lead to one rejected component, which is reasonable because each finger-jointed component of 2018 mm usually contains around 4–5 joints, and only a small percentage of the joints have sound knots nearby.

Several cases of a fixed safety zone were tested through simulation and compared with the strategy of using an adaptive zone based on sound knot size.

Sensitivity analysis

In a practical situation, there is variation both in the accuracy of the scanning of the boards and in the cross-cutting operation. However, the distribution of this variability is not known. It is reasonable to assume that it is normally distributed, since the errors in a calibrated industrial system should not be unevenly distributed around the mean.

In order to assess how this variability affects the model and the strategy, several simulation runs were made. In these simulations the sound knot length L, and the safety zone, were given random errors according to normally distributed functions with varying standard deviations and expected value 0. This was done in order to find the level of uncertainty, regarding these two values, where the strategy provides disadvantageous results in terms of overall length recovery. Three different standard deviations were used for both length and safety zone, with all combinations of those setups, for a total of nine runs. The same seed was used for the randomizing algorithm each time, according to the method of common random numbers (Law 2007).

Results

Measurement of knots

The distributions of the measured variables are presented for sound knot length *L*, in Figure 7, and in Figure 8, the distance between sound knot and finger-joint *D*. Figure 9 presents the distribution of a logarithmic transformation of *L*.

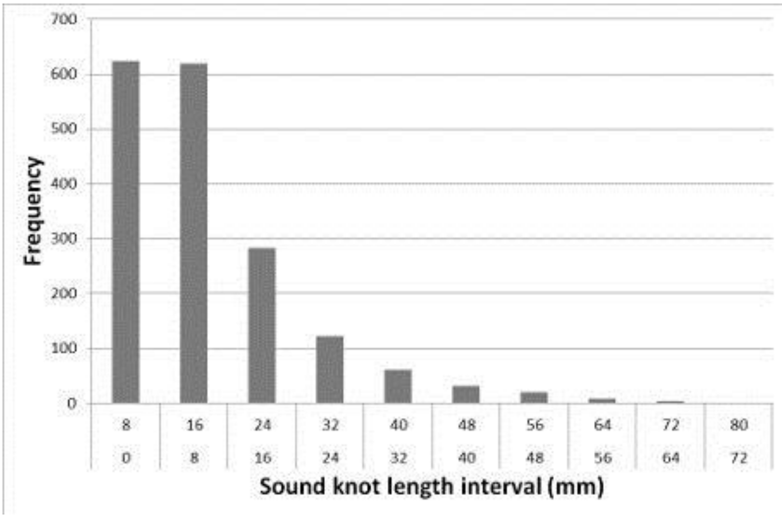

Figure 7. Distribution of the sound knot length or *L* variable.

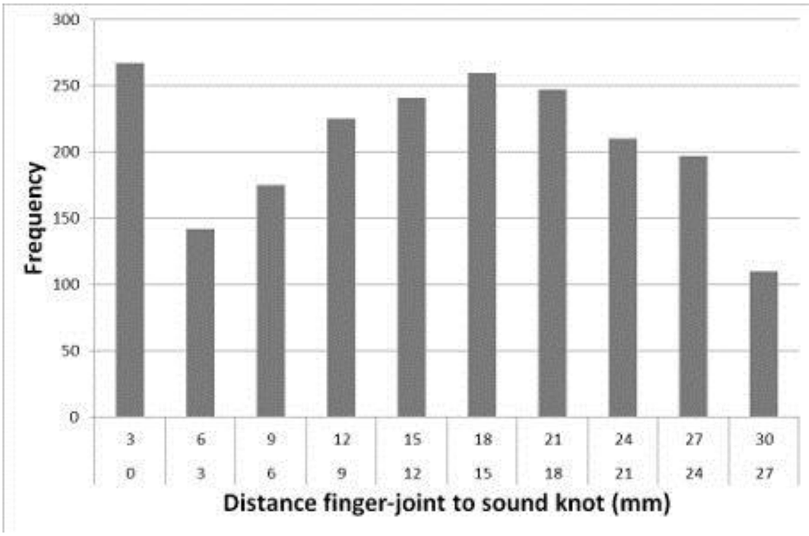

Figure 8. Distribution of the distance between sound knot and finger-joint or *D* variable. Note: The first interval contain all knots within or very near the finger-joint. This is thus a summary of the left tail of the distribution, and is an effect of not using a "negative distance" in the measurement principle.

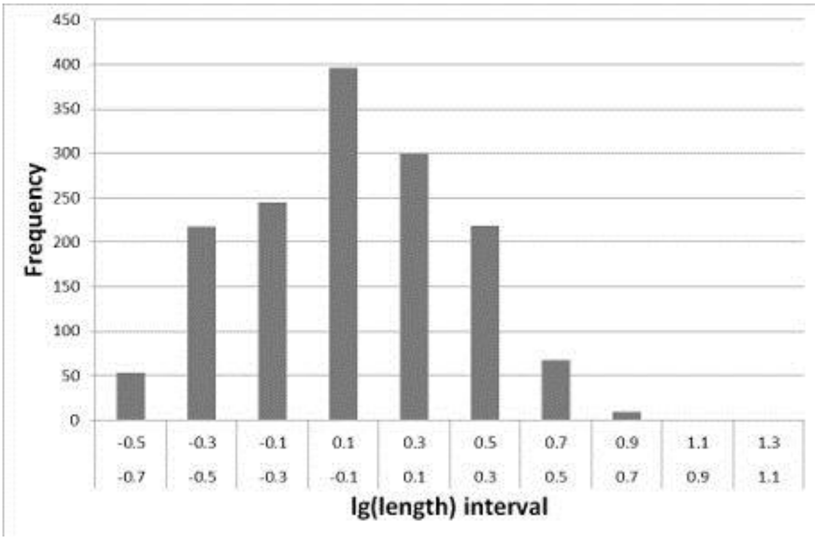

Figure 9. Distribution of the sound knot length or *L* variable, after logarithmic transformation.

