

Industrial X-ray and 3D Scanning

Johan Skog





Characterization of sawlogs using industrial X-ray and 3D scanning

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Doctoral Thesis Department of Engineering Sciences and Mathematics Luleå University of Technology

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Abstract

In the Nordic countries, sawlogs are typically sorted upon arrival at the sawmill based on species and dimension. By processing batches of logs with similar size, the sawing process becomes more efficient; the need to change sawing pattern between individual logs is reduced, and the handling of sawn goods is simplified, since the number of different dimensions produced simultaneously decreases. However, since wood is a biological material with great heterogeneity, there will be a large variation in the properties also of boards sawn from logs of similar size. This means that a significant amount of the boards may be carrying unwanted combinations of dimension and grade, so called off-grade products. The problem with off-grade products may be addressed before sawing by the selection of suitable sawing patterns for each log, *i.e.*, using the right logs for the right products. This requires knowledge of the internal quality of the log before sawing. Some information can be obtained from the outer shape measured by an optical three-dimensional (3D) scanner and more detailed information can be obtained using an X-ray log scanner.

Today, the use of X-ray log scanners is becoming increasingly common, and most sawmills installing an X-ray scanner already have a 3D scanner present. This raises the question of possible benefits from combining the X-ray and 3D scanning techniques. In this thesis, a method is presented whereby the outer shape of the log measured by a 3D scanner is utilized to estimate the X-ray path lengths through the wood. This converts the X-ray images into green density images of the log, which may in turn be used to calculate quality variables such as heartwood diameter, dry density, moisture content and presence of top rupture. The methods have been tested on Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) sawlogs using X-ray scanners with one or two measurement directions.

The developed methods show a great improvement in precision compared to calculations based on uncompensated X-ray images, and most of the algorithms presented in the thesis have now been implemented in industrial scanner software and are ready for use at the sawmills. This will give the sawmill industry new possibilities to control the production of special products where heartwood diameter and density are important and will lead to less waste and improved profitability for the sawmills.

The thesis also describes a method where X-ray scanning is utilized to automatically perform parts of the log grading for payment. Because the log grading for payment is a bottleneck in many sawmills, this method can lead to great improvements in sawmill productivity. An authorization of this method for semiautomatic log grading for payment is expected to further increase the industry's interest in X-ray scanning.

Keywords: 3D scanning, Density, Grading, Heartwood, Log sorting, Moisture content, Norway spruce, Path-length compensation, Resin pockets, Sawlogs, Scots pine, Top rupture, X-ray scanning

Sammanfattning

I Norden sorteras sågtimmer vanligtvis vid ankomst till sågverket, baserat på träslag och dimension. Genom att i följd såga ett stort antal stockar av liknande storlek kan sågningen effektiviseras eftersom behovet att byta postning mellan varje stock minskar och färre dimensioner av sågad vara behöver hanteras samtidigt. Eftersom trä är ett biologiskt material med stor olikformighet kommer dock även bräder sågade från stockar av liknande storlek att uppvisa stor spridning i egenskaper. Detta innebär att en stor andel av de bräder som sågas kommer bära oönskade kombinationer av dimension och kvalitet. Problemet kan åtgärdas före sågning genom att välja rätt sågmönster för varje stock, det vill säga genom att styra varje stock mot den bäst lämpade slutprodukten. Detta kräver kännedom om stockens inre egenskaper före sågning. Viss sådan kvalitetsinformation kan erhållas från den yttre formen, mätt med en optisk 3Dmätram och mer detaljerad information kan fås med hjälp av en röntgenmätram.

Idag har användandet av röntgenmätramar blivit allt vanligare, och de flesta sågverk som väljer att investera i ett röntgensystem har redan en 3D-mätram i sin timmersortering. Detta väcker frågan om vilka fördelar som kan nås genom att kombinera röntgen- och 3D-mätteknikerna. I den här avhandlingen presenteras en metod där stockens yttre form används för att uppskatta röntgenstrålningens gångväg genom stocken. Genom att kompensera för gångvägen är det möjligt att beräkna en rådensitetsbild för stocken, vilken i sin tur kan användas för att beräkna viktiga kvalitetsvariabler såsom kärnvedsdiameter, torrdensitet, fuktkvot och förekomst av toppbrott. Metoden har testats på sågtimmer av tall (*Pinus sylvestris* L.) och gran (*Picea abies* (L.) Karst.) och röntgenmätramar med en och två mätriktningar har använts.

De nyutvecklade beräkningsmetoderna uppvisar mycket högre precision än beräkningar baserade på okompenserade röntgenbilder. Flertalet av de algoritmer som presenteras i avhandlingen har nu implementerats i industriell röntgenprogramvara och är redo för användning på sågverken. Detta kommer att ge sågverksindustrin nya möjligheter att styra tillverkningen av specialprodukter med krav på exempelvis kärnvedsdiameter och densitet och kommer att leda till mindre spill och förbättrad lönsamhet för sågverken.

Avhandlingen beskriver också en metod där röntgenskanning nyttjas för att automatisera delar av den prisgrundande vederlagsmätningen av sågtimmer. Eftersom vederlagsmätningen är en flaskhals vid många sågverk kan detta leda till en kraftig förbättring av produktiviteten. Ett metodgodkännande för semiautomatisk vederlagsmätning förväntas därför ytterligare höja industrins intresse för röntgenmätteknik.

Nyckelord: 3D-mätning, densitet, fuktkvot, gran, gångvägskompensation, kådlåpor, kärnved, röntgenmätning, timmersortering, sågtimmer, tall, toppbrott, vederlags-mätning.

Preface

The work presented in this thesis has been carried out at the wood technology department of SP Technical Research Institute of Sweden, SP Trä in Skellefteå, in close collaboration with Luleå University of Technology, Wood Technology, Skellefteå Campus. All help and support from my tutors, professors Johan Oja and Anders Grönlund, is gratefully acknowledged. I also thank all of my friends at SP Trä and LTU for creating a both joyful and creative working environment. Special thanks to Linus Hägg for helping me with the final touch on the C++ version of the algorithms.

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Finally, my most special thanks go to my wife Josefin for her love and support, to my daughter Lilly for showing daddy what's truly important in life and to our God and Father, *for from him and through him and for him are all things. To him be the glory forever!* (Romans 11:36).

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Johan Skog

List of papers

- I. Skog, J. & Oja, J. (2007). Improved log sorting combining X-ray and 3D scanning A preliminary study. In: Grzeskiewicz, M. (Ed.), Proceedings of the Conference on Quality Control for Wood and Wood Products (pp. 133–140), October 15–17, 2007, Warsaw, Poland. Faculty of Wood Technology, Warsaw University of Life Sciences.
- II. Skog, J. & Oja, J. (2009). Heartwood diameter measurements in *Pinus sylvestris* sawlogs combining X-ray and three-dimensional scanning. *Scandinavian Journal of Forest Research*, 24(2), 182–188.
- III. Skog, J. & Oja, J. (2009). Combining X-ray and three-dimensional scanning of sawlogs – Comparison between one and two X-ray directions. In: Zinterhof, P. et al. (Eds.), Proceedings of the 6th International Symposium on Image and Signal Processing and Analysis (ISPA 2009) (pp. 343–348), September 16–18, 2009, Salzburg, Austria.
- IV. Skog, J. & Oja, J. (2010). Density measurements in *Pinus sylvestris* sawlogs combining X-ray and three-dimensional scanning. *Scandinavian Journal* of Forest Research, 25(5), 470–481.
- V. Skog, J. & Hägg, L. (2013). Measuring heartwood diameter and density in *Picea abies* using X-ray and three-dimensional scanning. Manuscript submitted to journal.
- VI. Skog, J., Vikberg, T. & Oja, J. (2010). Sapwood moisture-content measurements in *Pinus sylvestris* sawlogs combining X-ray and threedimensional scanning. *Wood Material Science and Engineering*, 5(2), 91– 96.
- VII. Skog, J., Lundgren, N. & Oja, J. (2011). Detecting top rupture in *Pinus sylvestris* sawlogs. 20th International Wood Machining Seminar: Recent Advances in the Field of Wood Machining (pp. 132–140), June 7–10, 2011, Skellefteå, Sweden.
- VIII. Skog, J. & Oja, J. (2009). Automatic detection of resin pockets in Norway spruce by X-ray scanning. Proceedings of the 16th International Symposium on Nondestructive Testing and Evaluation of Wood (pp. 39–44), October 12–14, 2009, Beijing, China.
- IX. Oja, J., Skog, J., Edlund, J. & Björklund L. (2010). Deciding log grade for payment based on X-ray scanning of logs. In: Ridley-Ellis, D. J. & Moore, J. R. (Eds.), *The Future of Quality Control for Wood & Wood Products, Proceedings of the final conference of COST Action E53* (pp. 173– 179), May 4–7, 2010, Edinburgh, UK.

Contribution to the papers:

In papers I–VI and VIII, Skog had the main responsibility for data collection, algorithm development and article writing, with valuable guidance along the way provided by the co-authors.

Paper VII, Lundgren had main responsibility for data collection and development of the top-rupture indicators and helped writing the article. Skog had main responsibility for writing the article, did the heartwood-shape calculations and contributed with ideas to the top-rupture indicators.

In paper IX, Oja had main responsibility for developing the log-grade models and article writing, and Skog contributed with ideas and helped with writing of the article.