Model

The linear model for predicting risk of chipping in a finger-joint, with regard to nearby sound knots, is:

Risk of chipped finger-joint $risk_{fjD} = 0.448 + 0.771 \cdot \log(L) - 0.752 \cdot D$ (3)

Where:
L = length of sound knot in board lengthwise direction in cm,
D = distance from finger-joint to knot in cm.

When applying the model on the 16 classes of knots, and setting all negative results to zero, this model yields a root mean square error (*RMSE*) of 0.067, and a calculated R^2 of 0.92, when comparing the observed risk of chipping within each class with the predicted risk. In this prediction the class center values for L and D were used. *RMSE* was calculated as the square root of the mean of the square errors for each class, which in turn was calculated as $\left(risk_{obs} - risk_{pred}\right)^2$, where:

$risk_{obs}$ = observed risk for the class, and
$risk_{pred}$ = predicted risk for the class.
R^2 was calculated as $1-\frac{SS_{err}}{SS_{tot}}$, where
SS_{err} = sum of square of residuals of the model, and
SS_{tot} = sum of total squares for the population.

Simulation

The results of the simulation using the two strategies are shown in Table 2, as overall length recovery, recovery for the finger-jointing process alone, average piece length, and average risk of chipping finger-joints. Average piece length is the length of the cross-cut pieces that are to be joined, which should be as long as possible for an efficient finger-jointing process.

Table 2. Strategy of using an adaptive safety distance based on knot size compared to using several values for a fixed distance.

Strategy	Overall recovery (%)	Recovery, finger-joint process (%)	Average piece length (mm)	Chipping risk (%)
10 mm fixed distance	70.7	83.1	533.9	14.9
20 mm fixed distance	79.9	80.8	531.2	1.2
30 mm fixed distance	78.3	78.3	524.5	0.0
Adaptive distance	83.1	83.1	533.7	0.0

Robustness of the strategy

The results of the simulations using different errors of the sound knot length and calculated distance are presented in Table 3. The fixed zone strategy with the highest overall recovery from Table 2, of 20 mm, is included as a reference. In the reference the sound knot length *L* and cutting position were not varied.

Table 3. Results when using different random variations in knot size and safety zone size. σ = standard deviation. The results when using a fixed safety distance of 20 mm are included as reference, see Table 2.

Knot size σ	Safety distance σ	Overall recovery (%)	Recovery, finger-joint process (%)	Average piece length (mm)	Chipping risk (%)
10	10	79.7	81.2	531.5	1.9
15	10	79.4	81.1	529.6	2.1
20	10	79.9	81.2	530.0	1.6
10	15	77.3	79.7	527.9	3.0
15	15	76.2	79.0	529	3.6
20	15	77.4	79.4	526.4	2.5
10	20	73.1	76.3	525.8	4.2
15	20	72.7	76.9	522.8	5.5
20	20	71.9	76.3	523.9	5.8
Ref. (fixed distance 20 mm)		79.9	80.8	531.2	1.2

Discussion

It has been shown that it is possible to model the risk of chipping in finger-joints, and account for this in a strategy for cross-cutting and finger-jointing in a robust way, by using an adaptive safety zone between sound knots and finger-joints. This is an approach that promises higher recovery for a finger-joint production process, than a strategy using a fixed safety zone. It has other benefits such as only needing information from greyscale cameras, thus reducing the need for expensive laser equipment, and that the average cross-cut piece length in the finger-jointing process is increased, which reduces the production cost per unit length of finger-jointed component. However, there are some limitations and issues regarding the strategy's applicability.

The boards that the measurements were made on were planed, (2.5-3 mm on each side) in contrast to the material scanned and thus used for the simulations. This means that the defects on the simulated boards did not have exactly the same dimensions as on the physical boards. However, the size of a knot is not changed by more than one or two millimeters in most cases by this level of planing, and thus does not have a substantial impact on the results, which is shown in the sensitivity analysis.

Some knots were excluded in the measurements; any knots of a size below two mm, and splay knots. This is not a significant issue because knots smaller than two mm have a very small impact on recovery in this type of production process, and the splay knots, at least in this study, account for a less than 10% of the total knot population near finger-joints.

The material is limited in size, and before any general conclusions can be drawn, tests need to be made on other material as well. It is also limited by species, i.e. to Scots Pine, and the conclusions should not be applied to other species. Furthermore, the material is geographically limited to the north of Sweden, where trees are rather slow-growing. The fiber deviation area around a knot is a little different in faster growing trees. For instance, the size of growth rings depends upon the growth rate of the tree, and the growth ring size affects the strength of the wood material, and thus the risk of chipping. The material is limited to boards from logs with a certain range of diameters, but from different types of logs. Renewed tests on a different material would strengthen the conclusions of this study.

The model is based on measurements of knots which were not cut away. This means that sound knots above a length of 45 mm are not included in the model, as this was the quality threshold for sound knots in the studied production process. It is not certain that extrapolating the model to these sizes will be correct, and this needs to be tested as well.

The strategy is risk-minimizing. This is in a large degree due to the final product length of 2018 mm. As the product is relatively long, the risk of chipping a finger-joint, and thus rejecting an entire component, makes it worthwhile to cut off a little extra material, usually a few mm, in order to reduce the risk to near zero. For a shorter component length the strategy will probably be more risk prone, as the potential recovery loss of sorting out rejected components is smaller.

In a practical application, the actual cutting position and the desired cutting position do not always match. This needs to be accounted for by a cutting offset, which will need to be included in the safety zone calculation. However, it will not interfere with the general idea behind the strategy.

As with most computer simulation, any predictions regarding the actual outcome of a certain strategy are difficult to make. In this study, two different cases are compared, and it can be concluded that one strategy is better than the other in terms of overall length recovery. Thus, no predictions regarding the actual length recovery are made, merely that it can be improved by an adaptive safety zone strategy.

The adaptive strategy is robust to variations in the input data of measured sound knot length and cutting position, which points to applicability in real situations. It is most sensitive to variations in the actual cutting position, where a standard deviation of over 10 mm will drastically reduce recovery with regard to the wanted position. This needs to be accounted for when applying this strategy practically, by ensuring that the actual cutting position does not deviate from the desired cutting position with a larger variance. Whether this is actually possible or not, is not addressed here.

The conclusion is that recovery in a finger-joint production process is increased by at least three percent, when using an adaptive strategy for creating a safety zone around sound knots. This increase is even higher when compared with the situation of the finger-jointing process used as reference in this study.

The strategy is based on a prediction model for predicting the risk of chipping in a finger-joint, depending on distance to, and size of sound knots near the joint, and offers significant advantages over using a fixed safety distance in terms of recovery. It is robust towards variations in input data up to a standard deviation of 10 mm regarding cutting position, and up to at least 20 mm regarding knot size.

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Paper IV

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ORIGINAL ARTICLE

Reconstruction of *Pinus Sylvestris* knots using measurable log features in the Swedish Pine Stem Bank

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Abstract
The objective of this study was to develop a method for reconstruction of parametrically described whorls and knots from data possible to extract from industrial scanning of logs, using X-ray scanners. The method was conceived using the logs in the Swedish Pine Stem Bank as a foundation, and was based on a few predictor features extracted from these logs; namely whorl volume, distance between whorls and distance between pith and surface. These features were not measured in images but calculated from existing parameterised knots. Simulated test sawing shows that the reconstruction method results in a representative model of the knot structure in the log, when considering the grade distribution of the sawn timber produced by the simulation program. The results of this study could, for instance, be used for improved online quality predictions at sawmills. One step in this direction is to use industrial X-ray data to enlarge the amount of log data available for sawing simulation research. Future work can, therefore, focus on developing a practical application of the results presented here.

Keywords: *Knot models, knots,* Pinus sylvestris, *wood quality, X-ray.*

Introduction

For many years it has been of interest to be able to predict the properties of sawn wood products from tree features. To facilitate this, different approaches have been tried; one example in recent times is the Swedish Pine Stem Bank (SPSB), which is a database that consists of properties for 198 Scots pine (*Pinus Sylvestris* L.) trees (Grönlund et al., 1995). The SPSB provides input data for the sawing simulation software Saw2003, described by Nordmark (2005), and a large amount of the data used in this sawing simulation is based on computed tomography (CT) scanning of the logs in the SPSB. In forest research, a number of statistical models for predicting whorl and knot attributes from a number of measurable features have been developed. Several types of features for prediction of knots are used in these models, and they can roughly be divided into site, stand, tree and internal features. Site, stand and tree features are measured in the forest before felling and bucking, while internal features are measured in sawlogs, by destructive or non-destructive means. There are models, such as those described by Mäkelä et al. (1997), Mäkinen and Colin (1998), Björklund and Moberg (1999) and Moberg (2006), that take into account both tree features and site or stand features, to predict the properties of Scots pine knots. Other models are based on tree features and internal features; for instance, those presented by Pietilä (1989) and Peterson (1998), which were made on Scots pine as well. Studies of knot characteristics that are based solely on internal features are uncommon. However, Moberg (2006) found positive correlations between number of knots per whorl and distance to the previous whorl; knot length and diameter; and branch angle and diameter, respectively. These models are also based on stand features not connected to the single tree.

The studies made on whorl and knot models are unfortunately mainly done in Scandinavia. There are, however, studies from other countries where knot measurements have been made, for instance, by Fenton (1960) on Corsican pine (*Pinus laricio* Poiret), Benjamin et al. (1999) on Black spruce (*Picea mariana* Miller) and Pinto et al. (2002) on Maritime pine (*Pinus pinaster* Aiton).

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Grundberg and Grönlund (1992, 1997) described models for extracting features, such as knot volume per whorl, dead knot volume per whorl, log type and distances between whorls, from simulated two-directional X-ray images of logs.

The possibility to perform sawing simulation on virtual models of sawmill logs in real time could be one way of improving log quality prediction. However, if the logs are scanned by a two-directional X-ray scanner it is difficult to determine the knot and whorl structure within the logs, since there is much less knot information available than in, for instance, CT data. Another problem, with using sawing simulation for research purposes, is the relatively small amount of available data today. Since the SPSB is limited to 198 trees, it is difficult to evaluate the validity of results of sawing simulation based on this material.

Thus, there is a need to:

- estimate knot structure in sawlogs online with a two-directional X-ray scanner, thus using less information than has been done earlier with CT data;
- enlarge the data available for sawing simulation with more logs.

One prerequisite for this is to be able to find the overall knot structure in sawmill logs, using data from industrial two-directional X-ray log scanning. Since there are few existing knot models based solely on two-dimensional internal log features, this requires a novel method of reconstructing knots from these features, which are far scarcer than features extracted from CT scanning. A method capable of this could be used to enhance the quality prediction of sawlogs and provide a source which would make it possible to add a significant number of new virtual logs to simulations, since a large number of logs are scanned in sawmills on a daily basis.

The reconstructed knots should be represented in the same parametric fashion as in the stem bank, to allow for sawing simulation. The shape of the logs, which is also necessary for creating logs for sawing simulation, can be obtained from optical three dimensional (3D)-measurements at sawmills, an issue which is not addressed here.

In a study by Grundberg et al. (1999), a reconstruction of the knots in the SPSB based on simulated two-directional X-ray data was made, and property- and experience-based methods were evaluated. Two methods were tested using sawing simulation, and the best of these resulted in the same grade for the board produced by CT-scanning and the one based on two-directional X-ray scanning in 60% of the cases, when sawing 45 logs. In 3% of the cases it differed by more than one grade. The conclusion from the study was that the developed methods were in need of further development.

Thus, this study aims at developing improved reconstruction methods, and the objective of this study was to recreate knot data for logs, equivalent to those in the stem bank today, based on a small amount of features that are possible to extract from industrial X-ray images and to calculate from the knots in the SPSB. In a first step, the models used to recreate knot data will be developed, not using actual X-ray images, but based on features calculated from the SPSB data. These features are ones that are possible to extract from X-ray images. The modelled knots should be representative of the real knot population at large in the logs, and produce sawing simulation results similar to those of a CT-scanned log. Measuring the knot and whorl features in actual two-directional X-ray images will be addressed in future work.