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Chapter 1: Introduction

1.1 Characterization of wood

Wood is a biological material with great diversity, therefore a need of characterizing various wood properties exists throughout the whole process, from forest to final products. This chapter summarizes some examples that are important from a Nordic perspective. Focus lies on the two dominating softwood species Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.).

1.1.1 Board grading

The main product from a sawmill is sawn boards of various dimensions and grades. Because of the heterogeneity of wood as a material, there will be a great variation between individual boards, both visually and in terms of mechanical properties. Therefore, it is necessary to sort the sawn wood according to its properties in order to find an appropriate use for each piece. This characterization process is known as board grading and is done either by visual inspection by skilled lumber graders or by various kinds of automatic measurement systems. The grading follows a set of rules adjusted to the kind of application being evaluated. The most common criteria for board grading are visual appearance and strength. Appearance grading is typically based on the principles of the Nordic Timber system (Anon., 1994), with the limits for each grade adjusted by the individual sawmill with respect to raw material and customer demands. Strength grading follow either rules for visual strength grading (EN 14081-1 (CEN, 2011); INSTA 142 (SIS, 2009)) or machine strength grading (EN 14081-1 (CEN, 2011); EN 14081-2 (CEN, 2010); EN 14081-3 (CEN, 2012)).

The final grade of the wood often has a large impact on the price being paid, therefore it is very important for the profitability to know what factors affect the grade and to control the process so that the highest possible share of high-grade products is obtained. The final grade obtained for a piece of wood depends on many factors. First of all, there is a great variation in the properties of the raw material, *i.e.*, the stems or logs. Secondly, how the initial log quality is transformed into sawn products quality greatly depends on the processing, including operations such as bucking, sawing, drying and handling.

1.1.2 Production control by board scanning

Both the ability to make good process decisions and the ability to execute the decisions properly will have a great impact on the final result. This means that characterization of wood properties has a wider use than only determining the grade of the sawn products. Measurements on the sawn wood can help control the process so that improved results are obtained. For instance, the drying schedule could be adjusted to the density, heartwood content and moisture content of the boards. Another important application for sawn wood measurements is providing feedback to the sawing. If problems like dimension errors or unexpected wane distributions are quickly discovered, the saw setup can be adjusted in order to obtain better results for the rest of the sawing batch.

Determining properties of sawn boards is of value for process control. At this stage of the process, however, the lumber dimensions have already been determined. This means that a significant amount of the boards may be carrying unwanted combinations of dimension and grade, so called off-grade products. The problem with off-grade products may be addressed before sawing by the selection of suitable sawing patterns for each log, *i.e.*, using the right logs and sawing patterns for the right products. This kind of optimization requires knowledge of the internal properties of each log before sawing.

1.1.3 Production optimization by tree modelling

Conditions such as temperature, access to sunlight, water and nutrients together with silvicultural treatment have a great influence on the growth of the tree, and consequently also on the properties of the wood. Therefore, forest inventory data can be connected to a large number of wood properties. For Scots pine and Norway spruce, tree models typically based on site, stand and tree variables such as age and diameter at breast height have been developed describing the mean values or expected variation along the tree of numerous properties, *e.g.*, heartwood diameter (Sellin, 1993; Wilhelmsson *et al.*, 2002; Gjerdrum, 2003), knot structure (Moberg, 2006), knot diameter (Moberg, 2000; Vestøl & Høibø, 2001), basic density (Molteberg & Høibø, 2007) and strength grade of sawn wood (Øvrum *et al.*, 2011). This means that selection of suitable stands or stems for a given end product can be made already in the forest, based on inventory data and tree models. In the Nordic countries, bucking is almost exclusively done in the forest, meaning that models of tree quality can be a useful tool for the bucking optimization (Uusitalo & Isotalo; 2005).

In order to transfer as detailed information on the log properties as possible from the forest to the sawmill, logs need to be traced on an individual basis rather than on batch level. Such tracing systems have been demonstrated, *e.g.*, systems based on radio-frequency identification devices (RFID) (Häkli *et al.*, 2010), but have not come into wide use because of the additional costs and logistical challenges entailed. Still, every tree is a unique individual, and every batch of logs will contain a significant variation from expected log properties, also in the case of individual tracing. Thus, forest inventory data are helpful in choosing appropriate felling areas, but do not contain information accurate enough to guarantee, for example, the production of heartwood-rich products (Björklund, 1999).

1.1.4 Production optimization by sawlog scanning

In order to achieve high production rates of desired products while maintaining an efficient use of raw materials, detailed measurements of the quality of each log is required. In the Nordic countries, logs are typically sorted based on species and top diameter upon arrival at the sawmill. This means that the log sorting station is a suitable place also for presorting of logs based on other parameters, such as predicted quality of sawn goods.

The purpose of the log sorting is to maximize the volume and/or value of the sawn timber, objectives that require the sorting process to take into consideration both special market demands and the actual sawmill production facilities.

Presorting of sawlogs according to dimension using, for example, an optical threedimensional (3D) scanner, improves productivity of the sawmill by making the sawing process more efficient. By batch-processing logs of similar size, the need to change sawing pattern between individual logs is reduced, and the handling of sawn goods is simplified, since the number of different dimensions produced simultaneously decreases.

Quality sorting of sawlogs requires a measurement system that allows the prediction of sawn goods' quality prior to actual sawing. Such predictions are typically based on outer shape measurements from 3D scanners (section 1.2.1), photographic inspection of end surfaces (section 1.2.2) or measurements of internal properties using X-ray technology (section 1.2.5).

Recently, an industrial computed tomography (CT) scanner has been introduced on the market that is capable of giving a full reconstruction of the inner properties of the log (Giudiceandrea *et al.*, 2012). By applying simulated sawing, it is possible to find the best sawing position for each log, thereby improving the value of the sawn boards (Berglund *et al.*, 2013).

1.1.5 Log grading for payment

At Swedish sawmills, logs are not only measured and graded for production optimization, but also in order to collect information for payment. The pricing of logs today is based on a combination of automatic volume measurement and manual grading. For most loads of logs, each log is individually graded according to the rules defined by the Swedish Timber Measurement Council (Anon., 2007).

The grader has to manually make decisions about species, amount and thickness of bark and log grade. The large number of decisions that have to be made limits the speed of log sorting. At many sawmills, this fact makes the log sorting, *i.e.*, the manual grading, a bottleneck in the production chain. Several authors have described methods that will aid the log grader by doing parts of the grading automatically. These methods are based on log-end images (Oja *et al.*, 1999; Norell & Borgefors, 2008) and outer shape measurements of the log (Oja *et al.*, 1999; Edlund, 2004). So far, none of these methods have been implemented for automatic grading for payment. The reason is, of course, that grading for payment is a very critical process. Before implementing a new method, there must be no doubt that a sawmill using the new, automatic grading will pay the same price for the logs as if manual grading was used. This makes the robustness of the method important, and therefore, X-ray scanning becomes interesting as it is little affected by external factors such as seasonal variation in bark or the existence of snow on the logs. Thus, it is of interest to investigate how information from industrial X-ray scanning can be used for automatic grading of logs for payment.

1.2 Methods of characterizing sawlogs

1.2.1 Optical three-dimensional scanning

The 3D scanners used in sawmills are laser triangulation scanners. In a triangulation scanner, a laser point or a laser line is projected onto the surface of an object and observed by a camera. The camera, the laser emitter and the laser point on the object form a right-angled triangle (see Figure 1). The angle from the camera to the object can be determined from the position of the laser light in the camera's field of view, and so it is possible to calculate the third corner of the triangle, *i.e.*, the position where the laser light hits the object. By this principle, the scanner can reconstruct the shape of the object as the laser light is swept over it.

A 3D log scanner is equipped with three or four triangulation units positioned evenly around the log, allowing the scanner to see all sides of the log (Figure 2). In early scanners, each triangulation unit consisted of a camera and a number of point lasers (Rickford, 1989; Dashner, 1993), but in newer scanners, the point lasers have been replaced by line lasers in order to obtain higher scanning resolution. The cross-sectional shape of the log is automatically calculated by combining the information from all the triangulation units, and the complete outer shape of the log is then collected one cross-section at the time during lengthwise transport of the log through the scanner. Even though a higher resolution is technically possible, the cross-sectional shape is typically reported as the radius at a number of fixed angles. In the appended papers, both point-laser- and line-laser-based scanners have been used. They give the radius at 72 angles per cross-section with a cross-sectional distance of 15–20 mm.

When logs are scanned for sorting purposes, it is the shape under bark that is relevant. If scanning is done before debarking of the logs, this presents a problem, because both the amount of bark and bark thickness vary significantly between different logs. However, some 3D scanners are able to tell whether the measurements are done on bark or on clearwood. The measurement principle is based on the tracheid effect, a phenomenon causing laser light to spread along the fibre direction in fibrous materials. This means that the light will spread more on a wooden surface than on bark, and therefore it is possible for the scanner to differentiate between wood and bark by checking the width of the laser line (Johansson & Ringström, 1993) (see Figure 3). Knowing which measurements are done on bark and which on wood, it is possible to estimate the bark thickness and thus to estimate the shape of the log under the bark.