Materials and methods

This study was based on 628 Scots pine logs from the SPSB, originating from 198 trees. The stem bank trees, from well-documented sites at different locations in Sweden, have been documented thoroughly regarding both tree properties and silvicultural treatments. They have been scanned with a medical CT scanner to record internal properties such as knots, pith location and sapwood/heartwood border. The SPSB knot database is based on 11 parameters named A to K, derived from CT-images of logs (Grundberg et al., 1995). The geometry of each knot is described by these parameters and the parametric description makes it possible to describe knots in a tree with a minimal amount of data. Figure 1 shows how a knot is represented geometrically in the SPSB, and the functions describing the geometrical features using the knot parameters are presented below. A further description of the knot parameters is included in Grönlund et al. (1995).

$$\Theta_p = 2 \cdot \left(A + B(r_p)^{1/4}\right) \quad (1)$$

Θ_p = radial knot angle in radians,
r_p = radial distance from the pith in pixels along the knot axis.

$$\Omega_{\text{axis}} = C + D \cdot \ln(r_p) \quad (2)$$

Ω_{axis} = angle position in radians of the knot axis,

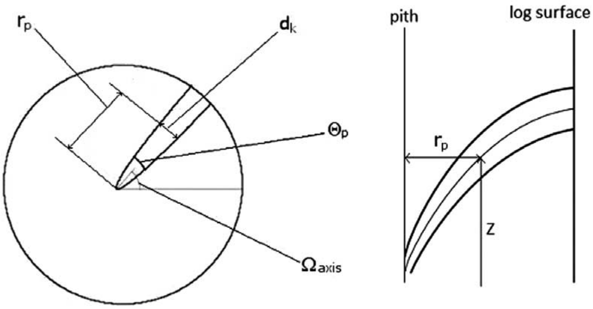

Figure 1. Description of the key geometrical features for SPSB knots. These features are calculated using the 11 Swedish Pine Stem Bank knot parameters *A*–*K*.

The parameters *E* and *F* are equivalent to the parameters *A* and *B*, but for the longitudinal diameter of the knot.

$$Z = G + H\sqrt{r_p} \quad (3)$$

Z = Height position of the knot axis in cm, from the butt end of the log,

I = Distance from the pith to the end of the knot in millimetre,

J = Distance from the pith to the dead knot border in millimetre,

K = Distance from the pith to where the knot axis hits the log surface, in millimetre.

A summary of the stages involved in this study is presented in Figure 2. The left-hand side of the chart represents the work that has been done in the SPSB (Grönlund et al., 1995) in addition to sawing simulation, while the right-hand side is the work presented in this article. The latter involves pre-processing of the SPSB knots to extract the desired features, reconstruction of the parameterised knots using only these features and sawing simulation to compare the two sets of knots, which are the same physical knots but constructed using different features.

The models should be based on features that are possible to extract (Grundberg & Grönlund 1992, 1997; Nordmark 2005) from industrial X-ray images. The features tabulated in Table I satisfy this condition and were extracted from the SPSB parameter files for each whorl, that is, these features are not measured in X-ray images, but calculated from parameter files created by CT-scanning and image analysis.

Feature extraction from the SPSB knots

The first step of this study (right-hand side in Figure 2) was to extract features from the SPSB,

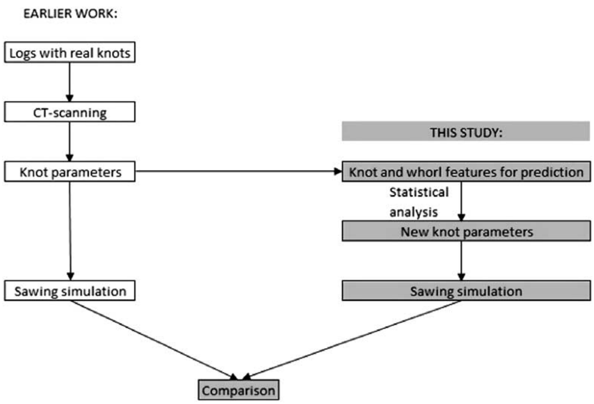

Figure 2. Description of the main structure of this study. Note the distinction between the physical knots in the log, the knots as represented in the Swedish Pine Stem Bank by parameters, and the knot features used for reconstructing the knots. Furthermore, at the last step the sawing simulation is made on the same set of physical knots, but reconstructed in two separate ways. The original SPSB knots (left) are considered ground truth and are the foundation for the new parameterisation of the SPSB knots (right).

Table I. Features used for reconstructing knots. These features are possible to extract using two-directional X-ray scanning, and in this study were calculated for the SPSB knots.

Features	Descriptions	Units
WhorlHeight	Height of the whorl in log	cm
△Height	Distance from one whorl to the nearest whorl in the downwards direction (intercept)	cm
Whorl volume	Total volume of all knots in the whorl	mm^3
SurfaceDist	Distance from the pith to the surface of the log	mm

WhorlHeight, ΔHeight, Whorl volume and *SurfaceDist*. In this study, 45,834 knots from the SPSB were analysed. The knots were sorted into whorls according to the following definition:

- If the height to a knot, measured from the butt end of the log to the starting position of the knot at the pith of the tree, is within 8 cm from the height of the whorl, the knot is added to the whorl. Eight centimetres was chosen because this conforms well to an earlier definition made by Björklund (1997) on the SPSB whorls; see Table II for more detail. Note that he excluded some of the whorls in his study, so the absolute numbers are different but the overall distribution of whorls is roughly the same.
- *WhorlHeight* is continuously updated each time a knot is added, and is defined as the average of the height, at the pith, of each included knot.
- If a knot cannot be assigned to a whorl, this knot forms a new whorl with height equal to the knot height (at the pith).
- "Whorls" with only one knot were omitted from the model.

The result of this definition is presented in Table II. Note that only whorls with 12 or less knots are presented here. In the SPSB, there are whorls with up to 23 knots, but the whorls with more than 12 knots account for less than five per mil of the total whorl population, so they are omitted in Table I for more convenient reading.

WhorlHeight was calculated as already described, while *ΔHeight* was the height distance between a whorl and its predecessor. If the whorl was the first in the log, *ΔHeight* was set to *WhorlHeight*. The *Whorl volume* was the sum of the volumes of each individual knot in the whorl, which were calculated using the function for knot diameter. The knots were, in this case, assumed to have a circular cross-section, using the parameters A and B that describe the knot size in the log cross section plane, since these are better described in the SPSB than their longitudinal counterparts E and F (Grönlund et al., 1995). Thus, the volume of each knot was calculated using the following equations:

$$V = \int_{o}^{L} \pi \cdot r^2 \mathrm{d}l \tag{4}$$

$$r = \frac{\mathrm{d}_k}{2} = \frac{(2 \cdot (A + B(r_p)^{1/4}) \cdot r_p \cdot \mathrm{scale}}{2} \tag{5}$$

from Nordmark (2005), see Equation 1.
Equations 1 and 2:

$$V = \frac{\pi}{4} \int_{0}^{L/\mathrm{scale}} (2 \cdot (A + B(r_p)^{1/4}) \cdot r_p \cdot \mathrm{scale})^2 \mathrm{d}r_p$$

V = knot volume in mm^3
L = knot length (SPSB knot parameter *I*)
scale = magnification in computer tomograph/256
A, B = knot parameters describing knot propagation angle
r_p = radial distance from the pith in pixels along the knot axis.
See Figure 1 and Equation 1 for details.

SurfaceDist in this study was already given in the stem bank for each knot, by parameter K.

Parameter reconstruction method

Reconstruction of parameters was the second step in the study; see Figure 2. This was made by statistically analysing the extracted features of the SPSB knots. The features that needed to be predicted, from the calculated features in Table I, to reconstruct the knots from the SPSB were K_f = knot frequency or knots per whorl, and all 11 SPSB knot parameters A–K.

Table II. Number of whorls with different knot frequencies, according to the definition used in this study. The sets of data in the two rows are both from the Swedish Pine Stem Bank; the first row is the number of whorls obtained with the above method, the second row is the number of whorls obtained by a method used in an earlier study by Björklund (1997).

Knots in whorl	2	3	4	5	6	7	8	9	10	11	12	Sum
Number of whorls	736	1496	2169	2584	1332	685	345	93	41	12	9	9502
Björklund (1997) number of whorls (ref.)	518	1303	1933	2339	1238	681	384	95	52	14	11	8568

A method for reconstructing the knot parameter files of the SPSB from the measurable features in Table II was constructed. The reconstruction method involved four main steps: assignment of K_f to each whorl, assignment of cardinal direction pattern to the whorl, assignment of volume to each knot and assignment of SPSB knot parameters to each knot. The first step was based on a linear function predicting the number of knots of a whorl using Δ*Height*. The second step was performed for each whorl, and was done to decide the cardinal direction of each knot in the whorl. In the SPSB logs, a small amount of typical patterns for cardinal direction of knots were very common. Thus, a whorl was given a certain chance of being sorted into a specific pattern depending on the relative distribution of these typical patterns. After this, the knots in the whorl were given a cardinal direction according to the pattern. The third step, distribution of the whorl volume over the knots in the whorl, tried to imitate the size distribution of the knots in the SPSB whorls, which was not even. This was done by randomly assigning each knot in the whorl a size order, and then distributing the knot volume according to the size order. The fourth and final step utilised a linear model relating the SPSB knot parameters to the knot volume when applicable, and in other cases the parameters were randomly chosen from a normal distribution. The linear models were chosen as the ones among several tested, that yielded the best coefficient of determination (R^2), when applied on the SPSB material. If R^2 was lower than 0.3 a stochastic method was chosen, for the most crucial parameters *A*, *I* and *J*. Figure 3 presents a summary of the reconstruction strategy. Dashed arrows denote connections with a random or a stochastic element, while solid arrows denote direct or linear relationships.

The resulting knot models are thus described in exactly the same manner as the original SPSB knots, with the same set of parameters (but with other values), to allow sawing simulation and comparison with the original SPSB knots.

Validating the method by simulation

The SPSB can be used for sawing simulation using the simulation software Saw2003, developed by Nordmark (2005). In Saw2003, the CT-scanned logs of the SPSB provide input, and the software allows the user to view and manipulate logs and boards in 3D. It models a sawmill that uses cant sawing with two sawing machines, edging and trimming. The latter two are value-optimised according to timber prices and grading criteria, and the simulation results in virtual boards with information about knots, value, dimensions and so forth.

The reconstruction method was thus tested using sawing simulation in Saw2003 of logs with the reconstructed knots from this study, which are the same knots as in the SPSB but parameterised in a different way using less information, that is, in the way that it would be done if the information was from a two-directional X-ray scanner instead of CT scanning. The results from this simulation were compared with sawing simulation of logs with the original stem bank knots, obtained from a medical CT-scanner. The latter knots are defined as the ground truth in this study.

Since the model involved random elements, three reconstructions and subsequent test sawings were made, with the same in-data. The simulations used the default sawing pattern for each individual log, which was chosen based on sawing class assignment of the log according to the top diameter.