From the outer shape measured by a 3D scanner, secondary variables such as taper and bumpiness can be calculated, and it has been shown that these variables may be used to estimate log quality (Grace, 1994; Jäppinen & Nylinder, 1997; Oja *et al.*, 1999). Such predictions, using partial least squares (PLS) modelling on 3D data in the quality sorting software Kvalitet On-Line (Anon., 2013g), has proven successful and become widely spread in Sweden. However, since wood is a biological material, there can still be a large variation between the properties of wood sawn from two logs with similar outer shape. These variations cannot be explained by means of 3D scanning only; instead, some technique for investigating the interior of the log is required.



Figure 1: Principle for laser triangulation. The distance between the laser and the object (d_1, d_2) can be calculated from the position of the laser point within the camera's field of view (x_1, x_2) .



Figure 2: Schematic of a 3D log scanner with three triangulation units, positioned evenly around the log to allow the scanner to see all sides of the log. A laser line is projected around the log and the outer shape is determined one cross-section at a time during lengthwise transportation of the log through the scanner.



Figure 3: Log in a 3D scanner photographed with flash (left) and without flash (right). The tracheid effect causes the laser light to spread along the fibre direction of the clearwood (Flodin, 2007).

1.2.2 Log end inspection

Besides looking at the lateral surface of the log, the easiest way to get some information on its interior is to inspect the log ends. For instance, the rules defined by the Swedish Timber Measurement Council state that a log's grade for payment "is based on its properties on the whole mantle surface¹ and on both end surfaces" (Anon., 2007). The manual graders look at the end surfaces to judge the width of growth rings and the presence of forest rot and blue stain.

Many authors have described methods for detecting features in photographic images of log ends. Often, these images are collected under laboratory conditions, but there are also examples wherein the log-end images are captured under industrial conditions, typically by handheld or stationary camera equipment installed in a log sorting station (Gjerdrum & Høibø, 2004; Enarvi, 2006; Norell & Borgefors, 2008). There are also applications where log-end images are captured at the time of felling, *e.g.*, Viitanen and Mattila (1999) have patented a method where optical fibres are mounted in the flange of the harvester's saw bar, turning the chain saw into a line camera. Results are promising, but at the time of writing this thesis, the saw bar camera had not yet been turned into an industrial application (Jouko Viitanen, personal communication, March 26, 2013). An alternative approach, that might be easier to implement, is that of Marjanen *et al.* (2008), wherein a regular camera is mounted on the harvester head.

Enarvi (2006) describes an automatic system that helps the manual grader by identifying all defect-free logs, but leaves the grading of defective logs to the manual grader. Many interesting features can, however, be detected by automatic image processing of logend images. For example, pine heartwood may be detected if the heartwood is elicited either using infrared light (Arnerup, 2002; Gjerdrum & Høibø, 2004 (Figure 4)), ultraviolet light (David *et al.*, 1993) or staining techniques (David *et al.*, 1993). Norell and Borgefors (2008) describe a method for detection of pith position in log-end images (Figure 5). Methods for detection of annual-ring width have been described by several authors, but most examples require carefully prepared surfaces. Österberg (2009), Marjanen *et al.* (2008) and Norell (2011) have all developed methods intended to find annual rings under industrial conditions.

The difficulty with all methods based on log-end inspection is that log ends may be of very poor quality, for example roughly sawn or covered by dirt or snow. Either the log end must be prepared by clear cutting, which causes expensive loss of material, or the algorithms must be made to cope with poor quality images. As an example, the algorithms by Norell (2011) are capable of handling partial coverage by snow and dirt. Sometimes, however, log ends will be so dirty that nothing can be seen, no matter how robust the algorithms are.

¹Author's comment: "mantle surface" refers to the lateral surface of the log.



Figure 4: Infrared image used for detection of heartwood, cool areas are darker and warm areas brighter (Gjerdrum & Høibø, 2004).



Figure 5: Detection of pith position in a photograph of a rough log end surface. The estimated pith position is seen as a white + sign and the correct position as a black + sign. (Norell & Borgefors, 2008).

1.2.3 X-ray scanning

There are several techniques available for nondestructive investigation of the internal properties in wood, *e.g.*, gamma radiation, X-rays, microwaves, ultrasound, nuclear magnetic resonance (NMR), vibrations and stress waves. In an overview of possible techniques, it was concluded that X-rays and gamma rays were best suited for scanning of logs (Grundberg *et al.*, 1990; Grundberg, 1999). Both these radiation types consist of high-energy photons, able to penetrate an object and give an image of its interior. Gamma rays are continuously emitted by radioactive isotopes, whereas X-rays can be obtained from an electronic source that can be switched on and off on demand. The half-life of the isotopes also causes the intensity of the radiation to decline over time, requiring frequent calibration of the equipment and replacement of the isotopes on a regular basis. Thus, it has been concluded that for both practical and safety reasons, scanning by an electronic X-ray source is preferable.

An X-ray scanner is a radiographic imaging system. The working principle is the same for all radiographic equipment: a beam of high-energy photons is generated by an Xray tube and sent through the object being imaged. The radiation transmitted through the object is then collected using some kind of detector, *e.g.*, a photographic film or a semiconductor diode array or matrix, resulting in an X-ray image, also known as a radiograph, showing a projection of the object.

As the X-ray photons pass through a material, interaction with the object causes the intensity of the radiation to decrease according to the exponential attenuation law. For a beam of monoenergetic photons of incident intensity I_0 , passing through a homogeneous material of thickness *t*, the transmitted intensity *I* will be:

$$I = I_0 e^{-\mu} \tag{1}$$

The amount of radiation being absorbed by a material is described by the linear X-ray attenuation coefficient μ and depends on material and photon energy. The attenuation coefficient may be written as the product of the density ρ and the mass attenuation coefficient μ_m :

$$\mu(E) = \rho \cdot \mu_m(E) \tag{2}$$

The mass attenuation coefficient μ_m is a material property and varies with the photon energy *E*. Values of μ_m for the chemical elements and many human tissues can be found in physical tables (Hubbell & Seltzer, 1996). Values of μ_m for other compound materials can be calculated as described by Tsai and Cho (1976), and Lindgren (1991) demonstrated how this calculation model can be applied to wood.

For an inhomogeneous material such as wood, μ will vary along the path of the X-rays, meaning that equation (1) has to be integrated along the ray path. Lindgren (1991) showed that μ_m is approximately constant for dry wood and that the μ_m of water is about 5% greater than the μ_m of dry wood. This means that the μ_m of green wood will vary slightly with moisture content. However, since almost all variation in μ is explained by density variation, the integration of equation (1) can be simplified by treating μ_m as a constant. This implies that, for monoenergetic X-rays, the attenuation will be given by:

$$I = I_0 \cdot e^{-\int \mu(t)dt} \approx I_0 \cdot e^{-\mu_m \int \rho(t)dt} = I_0 e^{-\mu_m \rho_{av} t} = I_0 e^{-\mu_m x}$$
(3)

where the mass thickness x is defined as the product of the average density ρ_{av} along the ray path and the path length t through the wood:

$$x \equiv \rho_{av} t \tag{4}$$

Typically, the X-ray source is not monoenergetic. Thus, in order to find the total transmitted intensity, equation (3) has to be integrated over the whole photon energy spectrum of the X-ray source:

$$I_{tot} = \int_{E_{min}}^{E_{max}} I_0(E) \cdot e^{-\mu_m(E)x} dE$$
(5)

where E_{\min} and E_{\max} define the photon energy range of the X-ray source. Figure 6 shows an example spectrum from a 160 kV tungsten X-ray tube, corresponding to a maximum photon energy of $E_{\max} = 160$ keV.

The intensity of the transmitted radiation is registered by a detector, and the resulting radiographic image gives information about the attenuation of X-rays that have travelled through the object along different paths. This reveals parts of the object with contrasting attenuation, caused either by deviations in the path length (*t*) or by deviations in the material properties mass attenuation (μ_m) or density (ρ).

Knowing the intensity spectrum of the X-ray scanner (Figure 6), it is possible to convert the observed intensity I_{tot} to a measure of the mass thickness x. By discretizing equation (5), the intensity I_{tot} becomes a sum of exponential functions of x, the mass thickness:

$$I_{tot} = \int_{E_{\min}}^{E_{\max}} I_0(E) \cdot e^{-\mu_m(E)x} dE \approx \sum_{E=E_{\min}}^{E=E_{\max}} I_{0,E} \cdot e^{-\mu_m(E)x}$$
(6)

In order to calculate the mass thickness from a radiograph, equation (6) must be solved for x. This is done by approximating the sum of exponentials by a single exponential function of the effective initial intensity $I_{0,eff}$ and mass attenuation $\mu_{m,eff}$:

$$I_{tot}(x) \approx \sum_{E=E_{\min}}^{E=E_{\max}} I_{0,E} \cdot e^{-\mu_m(E)x} \approx I_{0,eff} \cdot e^{-\mu_{m,eff}x}$$
(7)

Figure 7 shows the intensity calculated as a sum of exponentials (equation 6) and the corresponding approximate single exponential function (equation 7), the effect of this approximation is negligible.

From equation (7), the mass thickness x of the object can be expressed as a function of the measured intensity I_{tot} :

$$x \approx \left(\ln I_{0,eff} - \ln I_{tot} \right) / \mu_{m,eff} = c_0 + c_1 \ln I_{tot}$$
(8)

where c_0 and c_1 are constants. It should be noted that any intensity scale can be used in equation (8), as long as 0 on the scale represents no intensity. Simulations performed for the particular scanner used in this study show that $c_0 = 52.9$ and $c_1 = -5.74$ and that the error in x introduced by the approximation in equation (7) does not exceed 1%.



Figure 6: X-ray intensity as a function of photon energy for a 160 kV tungsten X-ray tube. The radiation consists of bremsstrahlung (the base curve) and K-characteristic radiation (the thin peaks).



Figure 7: Remaining X-ray intensity as a function of mass thickness for green wood of moisture content 100% (solid line) and approximation of this function to a single exponential function $I = I_{0.eff} \cdot e^{-\mu_{m.eff}x}$ (dotted line).

1.2.4 CT scanning

X-ray scanning by computed tomography (CT) is a technique in which X-ray projections of the object are gathered from a large number of directions. Using a back-projection algorithm processed by a computer, it is possible to reconstruct an image of the X-ray attenuation μ throughout the object. Images from a CT scanner are known as tomograms or CT images and provide very good knowledge of the interior of the object (Figure 8). In medical imaging, CT images are used to differentiate between tissues with different density or mass attenuation. For wood, mass attenuation is approximately constant, meaning that CT data can be used to find the density of the object. Lindgren (1991) showed that density of wood can be measured with a 95% confidence interval of ± 4 kgm⁻³ for dry wood and ± 13 kgm⁻³ for green wood using a CT scanner. The major contributor to the measurement error observed for green wood (at least ± 6 kgm⁻³) was the uncertainty in mass attenuation of green wood caused by the difference in μ_m between dry wood and water. When measuring the same set of wood pieces using balance and vernier calliper, Lindgren (1991) observed an accuracy of about 2.5 kgm⁻³.



Figure 8: Cross-sectional CT images of: a) a Scots pine log, b) a whorl of sound knots in a Scots pine log and c) a Norway spruce log. Dark grey pixels represent low density heartwood and bright grey pixels represent high density sapwood or knots. In the spruce, intermediate wood causes a less distinct transition between heartwood and sapwood.

The high-resolution information on the density distribution in the log obtainable by CT scanning has proven very valuable for research purposes. Examples are the Swedish pine stem bank (Grundberg *et al.*, 1995) and the European spruce stem bank (Anon., 2000), large collections of CT-scanned Scots pine and Norway spruce stems that have been used as material in a large number of scientific studies.

Even though the speed of medical CT scanners has increased markedly over the last decades, these scanners are still much too slow for most industrial applications. Furthermore, medical CT scanners are not built to withstand the rough environment of sawmills. Instead, Rinnhofer *et al.* (2003) evaluated the use of airport security CT scanners in the sawmill industry. It was found such a CT scanner would help to optimize breakdown and improve the value of the sawn wood, but the scanning speed of the evaluated system was only 1.5 m/min, which is about 100 times too slow for use in high-speed sawmills. In 2012, however, the first high-speed CT scanner for the

sawmill industry was released on the market (Giudiceandrea *et al.*, 2012), using a fast spiral cone-beam reconstruction algorithm developed by Katsevich (2004). By CT-scanning the logs in the saw line and optimizing the sawing position, there is a potential for increasing the value of the sawn boards by around 10% (Johansson & Liljeblad, 1988; Berglund *et al.*, 2013).

1.2.5 Industrial X-ray scanning

Except for the CT scanner by Giudiceandrea *et al.* (2012), all industrial X-ray scanners use a limited number (typically 1–4) of fixed measurement directions (*e.g.* Aune, 1995; Pietikäinen, 1996; Grundberg & Grönlund, 1997). The most common solution on the market is two-directional X-ray log scanners producing two perpendicular radiographs as the log is fed through the scanner (Figures 9 & 10). These X-ray projections are collected one cross-section at a time using a detector array that measures the intensity of the X-ray radiation arriving at each pixel.

The X-ray projections of the log contain data describing the internal attenuation distribution of the log. From these data, it is possible to distinguish internal features of the log, such as heartwood border, knots and other geometrical features and anomalies. Variables calculated from the X-ray log scanner data have been related to a number of sawlog properties, *e.g.*, species (Grundberg & Grönlund, 1996), knot structure (Pietikäinen, 1996; Grundberg & Grönlund, 1998), plank grade (Grundberg & Grönlund, 1997; Öhman, 1999), heartwood content (Skatter, 1998; Oja *et al.*, 2001), density (Oja *et al.*, 2001), diameter under bark (Oja *et al.* 1998*a*; Skatter 1998), strength (Oja *et al.*, 2005), stiffness (Oja *et al.*, 2001), spiral grain (Sepúlveda *et al.*, 2003) and annual-ring width (Grundberg & Grönlund, 1998; Wang, 1998; Burian, 2006). Measuring the size and position of individual knots requires at least six directions (Sikanen, 1989; Grundberg, 1994). However, simulations have shown that the number of high quality boards can be increased if information about knot-whorl asymmetries obtained from a two-directional X-ray log scanner is used for finding an improved sawing position (Oja *et al.*, 1998*b*).



Figure 9: Schematic of the X-ray log scanner described by Grundberg and Grönlund (1997).



Figure 10: Two perpendicular X-ray radiographs from an industrial X-ray log scanner. Dark pixels represent low attenuation and bright pixels represent high attenuation. The metal carriers, seen as white areas in the images above, are filtered away before any further image processing is done.

1.2.6 Combining X-ray and three-dimensional scanning

Most sawmills investing in an X-ray log scanner already have an optical 3D scanner installed in the log sorting. Therefore, an important research question is how X-ray and 3D scanning techniques can be combined in order to further improve the precision of log scanning.

Oja *et al.* (2004) compared the grading performances of the X-ray and 3D log scanning techniques and found that both methods could be used for quality sorting of sawlogs. For 3D scanning, 57% of the centre boards received the correct grade, and for X-ray scanning this figure was 62%. It was also found that grading was further improved by the combination of variables from both methods in a partial least squares (PLS) model, to 64% correct grade when 3D scanning was combined with one X-ray direction and 65% correct grade when 3D scanning was combined with two X-ray directions. Because some logs yield centre boards of different grade, the highest possible result in this study was 81% centre boards of correct grade with ideal log grading.

In the study by Oja *et al.* (2004), data from the X-ray and 3D scanners were analysed separately and the calculated variables from each scanner type were then combined in a common PLS model. Because the combination of X-ray and 3D scanning seemed promising, it was concluded that future studies should focus on the development of methods that better utilize the potential of combining data from the two scanner types.

From in the early stages of the development of the X-ray log scanning technique, it has been shown that path-length compensation can be used to improve image contrast (Grundberg *et al.*, 1990). The principle behind the path-length compensation is that the measured X-ray intensity is related both to the path length travelled by the X-rays through the log and to the average density along the path (see equations (4) and (8)). This means that, by compensating the X-ray radiographs for the varying path lengths, contrast between regions of different density can be improved. The path lengths can be calculated from an estimated circular or elliptical cross-sectional shape of the log, but the best compensation is obtained when using the true outer shape. In practice, the best measurement of the outer shape available is the log shape data from a 3D scanner and, consequently, by using this outer shape description for the path-length compensation the best final result is expected.

Chapter 2: Project description

2.1 Hypothesis

The hypotheses of this project were:

- 1) Precision in log sorting can be improved by combining X-ray and 3D scanning.
- 2) A good path-length compensation can be obtained by combining data from X-ray and 3D log scanners.
- 3) Through path-length compensation, it should be possible to calculate both the green density of the log and secondary variables such as heartwood content, dry density, sapwood moisture content and presence of top rupture with improved precision.
- 4) Through path-length compensation using 3D data, it should be possible to obtain good precision from a one-directional X-ray log scanner.

2.2 Aim

The aim of this project was to develop new methods based on X-ray and/or 3D scanning for measurement of important quality variables in sawlogs. In particular, algorithms combining data from X-ray and 3D scanners using path-length compensation should be developed, and the potential of using this method to create a cost-efficient system based on a one-directional X-ray scanner should be evaluated.

2.3 Objectives

The objectives of this project were:

- 1) Develop a method for path-length compensation of X-ray data using the outer shape from a 3D scanner (papers I–III).
- 2) Compare the precision of 1- and 2-directional X-ray scanners when applying path-length compensation using the outer shape from a 3D scanner (paper III).
- 3) Compare path-length compensation based on the outer shape acquired from 3D scanning and the outer shape acquired from X-ray scanning (paper V).

- 4) Use path-length compensation for the calculation of:
 - a) heartwood diameter (papers II, V)
 - b) dry heartwood density (papers IV-V)
 - c) sapwood moisture content (paper VI)
 - d) top rupture (paper VII)
- 5) Evaluate whether resin pockets can be detected in images from high-resolution X-ray log scanners (paper VIII).
- 6) Develop a method capable of determining the log grade for payment based on X-ray log scanning (paper IX).

2.4 Limitations

The algorithms presented in this thesis have only been evaluated on Scots pine and Norway spruce, predominately of Swedish origin. The algorithms have been developed using green logs only, meaning that partial drying of logs may affect the calculation results. For completely dry logs, the algorithms cannot be expected to work as they rely on a difference in moisture content between heartwood and sapwood.

The spruce algorithms in paper V have only been tested for a small number of logs from a limited geographical region, meaning that a larger evaluation is needed in order to draw general conclusions.