In this comparison, log shape and heartwood/sapwood border were the same for both sets of logs. The resulting boards were graded A, B or C according to the Nordic Timber Grading Rules (Anon., 1994). Grades are ordinally scaled, with grade A considered as the one with the strictest rules. Concerning knots, grading is done according to size

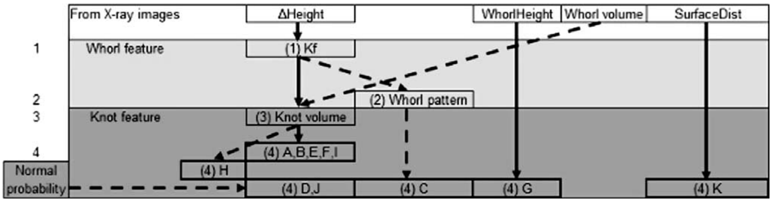

Figure 3. Reconstruction of knot parameters, from measurable log properties. From the features Δ*Height*, *WhorlHeight*, *Whorl volume* and *SurfaceDist*, each whorl is reconstructed (i.e. number of knots in the whorl and a typical pattern for cardinal direction of the knots). The individual knots are finally modelled in a parametric fashion from the whorl features. Note: solid arrows denote direct or linear relations; dashed arrows denote models with some sort of random element involved. K_f = number of knots per whorl, *A–K* = SPSB knot parameters. Darkest area: knot features/parameters, semi-dark area: whorl features, light area: features from the SPSB. The numbers represent the different steps in the overall model, numbered 1–4.

of and number of knots per board surface. Also, different criteria are used for sound knots and dead knots in grades A and B. One of the decisive quantities that are regarded when grading boards is the size of the largest knot on each board surface.

In the sawing simulations, the price list shown in Table III was used. Because Saw2003 utilises value optimising in edging and trimming, a sensitivity analysis with regard to pricing was performed. This was done to investigate whether the prices for sawn timber affect the end result, since price is a quantity that constantly changes, and is subject to other factors than the raw material itself. The different prices are presented in Table III. In the price sensitivity analysis, only one set of reconstructed knots was evaluated.

Results

Within this section, results of the four main steps are presented in Figure 3; models for K_f, cardinal direction, knot volume and finally the knot parameters themselves. The models are based on the features extracted from the SPSB.

Knots per whorl

In this study, the prediction model for knot frequency per whorl (K_f) was based on distance between whorls, *ΔHeight*. A linear model using the natural logarithm of *ΔHeight* was used, and the least square regression function between K_f and ln (*ΔHeight*) was calculated as $K_f = 1.570 + 0.988 \times \ln(\Delta Height)$. This model resulted in a coefficient of determination (R^2) of 0.13. However, when using this model and rounding the result to the nearest integer, which is necessary since knot frequency is a discrete quantity, the result differed from the SPSB whorl by less than or equal to one knot in 70% of the cases. In comparison, a normally distributed random function only achieved this in 49% of the cases, on average. For the whorls with 3–6 knots, which are by far the most common cases, accounting for around 4/5 of the whorl population, this number was higher: 86%. An untransformed model was slightly worse than the one using the natural logarithm of the intercept, with 66% of the whorls predicted within one knot. Furthermore, a model not using the natural logarithm of *ΔHeight* resulted in whorls with three or more knots only, thus not accounting for the two-knot whorls.

Table III. Sawn timber prices used in this study.

Grade Centreboard/ sideboard	A Centre	A Side	B Centre	B Side	C Centre	C Side
Price in sawing simulations (SEK/m^3)	1850	3000	1600	1400	1000	1100
Price in sensitivity analysis (SEK/m^3)	2500	2800	2000	1700	800	900

Note: The first row of prices were used for the three simulated test sawing runs, while the second row was used in the (one) sensitivity analysis sawing simulation run.

Cardinal direction of knot

Many of the whorls in the SPSB behave in a similar manner with regard to the cardinal direction of the knots near the pith. Whorls with five or more knots usually have their knots symmetrically distributed around the radial plane. Thus, a number of typical patterns (Figure 4) for whorls with three or four knots were defined. The special case of whorls with two knots can be handled in a more simplified way. Nine and 13 respective patterns were defined for whorls with three knots and whorls with four knots (in total 22 typical patterns). This classification was made to decide the parameter *C* for each knot in a whorl, based on the number of knots in the whorl.

The typical patterns start with the first knot in a clock-wise direction (viewed from the top end of the log) from the 0° direction, which is the same as the north direction in the standing tree. The *C* parameter of this knot was defined within a specific interval of positions for each pattern, as shown in Figure 4. All other knots were defined in relation to this first one, also within a degree-interval. These 22 type patterns represent 88% of the CT-scanned SPSB whorls. Reconstruction of whorls could thus be made using these typical patterns, randomising the actual position of the knot within the pattern intervals. Each three- or four-knot whorl was randomly assigned a typical pattern based on how common the case was, and then the knot direction was randomised within the pattern restrictions.

For whorls with more than four knots, it was more convenient to begin with the southernmost knot, since the northernmost knot could have either very high values (slightly below 360) or very low values (slightly above 0) of the parameter *C*, which makes it more difficult to handle. In the entire SPSB, the direction of this knot was, in general, approximately normally distributed around 180°, with a standard deviation that decreases with the number of knots in the whorl, but is around 26° on average.

The other knots were, in general, spread out with a distance of 360°/K_f. In this case as well the standard deviation decreases with the amount of knots in the whorls, but on average it is around 28°. This meant

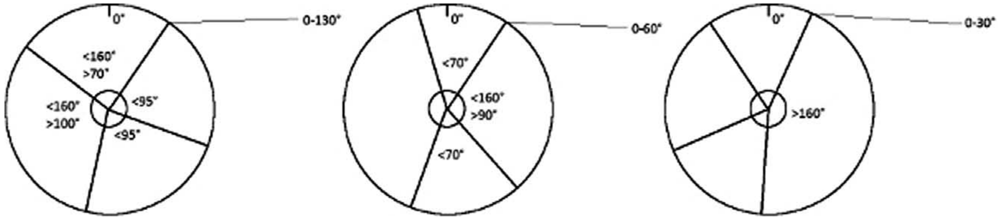

Figure 4. Three examples of typical whorl patterns, from the Swedish Pine Stem Bank, for whorls with four knots. This figure shows the cross-sectional view of a log, seen from the top end. Note: The zero-degree direction corresponds to north in the standing tree. Each straight line corresponds to the cardinal direction, at the pith, of a knot. The uppermost right degree-interval limits the direction of the first knot, clock-wise, from the northern direction. All other degree-intervals limit the angular distances between knots.

that the reconstruction of the whorls with a knot frequency over four could be made by first defining the direction of the southernmost knot, using a normal distribution function with expected value 180° and standard deviation of 26°. Then the other knots were spread out, starting from the southernmost knot. The angular distance between a knot and the next one was decided according to a normal distribution function with an expected value of 360°/K_f and a standard deviation of 28°.