Chapter 3: Materials

Within this project, two different kinds of data have been used as input. In papers I, II, V, VII and IX, actual data from industrial X-ray and 3D log scanners have been used. In papers III–IV and VI–VIII, X-ray and 3D scanner data have been simulated from the CT-scanned logs of the Swedish pine stem bank (Grundberg *et al.*, 1995).

3.1 Industrial data

Industrial X-ray and 3D scanner data have been collected at several Swedish sawmills. Figure 11 shows a typical scanner setup, with the X-ray scanner and the 3D scanner installed approximately one meter apart in the log-sorting station of the sawmill.

The X-ray data were collected using either one-directional (papers I, II) or twodirectional (papers V, VII, IX) RemaLog XRay log scanners (Anon., 2013*e*). The onedirectional scanner measured the attenuation of X-rays through the log every 13 mm at a resolution of 576 pixels per scan, each pixel corresponding approximately to 0.8 mm of log diameter. The two-directional scanners were of higher resolution, 1152 pixels per scan, corresponding to approximately 0.4 mm of log diameter per pixel.

The 3D data were collected using optical 3D scanners of the brands MPM Engineering (Anon., 2013*d*) (papers I, II) and RemaLog Bark (Anon., 2013*e*) (papers V, VII, IX). Both scanner types measure the shape of the log with a cross-sectional distance between 15–20 mm and describe the shape by reporting the radius at 72 angles per cross-section.

It should be noted that when using the MPM 3D scanner, measurement was done after debarking. At the other sawmills, measurement was done on bark using a 3D scanner capable of subtracting the bark thickness using the tracheid effect (section 1.2.1).

For a total of 48 Norway spruce logs (paper V) and 32 Scots pine logs, a 30-cm-long piece was cut from the top end of each log after scanning with the X-ray and 3D scanners. The log pieces were brought to the tomography lab at Luleå University of Technology in Skellefteå where they were scanned using a Siemens Emotion Duo medical CT scanner (Anon., 2013*f*) in green and oven-dry condition. The CT images were used for reference measurements of density and heartwood diameter.



Figure 11: Two of the industrial log scanners used when collecting data; an MPM Engineering 3D optical scanner (left) and a one-directional RemaLog X-ray scanner (right).

3.2 Stem bank data

As described in section 1.2.4, the Swedish pine stem bank (Grundberg *et al.*, 1995) is a large collection of CT-scanned Scots pine logs, showing a large diversity in both geographical origin and growth conditions. All logs were CT-scanned in green condition, then a slice was cut off from the butt end of every log, conditioned to 9% moisture content (MC) and CT-scanned again. Thus, for every log, the green density distribution is known for the whole log and the dry density at the butt end can be calculated from the images of the conditioned slices.

The CT-scanning of the logs was performed at Luleå University of Technology in Skellefteå using a Siemens Somatom AR.T medical CT scanner (Anon., 2013*f*). In this project, the original full-resolution images with 512×512 pixels and 12-bit depth have been used, whereas previous studies on the stem-bank data have used downscaled images with 256×256 pixels resolution and 8-bit depth (Grundberg *et al.*, 1995). The 12-bit depth of the original images was distributed so that there is one intensity level per CT number, corresponding approximately to a density resolution of 1 kgm⁻³. The beam width was 5 mm and the reconstructed image width was between 350 and 450 mm, depending on the log size. Thus, each pixel in the CT images describes a volume element (voxel) of size ranging from $0.68 \times 0.68 \times 5$ mm³ to $0.88 \times 0.88 \times 5$ mm³. The distance between cross-sections was 10 mm within knot whorls and 40 mm between the knot whorls (Grundberg *et al.*, 1995).

The green CT images from the stem bank were used as the basis for simulation of X-ray and 3D scanner data (section 4.1) as well as for reference measurements of green density, top ruptures and resin pockets. The 9% MC disks were used for reference measurement of dry density.

3.3 Calibration data

In order to calibrate the relationships between mass thickness and observed intensity in the industrial X-ray scanner (equations (6) and (8)), a Scots pine sawlog was scanned using an industrial X-ray scanner (see section 3.1). The sawlog was then brought to the tomography lab at Luleå University of Technology in Skellefteå where it was scanned with the same settings used for the Swedish pine stem bank (see section 3.2). Rotational position of the log was tracked so that it could be scanned at the same position in both sets of equipment.

Chapter 4: Methods

This chapter summarizes the methodology used in the appended papers. For more details, please refer to the respective papers.

4.1 Simulation of industrial data

4.1.1 X-ray log-scanner data

Simulation of industrial X-ray log-scanner radiographs from the CT logs of the stem bank is described by Grundberg and Grönlund (1997). For this project, an updated code was written, using the full-resolution versions of the CT images. The new code allows simulation of an arbitrary number of X-ray directions at a resolution of 576 or 1152 pixels per cross-section and a depth of 12 or 16 bits (4096 or 65536 grey-scale levels respectively). The simulations used in papers III, IV and VII were carried out at 576 pixels resolution and 12-bit depth. In paper VIII, 1152 pixels and 16-bit depth were used.

A CT image was positioned in a simulation model of the X-ray log scanner (see Figure 12). Since the CT image is a density chart of the cross-section, this allowed for the calculation of the average density along the ray paths to every detector pixel. The mass thickness *x* along each ray path was then calculated by multiplication of the path length through wood and the average density along that ray path (equation (4)). The X-ray intensity transmitted through the log could then be calculated by taking the sum in equation (6) over the energy spectrum of the X-ray log scanner (Figure 6). Next, the simulated intensities were scaled so that the intensity levels matched those of an industrial X-ray scanner. This gave a maximum intensity level of either 4095 or 65535, depending on the bit depth being simulated. As a final step of the simulation, an artificial electronic noise was added to the signal (except in paper III). The noise was normally distributed with a standard deviation proportional to the square root of the intensity. The noise level was chosen so that the simulated noise would correspond to the actual noise observed in the industrial X-ray radiographs.



Figure 12: Principle for simulation of X-ray log scanner data. a) A CT cross-section is inserted into a simulation model of the log scanner and the mass thicknesses along rays hitting each detector pixel are calculated. b) The intensity transmitted through the log (grey line) is calculated from the mass thickness (black line) by integration over the full energy spectrum of the X-ray log scanner.

4.1.2 3D scanner data

The outer shape of the logs was derived from the CT images of the logs by a simple threshold filter. A normally distributed measurement error with 1.0-mm standard deviation was added to every radius. The outer shape was then stored in a standard 3D scanner format, with 72 radii per cross-section and a cross-sectional distance of 40 mm.

4.2 Path-length compensation

The principle applied when combining cross-sectional X-ray and outer shape data is very similar to the principle used when simulating X-ray log-scanner data from CT images (section 4.1.1). For each X-ray cross-section, the corresponding outer shape was identified and positioned in a simulation model of the X-ray scanner. By doing this, it was possible to calculate the path lengths through wood of X-rays hitting each detector pixel (Figure 13*a*). In general, the outer shape measured by a 3D scanner was used, but in paper V the use of an elliptical outer shape derived from the X-ray data was also evaluated.

The cross-sectional outer shape was positioned to match the outer border of the log in the X-ray data; the X-ray scanner is calibrated so that this position corresponds to the border between bark and wood. In this project, X-ray log-scanner data with both one and two measurement directions have been used. When using one X-ray direction, the two X-ray borders constrain the position of the log in one dimension only, and the 3D cross-section was aligned to match the two X-ray borders. When using two directions, the position of the log is constrained at the two borders of each X-ray direction, which
simplifies the positioning. In this case, the outer-shape cross-section was placed so that the path lengths at all four X-ray borders were as equal as possible.

The mass thickness along each ray path through the log was obtained from the intensity measured by the X-ray scanner. This was done using equation (8), which had been previously calibrated using the calibration data set described in section 3.3.

Using equation (4), the mass thickness obtained from the X-ray data was divided by the corresponding path length calculated from the outer shape, and so the average green density along that ray path was obtained (Figures 13b & 14). Finally, the average green densities along all rays in all cross-sections were arranged together as a green-density profile of the log, see Figure 16 in the results section (5.1). In the appended papers, this method of combining data from 3D and X-ray scanners is referred to as the 3D X-ray method and the combined data as 3D X-ray data.



Figure 13: Principle for path-length compensation of X-ray data using log-shape information from either an optical 3D scanner or an X-ray scanner. a) Simulation model of a two-directional X-ray log scanner showing the measured X-ray attenuation through the log cross-section (grey line). The outer shape of the cross-section is inserted into the simulation model, and the path lengths through wood of X-rays hitting each detector pixel are calculated (black line). b) The path-length-compensated X-ray cross-section for each detector (black line) is calculated by combination of the measured X-ray attenuation (grey line) and the calculated path lengths.

4.3 Detecting specific log features using X-ray and 3D data

4.3.1 Heartwood diameter (papers II, V)

The path-length-compensated X-ray data comprise average green density profiles for every cross-section of the log, one for each measurement direction. At the edges of such a profile, the average density is high, since the X-rays arriving at these pixels have passed through moist sapwood only. In the centre of the profile, the average density is lower, since these rays have passed through both sapwood and heartwood (Figure 14).