Lastly, the whorls with just two knots were handled in a separate way. Here, the orientation of knots was evenly distributed, but the angle between the two knots was normally distributed with an expected value of 104° and a standard deviation of 44°. The consequence of this was that the first knot in a whorl with two knots could be randomly assigned a *C*-parameter (0–360), while the second knot could be positioned according to a normal probability function in relation to the first.

The value of the parameter *D* (i.e. bending of the knot in the radial plane) was normally distributed around 0.25 in the entire stem bank, with a standard deviation of 5.1. No significant differences due to cardinal direction or size could be found in the material; nor were there any clear similarities within the whorls or logs. All knots were thus assigned a *D*-parameter according to a normal probability function.

Distribution of knot volume

The total volume of a whorl was not evenly distributed among the knots in the whorl. The largest knot in the whorl had on average 183% of the average knot volume in the whorl, in a whorl with four knots. This percentage was approximately linearly related to the number of knots in the whorl; see Figure 5.

Similar relationships existed for knots of other size orders (second largest knot in whorl, third largest knot in whorl, etc.).

There was no correlation (correlation coefficient $R = 0$) between knot volume and cardinal direction found in the material. The knot volume was thus decided by randomly giving each knot a size order, and assigning the volume according to this rank and the average knot volume in the whorl. This was made using the linear model above.

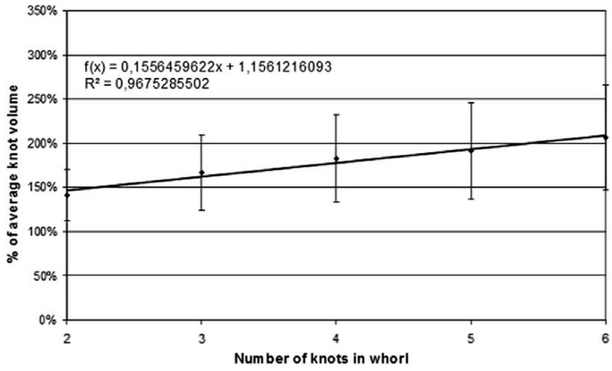

Figure 5. The largest knot's percentage of the average knot volume, plotted against number of knots in the whorl. The vertical lines show the distance of one standard deviation around the average.

Table IV. Models for reconstructing knot parameters from the knot volume (V). Note that the models for parameters *H*, *J* and dead knot percentage were not used in the final method.

Parameter	Parameter roughly equivalent to	Model	R^2
A	Knot propagation angle at pith (cross section plane)	$A = (0.071964 + 0.088116\ \text{In}(V))^2$	0.34
B	Propagation angle change with distance to pith (cross section plane)	$B = -(0.1517 + 0.03891\ \text{In}(V))^2$	0.17
E	As *A* but longitudinal	$E = (0.4966 + 0.1583\ \text{In}(V))^2$	0.06
F	As *B* but longitudinal	$F = -(0.5441 + 0.06156\ \text{In}(V))^2$	0.02
H	Knot angle	$H = -1.831 + 0.2895\ \text{In}(V)$	0.28
I	Knot length	$I = 20.12\ V^{0.1596}$	0.55
J	Dead knot length	$J = 10.07\ V^{0.1715}$	0.42
Dead knot%		$DK\% = 0.4232 \cdot e^{-2.8 \cdot 10^{-6} \cdot V}$	0.02

Parameter reconstruction

The parameters, *A*, *B*, *E*, *F* and *I*, are related to the size of the knot, that is, diameter and length. Hence, it was possible to predict the values of these parameters using the knot volume. Table IV shows the coefficient of determination (R^2) values for linear models of each of these parameters, using the knot volume as a predictor. Remember that parameters, *C*, *D*, *G* and *K*, are determined using other features than knot volume. The models tabulated are the ones among several tested, with different transformations of the data that yielded the highest R^2. Parameters *H* and *J* are also included, as well as dead knot percentage, which is expressed as $(I-J)/I$, that is, the dead knot length divided by total length.

Parameter *H* was reconstructed using a normal probability function with expected value along the regression model line, and a standard deviation equal to the root mean square error (RMSE = 0.59) 0.59) of the model compared with the SPSB data. *J* was created purely by a normal probability function, but using dead knot percentage. This method is preferred over a direct approach since the knot length limits the dead knot length, thus making the value of the latter highly dependent on the value of the former. The expected value for this normal probability function is 0.43 and standard deviation 0.11. Parameters *E* and *F*, also with low R^2, are deemed as less important since they are poorly modelled in the SPSB itself, and are thus not crucial for the sawing simulation results. Hence, the models for these can be accepted even with such a low R^2.

In this study, the parameter *G* was set to the height of the whorl in the log, and the parameter *K* was set as the parameter *K* from one of the knots in the whorl which knots were reconstructed from, and copied to all the reconstructed knots in the whorl.

Validating the method by simulation

Using the strategy described, the whole SPSB was analysed and all whorls were reconstructed. Sawing simulation using the software Saw2003 was done on logs with the original knots, obtained from a medical CT-scanner, as well as logs with the reconstructed knots. This was done on all 628 logs of the SPSB. The result showed that the resulting boards with reconstructed knots had the same grade as the boards with the original knots in 63.5% of the cases, on average over three test runs using different but equivalent random sets for the knot reconstruction. In 10.4% of the cases, the difference was more than one grade.

The grade distributions of boards for the three different test runs were very similar, despite the random elements in the model. The average numbers of boards in each grade for the reconstructed and original knots, respectively, are presented in Table V.

Figure 6 presents the value of boards produced by sawing simulation, for each log in the SPSB, for the first simulation run. The horizontal axis shows the value produced when using the original SPSB knots, and the vertical axis the value when using reconstructed knots.

A sensitivity analysis with regard to prices of the sawn timber was made. Only one sawing simulation was performed here, since the variation in overall grade distribution is very low between different runs. The grade distribution with the changed prices is shown in Table VI for original SPSB logs, as well as those with reconstructed knots. In this case, the sawing simulations produced boards of the same grade as in the original SPSB in 60.9% of the cases.

Table V. Comparison of the grades assigned to boards which have knots reconstructed by the method described, and the original SPSB knots.

		Original		
		A	B	C
Reconstructed	A	918	117	150
	B	248	584	248
	C	214	302	718
	Correct (%)	66.5	58.2	64.3

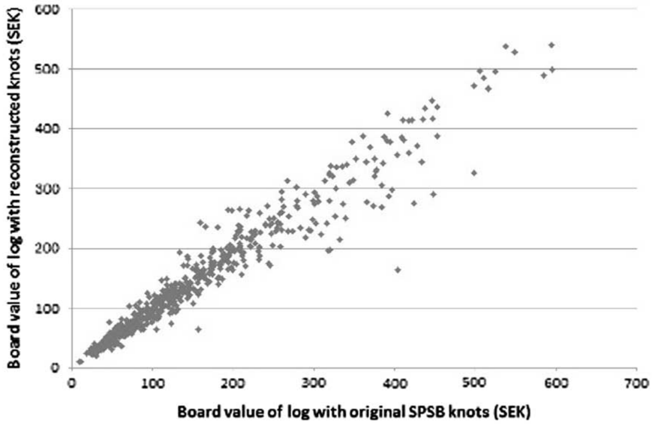

Figure 6. Simulated value of logs with reconstructed knots, plotted against the simulated value of logs with the original SPSB knots; values in Swedish Crowns (SEK).

Table VI. Comparison of grade distribution between reconstructed and original knots, when using a different pricelist than in Table V. Note that the amount of C grade boards is much smaller since these are valued much lower than in the first simulation run.

		Original		
		A	B	C
Reconstructed	A	812	193	93
	B	395	948	256
	C	127	302	371
	Correct (%)	60.9	65.7	51.5

Discussion

Reconstruction of knots requires data to work with; in this case internal knot features extracted from two-directional X-ray scanners. It also requires knowledge about how knots and whorls are structured within a log. Building this knowledge has been in focus with this study.

The results of this study are very promising, with a prediction rate (the amount of boards which were given a correct grade using the reconstructed knots) of almost 64%. This is higher than the figures presented in Grundberg et al. (1999), and indicates that the model is worthy of future attention. The values of boards are similar when comparing simulations on logs with original knots with logs with reconstructed knots, as shown in Figure 6. The difference to Grundberg et al. is mainly that the model presented here is, to a large degree, based on geometrical measurements, whereas the earlier study was feature and knowledge based. Geometrical considerations thus seem to play a major role in proper knot modelling. Since one of the key features considered when grading boards is size of the largest knot on each board side, the knot volume distribution is probably a crucial part of the model presented.

The typical whorl patterns (whorls with three or four knots) for cardinal direction are based on quite large intervals in degrees. This is a balancing issue, between covering enough whorls with the patterns, and introducing a random element in the whorl generation, which makes the reconstructed whorls differ more from the real ones. Moreover, the whorls are assigned a typical pattern in a random way. This strategy could be replaced with a more elaborate approach, and there is probably room for some fine-tuning regarding both these issues. The results of the sawing simulation are a strong indicator that the balancing has been performed quite well in this case, however. The last issue regarding cardinal direction is that all whorl patterns are defined in relation to the northern or southern direction. This is not a piece of information that is available in a practical application. However, this could be solved either by randomly assigning each log a "south" direction or by some distinguishable feature of the log. The choice of solution is open for future discussion and research.

There is also room for improvement with regard to the amount of knots per whorl. For instance, one might consider using the knot bumps on the surface of the log instead of *ΔHeight*, which is a rather weak indicator.

Many of the correlations used in the model are weak, due partly to the biological origin of the data, but also to the small amount of features available for prediction. This does not seem to be a large problem in this case though, since the overall quality of the logs in terms of knot features seem to be predicted quite well despite this. Furthermore, this study is based on data which is possible to extract from X-ray images using image analysis. In this study, the data have been extracted from the stem bank logs, but in an industrial application the data is expected to show a larger degree of noise. The consequence of this is that the model presented in this study needs to be verified and/or calibrated using real material.

Finally, the decision to build the models based on the logs in the SPSB can be considered as a bit dubious. One of the intended applications of the study is to be able to increase the size of the SPSB with more representative logs, using industrial X-ray data. If we do so by using models that are based on these trees, will they be valid for the real material? This is probably the case, since care has been taken to treat the trees in a varied fashion to achieve a population representative of the results of common practice today. The trees were, furthermore, located at a wide range of geographical locations, albeit limited to Sweden. This is, however, a matter that needs to be addressed in future work, again by testing on real X-ray data. Also, one has to bear in mind that the results presented here are only tested on Swedish data which is why a general conclusion regarding these knot characteristics is difficult to make from this study. Another issue is that the developed model recreates knots that are representative of the average tree, but it is not known what happens when a tree that differs significantly from the rest of the population is used as in-data to the model. This is shown in the correlation coefficient for some of the sub-models, which is low, not due to a lack of trend or linearity of the data, but due to a large spread around the average line. Whether this is an important issue depends on the intended application of the model.

Overall, the models predict the grade of the sawn timber to a very high degree on a larger scale with several logs, while on the single board level the error is larger. The conclusion of the study is that it is possible to use data obtainable from a two-directional industrial X-ray scanner to reconstruct realistic whorls and knots for sawlogs, to facilitate improved online sawing simulation, in sawmills with a two-directional X-ray scanner together with an optical three dimensional scanner. A secondary application is to enlarge the amount of data available for sawing simulation for research purposes. The method needs to be tested using measurements made in actual two-directional X-ray images, however.

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