For Scots pine, there is in general a distinct transition between heartwood and sapwood that can be clearly seen in density images of the green log (Figure 8*a*). Because of the existence of intermediate wood in Norway spruce (Hillis, 1987), the moisture-content transition between heartwood and sapwood is less distinct in Norway spruce (Figure 8*c*). Therefore, two different algorithms have been developed for the detection of the heartwood/sapwood border in the cross-sectional density profiles (Figure 14). The algorithm for Scots pine (paper II) assumes a distinct border and looks for the maximum and minimum derivative in the density profile. The algorithm for Norway spruce (paper V) on the other hand applies an adaptive threshold in order to find a position where the density exceeds the heartwood density by a predefined percentage.

Once the heartwood border has been established, the pine and spruce algorithms proceed in the same manner. The heartwood content of the individual cross-sections is calculated as the ratio between the heartwood diameter and the log diameter. For the two-directional case, the average heartwood content of the two measurement directions is used. The heartwood content at the top of the log is then found by linear



Figure 14: Path-length-compensated X-ray cross-section of a Scots pine log, describing an average green density profile of the log. A and B = valid regions when looking for the two heartwood borders of the cross-section; $\alpha =$ inflection point carrying the minimum derivative within region A and the maximum derivative within region B, respectively; $\beta =$ heartwood border in each region, selected as the point where the tangent line through the inflection point equals the average sapwood density.

extrapolation from the heartwood content values of all knot-free cross-sections within 300–2500 mm from the top end of the log. Finally, the heartwood diameter at the top of the log is obtained by multiplication of the heartwood content at the top of the log and the top diameter measured by the 3D scanner.

The heartwood diameter values are compared to manual reference measurements done either on log-end surfaces or on CT images. In paper II, the top heartwood diameter of each log was manually measured on the top end surface in a direction selected to avoid extreme values in the case of oval or otherwise irregular heartwood shape. In paper V, the reference measurements were done in cross-sectional CT images of the logs located 20 cm from the top end. In this case, the heartwood diameter was defined as the average diameter of the largest ellipse that could be inscribed in the heartwood.

4.3.2 Dry density (papers IV, V)

Because the moisture content of the heartwood is approximately constant, the green density of the heartwood may be used to estimate the dry density of the log. However, since all X-rays passing through the heartwood also pass through sapwood, the green heartwood density cannot be obtained directly from the path-length-compensated X-ray density profiles (Figure 15). Instead, the density profiles contain values of the average green density ρ_a along rays passing through both sapwood and heartwood. For such a ray, ρ_a is given by:

$$\rho_a = h\rho_h + (1-h)\rho_s \tag{9}$$

where ρ_s is the average green sapwood density along the ray, ρ_h is the average green heartwood density along the ray and h is the share of the path travelling through the heartwood.



Figure 15: Cross-section of a log with an estimated oval heartwood shape inscribed. The dashed lines show example X-ray paths through sapwood only (1.) and through sapwood and heartwood (2.). The path length through wood of a ray is s, and the path length through heartwood along the ray is $h \times s$.

In the region between the log border and the heartwood/sapwood border, the rays pass only through sapwood. A median value of the densities along these rays is used to estimate the local green sapwood density ρ_s in each cross-section.

In order to find the share h of the path travelled through heartwood, an oval heartwood shape is estimated from the detected heartwood border. This heartwood shape is inserted into the simulation model in Figure 13, and the path length through heartwood is calculated for every ray using the same methodology as for the total path lengths in section 4.2. The share h is then calculated by division by the previously calculated total path length through wood for the ray (Figure 15).

By applying equation (9), a value of the green heartwood density ρ_h is then calculated for every ray passing through the heartwood. For each cross-section, an average green heartwood density $\rho_{h,c}$ is calculated. These green-density values are then translated to the corresponding cross-sectional dry-density values $\rho_{0,c}$ by assuming the heartwood moisture content of all logs to be 35% and the volume swelling to be 14.2% (Esping, 1992). Finally, the dry density of the log as a whole can be calculated by averaging the cross-sectional values. A dry-density prediction at a specific position can be obtained by developing a linear model using the $\rho_{0,c}$ values of all knot-free cross-sections and then evaluating the linear model at the desired location.

Reference measurements of the dry densities were done in CT images of dry disks that had been cut from the log ends. In paper IV, the disks had been cut from the butt end and conditioned to 9% MC, and in paper V the disks had been cut from the top end and dried to oven-dry condition (0% MC). The densities were calculated by averaging over a segment of the heartwood, avoiding cracks and other defects.

4.3.3 Sapwood moisture content (paper VI)

The sapwood moisture-content calculations are based on the density calculations described above. The dry sapwood density is predicted from the dry heartwood density using a linear model. An estimate of the sapwood moisture content is then calculated by combining the dry sapwood density with the average green sapwood density of the log. The green sapwood density is calculated on a cross-sectional basis as described in section 4.3.2, and a log average is then calculated and used to estimate the moisture content.

The moisture-content reference values were calculated using density measurements in CT images. For each log, a reference value for the green sapwood density was calculated by taking the average over the sapwood in a knot-free cross-section approximately 400 mm from the butt end. Similarly, a reference value for the sapwood density at 9% MC was calculated by taking an average in the conditioned butt disk of each log. The moisture content reference was then calculated using these two density values.

4.3.4 Top rupture (paper VII)

The detection of top rupture is based on the heartwood shape, obtained as described in section 4.3.1. The two contours describing the geometrical centre of the heartwood and the geometrical centre of the log are compared, and a value indicating the heartwood irregularity is calculated. Two similar values indicating the outer shape irregularity from 3D and X-ray scanning respectively are also calculated.

The predictive power of the three indicator values was evaluated by comparing them to the top ruptures that could be detected manually by skilled graders either on the logs or on the sawn boards. First, the calculation models were developed using simulated X-ray and 3D data from 540 logs in the pine stem bank, and then the calculation models were verified using 508 pine logs that had been scanned using industrial X-ray and 3D log scanners.

4.3.5 Resin pockets (paper VIII)

For resin pockets, no automatic detection algorithm has been developed; only the potential of developing such an algorithm has been studied. This was done by simulating X-ray log scanner images for a number of resin-pocket-rich Norway spruce logs. Each log was simulated in 16 different measurement directions with spacing of 11.25°, and the simulated X-ray images were then investigated by eye. The resin pockets were categorized according to their contrast to the surroundings, and the probabilities of detecting the resin pockets in a scanner with two, four or eight measurement directions respectively were estimated.

4.4 Determining the log grade for payment (paper IX)

In a preliminary study, a total of 160 Norway spruce and 160 Scots pine logs were scanned with an industrial X-ray scanner and an optical 3D scanner, and for each log, a large amount of variables describing different properties of the logs, such as unevenness and amount and distribution of knots, were calculated by the scanner software. The logs were then graded by a skilled log grader according to the VMR 1-99 rules defined by the Swedish Timber Measurement Council (Anon., 1999), and models for prediction of the log grade based on the X-ray and 3D data were developed using partial least squares (PLS) regression in Umetrics Simca-P+11 (Anon., 2013*h*).

Chapter 5: Results and Discussion

In this chapter, the main results from the appended papers are collected and briefly dicussed, for more details, please refer to the respective papers.

In section 5.1, the general properties and benefits of path-length compensation are discussed, including a comparison of X-ray- and 3D-based outer shape, and a comparison of different numbers of measurement directions. In section 5.2, the results obtained when applying the path-length compensation for calculation of specific log features are described in more detail. Section 5.3 covers log grading for payment. Finally, the chapter finishes with two sections on industrial implementation of the results (5.4) and comparison with CT scanning (5.5).

5.1 Path-length compensation

Value of path-length compensation

The presented method for combining data from 3D and X-ray scanners using pathlength compensation (papers I–III) has proven useful for a range of applications, such as measurement of heartwood diameter (papers II, V), estimation of dry density (papers IV, V) and sapwood moisture content (paper VI) and detection of top rupture (paper VII). It has also been concluded that the algorithms developed are robust enough for application in an industrial setting (papers I, II, V and VII). Both paper II and paper V show a significant improvement in the heartwood diameter (section 5.2.1) and density (section 5.2.2) calculations based on the 3D path-length-compensated algorithms when compared to the corresponding calculations based on uncompensated X-ray data. The primary reason for this improvement is the enhanced contrast of the X-ray images gained by the path-length compensation (Figure 16). For the log in Figures 16*a*,*b* the contrast between heartwood and sapwood is sufficient to locate the heartwood border also in the uncompensated data, but for the log in Figures 16*c*,*d* path-length compensation is necessary in order to locate the heartwood/sapwood border properly. The low contrast in Figure 16*c* may be caused by, *e.g.*, partial drying of the sapwood.



Figure 16: *a*),*c*): X-ray radiographs of two Scots pine logs collected using a one-directional X-ray log scanner. b),d): X-ray radiographs of the same two logs, path-length-compensated using the outer shape from an optical 3D scanner.

Source of outer shape

The path-length-compensation algorithm developed in this project does not depend on a 3D scanner as source for the outer shape; it can use any source of outer shape available. Previous studies (Oja *et al.*, 1998*a*; Skatter, 1998) have shown that for X-ray scanners with more than one direction, it is possible to calculate the outer shape of the log directly from the X-ray data. Therefore, the potential of using an elliptical outer shape from a two-directional X-ray scanner for the path-length compensation is evaluated in paper V.

Although this study is only done on a limited amount of data, 48 Norway spruce logs, the results are very promising. For heartwood diameter, the results are in practice equivalent, and for dry density, the results using an X-ray-based outer shape ($R^2 = 0.75$) are almost on par with those obtained using a 3D-scanned outer shape ($R^2 = 0.78$). This suggests that the great improvement is found by application of the pathlength compensation and that obtaining exactly the right path lengths when performing the compensation is less significant. A separate study on a small group of 32 Scots pine logs (Figures 22 & 24) confirm that, also for this specie, it is possible to obtain good results when using an X-ray-based outer shape, although in this case no comparison was done with a 3D-scanned outer shape.

Using only X-ray data gives a simple and robust implementation, but does not utilize the whole potential of path-length compensation. In the case of shape irregularities and predrying of the logs, the outer shape from the X-ray scanner will contain more errors, and in this case, the benefit of using a 3D scanner is expected to be greater. However, there are also difficulties associated with using the outer shape from a 3D scanner. In combining data from the two scanner types, an additional uncertainty is added. The first reason for this uncertainty is that the log may rotate between the two scanners, causing an outer-shape error. The second reason is that, sometimes, it is difficult to connect the right 3D cross-section to each X-ray cross-section; in the current implementation, this matching is done using only the lengthwise position of the crosssections collected using a rotary encoder. These two error sources explain to some extent why the advantage observed when using a 3D-scanned outer shape instead of an elliptical outer shape from the X-ray scanner was not greater. Both of these problems could, however, be remedied by building a system where the X-ray and 3D scanners are more closely integrated. If the two scanners are mounted on the same frame instead of a few meters apart, the risk of the log moving around between the scanners is minimized, and if the scanners are run synchronously by a single integrated system, the cross-sections could be matched almost perfectly.

One hypothesis of this project was that the best path-length compensation can be obtained using the outer shape from a 3D scanner. The results in paper V to some extent contradict this hypothesis, since in principle equivalent precision could be obtained using an outer shape from a two-directional X-ray scanner. However, the study in paper V is done on a limited amount of logs and the data were collected from 3D and X-ray scanners positioned a few meters apart, therefore the results obtained cannot be used to reject this hypothesis completely. As argued above, it still seems likely that the hypothesis will hold for a system where the two scanners are positioned closely together and run synchronously.

Number of X-ray directions

One of the most important findings of this project is that the combination of X-ray and 3D scanning makes it possible to gain high precision even when using only one X-ray direction (papers I–III). In paper III, the heartwood diameter and green heartwood density calculations are evaluated for one and two X-ray directions. This evaluation was done on simulated data without artificial noise. Therefore, the results obtained are only intended for comparison between one and two X-ray directions. For information on the precision obtainable under industrial conditions, the results presented in sections 5.2.1 and 5.2.2 should be used.

Under these ideal simulation conditions, it was found that the precision of a pathlength-compensated two-directional system was slightly higher than that of a pathlength-compensated one-directional system (Figures 17–20). By adding a second X-ray direction, around 30% of the remaining variation in the heartwood diameter could be explained (R^2 improved from 0.987 to 0.991), and the RMSE was reduced by 16% (RMSE improved from 4.5 mm to 3.8 mm). For the green heartwood density, 26% of the remaining variation was explained by a second X-ray direction, and the RMSE was reduced by 14%.

The X-ray sources and detectors make up a large amount of the costs in an X-ray scanning system, therefore it should be possible to sell a one-directional system at a significantly lower price. Because the loss in precision compared to using a two-directional system is not great, this makes a system combining a 3D scanner and a one-directional X-ray scanner a cost-efficient alternative that should be a good choice for many applications.



Figure 17: Heartwood diameter 1000 mm from top end in Scots pine logs, reference measurement in medical CT images versus predictions using **one** 3D-path-lengthcompensated X-ray direction. The outlier (\times) is an oversize butt log. Measurements are based on simulated data without artificial noise.



Figure 18: Heartwood diameter 1000 mm from top end in Scots pine logs, reference measurement in medical CT images versus predictions using two 3D-path-lengthcompensated X-ray directions. Measurements are based on simulated data without artificial noise.



Figure 19: Green heartwood density 400 mm from the butt end in Scots pine logs, reference values from medical CT images versus predictions using one 3D-path-length-compensated X-ray direction. Measurements are based on simulated data without artificial noise.



Figure 20: Green heartwood density 400 mm from the butt end in Scots pine logs, reference values from medical CT images versus predictions using two 3D-path-length-compensated X-ray directions. Measurements are based on simulated data without artificial noise.

5.2 Detecting specific log features using X-ray and 3D data

5.2.1 Heartwood diameter

Calculations of the heartwood diameter using various numbers of X-ray directions and calculation algorithms are presented in papers II and V. The coefficients of determination (R^2) and root mean square errors (RMSE) obtained using the different configurations are tabulated in Table 1.

In papers II and V, the precision of the heartwood-diameter calculations using pathlength compensation are compared to the precision obtained using uncompensated X-ray images. In both studies great improvements in precision are found. For pine, R^2 improved from 0.84 to 0.94, and for spruce, R^2 improved from 0.58 to 0.95.

It is clear that the old heartwood-diameter algorithms working on uncompensated Xray images perform much better for pine ($R^2 = 0.84$) than for spruce ($R^2 = 0.58$). Also, the path-length-compensated algorithm developed for pine was not working as well for spruce ($R^2 = 0.90$) as it was for pine ($R^2 = 0.94$), which is why the heartwooddetection part of the algorithm had to be modified for spruce in order to obtain desired precision ($R^2 = 0.95$). The reason that the precision of the unmodified algorithms is lower in Norway spruce is, as mentioned in section 4.3.1, the less distinct moisture content transition between heartwood and sapwood in spruce.

The algorithm for spruce was evaluated using path-length compensation based on both 3D and X-ray outer shape, but no significant difference could be found. The precision using path-length compensation based on X-ray outer shape has been also evaluated on a smaller set of pine logs (Figure 22). For this independent verification set, very high precision was obtained ($R^2 = 0.98$; RMSE = 4.6 mm). These figures are significantly better than those obtained using one X-ray direction and 3D outer shape ($R^2 = 0.94$; RMSE = 10.3 mm (Figure 21)). The difference probably has nothing to do with the source of the outer shape, and only to some extent can the difference be explained by the addition of a second X-ray direction. Most likely, the main cause of the higher precision is the more exact reference values used in Figure 22, where the heartwood diameter is measured in a medical CT cross-section of the log and defined as the mean diameter of the largest ellipse fitting into the heartwood. In the data set of Figure 21, the heartwood diameter was measured by hand on the log ends in a direction avoiding extreme values. This reference method is much less exact, and the reference values were rounded to the nearest centimetre, meaning that there is a considerable contribution from the reference values in the observed errors of Figure 21. Therefore, although based only on a small number of logs, Figure 22 gives a more realistic description of the precision obtainable in the automatic heartwood-diameter calculation for pine.

Table 1: Heartwood-diameter calculation in Scots pine and Norway spruce. Tabulated are the coefficients of determination (R^2) and root mean square errors (RMSE) obtained using various numbers of X-ray directions, calculation algorithms and data sets.

Paper	Data type	Reference type	Species	Number of logs	X-ray directions	Path-length compensation	R^2	RMSE [mm]
II	Industrial	Manual	Pine	423	1	None	0.84	17
II	Industrial	Manual	Pine	423	1	3D	0.94	10.3
_	Industrial	СТ	Pine	32	2	X-ray	0.98	4.6
V	Industrial	СТ	Spruce	48	2	None	0.58	25
V	Industrial	СТ	Spruce	48	2	3D	$0.90 \star$	12.3*
V	Industrial	СТ	Spruce	48	2	3D	0.95**	9.2**
V	Industrial	СТ	Spruce	48	2	X-ray	0.95	8.9

*) Using heartwood-detection algorithm developed for pine.

**) Using heartwood-detection algorithm developed for spruce.



Figure 21: Top heartwood diameters for 423 Scots pine logs. manual reference measurements on log ends vs. predictions based on one X-ray direction, path-lengthcompensated using outer shape from a 3D scanner. The two outliers (\times) were excluded when calculating \mathbb{R}^2 and RMSE. Measurements are done on industrial data.



Figure 22: Top heartwood diameters for 32 Scots pine logs, manual reference measurements in medical CT images vs. predictions based on two X-ray directions, path-length-compensated using an X-ray based outer shape. Measurements are done on industrial data.

5.2.2 Dry density

Results for the automatic prediction of dry density are presented for Scots pine in papers IV and VI and for Norway spruce in paper V. For pine, simulated data including artificial noise were used, and for spruce, industrial data were used. The calculations have also been verified on a small set of 32 industrially scanned pine logs (Figure 24). The coefficients of determination (R^2) and root mean square errors (RMSE) obtained using these three data sets are presented in Table 2.

The dry reference densities were, in general, measured in the heartwood part of the log. One reason for this is that the dry-density prediction is done by calculating the green density of the heartwood and then converting this value into a dry-density prediction assuming constant moisture content of the heartwood. By using the dry heartwood density as a reference, it is easy to evaluate how well this prediction model works. Another reason for predicting the dry density in the heartwood region of the log is that it will correspond quite well to the density of the centre yield, meaning that the predicted density can be used for estimating strength properties of the centre boards.

For the two industrial data sets, the reference measurements are done in the top end of each log, but in the simulated data set, the reference measurements are made in the butt end, because this is where dry density information was available. For upper logs, this does not make any difference, but for butt logs, the behaviour will be very different in the butt end. In the butt end of the tree, the moisture content is lower, and the dry density is higher (Esping, 1992). Thus, the relation between measured green density and actual dry density will be different for butt logs and upper logs. In order to handle this, separate linear models for butt logs and upper logs were used when predicting the dry densities of the simulated data set.

For both of the pine data sets, the RMSE is around 30 kgm⁻³, but R^2 is smaller for the industrial data set (0.71; Figure 24) than for the simulated data set (0.83; Figure 23). Because the RMSE values are similar, it is likely that the observed difference in R^2 is only a mathematical effect caused by the smaller range of densities covered in the industrial data set. Because these two sets have different reference positions (butt end and top end respectively), it can be concluded that butt-end density and top-end density can be predicted with similar precision. The use of butt-end reference position in the simulated data set is also the main reason for the wider range of densities covered by that data set.

In paper VI, the dry density of the sapwood is predicted from the green heartwood density. The precision obtained ($R^2 = 0.47$; RMSE = 43 kgm⁻³) is much lower than for the prediction of the dry heartwood density. This is expected, because there is a tight relation between green and dry heartwood densities, but the relation between dry heartwood and sapwood densities is uncertain and depends on the growth conditions throughout the life span of the tree. Therefore, it is possible that the predictability of the dry sapwood density could be improved by including variables from forest inventory data in the modelling. This requires, of course, tracing of the logs from the forest to the sawmill on an individual or batch level.

Table 2: Dry density calculation in Scots pine and Norway spruce. Tabulated are the coefficients of determination (R^2) and root mean square errors (RMSE) obtained using various calculation algorithms and data sets.

Paper	Data type	Reference region	Species	Number of logs	X-ray directions	Path-length compensation	R^2	RMSE [kgm ⁻³]
IV	Simulated	Heartwood	Pine	553	2	3D	0.83	31
-	Industrial	Heartwood	Pine	32	2	X-ray	0.71	27
V	Industrial	Heartwood	Spruce	48	2	None	0.31	38
V	Industrial	Heartwood	Spruce	48	2	3D	0.69*	24*
V	Industrial	Heartwood	Spruce	48	2	3D	0.78**	20**
V	Industrial	Heartwood	Spruce	48	2	X-ray	0.75	21
VI	Simulated	Sapwood	Pine	553	2	3D	0.47	43

*) Using heartwood-detection algorithm developed for pine.

**) Using heartwood-detection algorithm developed for spruce.



Figure 23: Dry heartwood density in the butt end of 553 Scots pine logs. Reference measurements in dry medical CT images versus predictions based on two X-ray directions, path-length-compensated using outer shape from 3D scanning. Separate linear models for butt logs and upper logs have been used. Measurements are done on simulated data including artificial noise.



Figure 24: Dry heartwood density in the top end of 32 Scots pine logs. Reference measurements in dry medical CT images versus predictions based on two X-ray directions, path-length-compensated using X-ray based outer shape. Measurements are done on industrial data.

Finally, it should be noted that the density predictions presented in this study are evaluated at single cross-sections near the log end. Because the single cross-section values are influenced by local variations, this means that even better precision should be expected if the developed method is applied for the prediction of an average dry density of, for example, the centre planks of the log.

Because of the strong relationship between density and mechanical properties of the wood (*e.g.* Kollmann & Côté, 1968), presorting of logs based on dry density is of value for the production of strength graded products. Furthermore, dry density is related to the drying properties of the wood and it is known that density variations within a drying batch can result in large variations of the final moisture content of the boards (Esping, 1992). Thus, by adjusting the drying process to the material, improved product quality can be obtained. By avoiding over drying, energy consumption can also be reduced.

5.2.3 Sapwood moisture content

In paper VI, the results obtained for automatic prediction of sapwood moisture content (MC) in green sawlogs of Scots pine are presented. Because the prediction of the sapwood dry density is associated with a significant uncertainty, this is true also for the sapwood MC prediction. However, there is a clear indication that the method can be used to separate between logs of high and low sapwood MC as they arrive at the log-sorting station.

Figure 25a shows the sapwood MC and Figure 25b shows the ratio between observed MC and the density-dependent maximum MC of saturated wood. This ratio is a measure that could be used to find logs that have started drying. It should be noted, though, that because the logs in the study all had been scanned soon after felling, they had not been drying much. Consequently, there is still a need for evaluating the method for a set of logs that have actually started to dry.

A successful method for separating between fresh and predried logs would be of high value especially in the spring season, when it is common that the logs are stored for longer periods than usual in the forest. The predrying of the logs affects the drying properties of the sawn goods: thus, many Swedish sawmills need to alter their drying schedules during springtime to avoid problems with cracks and large standard deviations in the final MC. When performing this adjustment of the drying schedules, it would be a great advantage if the raw material were sorted into batches according to the amount of predrying. Alternatively, even if the logs are not sorted according to MC, a continuous measurement of the sapwood MC in the arriving logs would provide an important indication about when it is time to start adjusting the drying schedules.



Figure 25: a) Sapwood moisture content (MC) and b) sapwood MC relative to the theoretical maximum MC of saturated wood for 553 Scots pine sawlogs: reference measurements in medical CT images versus predictions based on two-directional X-ray data, path-length-compensated using outer shape from 3D scanning. Measurements are done on simulated data including artificial noise.

5.2.4 Top rupture

The results of the automatic detection of top rupture for both the stem bank and the industrial verification data sets are presented in paper VII. The results for the verification data are shown in Figure 26, where it can be seen that many of the logs in which top rupture was manually detected already at the log level get high indicator values from both the heartwood indicator and the outer shape indicators. However, a number of logs not containing any top rupture also get high values from the two outer-shape indicators (bottom right in Figures $26b_{,c}$), making it difficult to use the outer-shape methods to separate between logs with and without top rupture. Using the heartwood shape as indicator gives much better separation between logs with and without top rupture. This means that it is possible to set a threshold on the indicator value that sorts out the worst top rupture logs without risking false positives, *i.e.*, including logs that are free from top rupture (bottom right in Figures $26a_{,b,c}$), therefore it is not possible to automatically detect all top rupture logs.

Implementing top-rupture identification in a sawmill would be a great tool for avoiding the problem logs when making products that are sensitive to top rupture. It will, however, not be desirable to completely remove the detected logs from production. Instead, the top-rupture logs could be used for alternative products that are not sensitive to top rupture, one example being wood for finger jointing.

Because of the rapid variations in density and grain direction near a top rupture, it is likely that top ruptures are one of the factors limiting feeding speed and saw-blade thickness. If problem logs, including top-rupture logs, can be automatically identified and sawn at a lower feeding speed, it should be possible to use thinner saw blades, thereby improving the yield. Important tasks for the future will be further investigation of this hypothesis and the development and implementation of such strategies.



Figure 26: Top rupture in 508 Scots pine logs from a Swedish sawmill. The graphs show manual top-rupture notation versus automatic top-rupture indicator values based on a) heartwood shape from combined X-ray and 3D scanning, b) outer shape from X-ray scanning and c) outer shape from 3D scanning respectively. Triangles are logs manually detected as top-rupture logs and circles are top ruptures noted during board grading. The dashed lines are suggested threshold values for separation between logs with top rupture (right of threshold) and without top rupture (left of threshold). The calculations are based on industrial X-ray and 3D log-scanner data.

5.2.5 Resin pockets

The results from the manual inspection of resin pockets in simulated X-ray radiographs are presented in detail in paper VIII. It was found that it should be possible to automatically detect resin pockets that are situated in the heartwood and have a width corresponding to at least 10% of the log diameter, but only if the X-rays pass through the resin pocket in an almost tangential direction. Therefore, the probability of identifying an individual resin pocket is fairly small. However, the more resin pockets there are in a log, the higher is the probability of detecting at least one of them (Figure 27).

For a log with ten detectable resin pockets, *i.e.*, with a size of at least 10% of the log diameter, the probability of detecting at least one of these resin pockets is no less than 44% using a two-directional X-ray scanner, 69% using a four-directional scanner and 92% using an eight-directional scanner (Figure 27*a*). For larger resin pockets, these probabilities increase quickly (Figure 27*b*). Resin pockets in upper logs are larger relative to the log diameter (Temnerud, 1999), therefore the conclusion is that it should be possible to automatically detect upper logs with many resin pockets. At least four X-ray directions are to be preferred for such an application.



Figure 27: Probability of detection of at least one resin pocket as a function of the number of resin pockets of widths a) 10% and b) 15% of the log diameter, using X-ray log scanners with two (2X), four (4X) or eight (8X) measurement directions respectively. The probability curves refer to at least one resin pocket being situated within the interval within which resin pockets are with certainty automatically detectable. The intersections between the dotted lines and the probability curves mark the probabilities of detecting at least one resin pocket in the case of ten detectable resin pockets.

5.3 Determining the log grade for payment

In paper IX, a preliminary study on automatic log grading for payment based on the VMR 1-99 grading rules (Anon., 1999) is presented. For Norway spruce, the logs were sorted into four different grades with an accuracy of 86% correctly sorted logs (Table 3), and for Scots pine, the logs were sorted into five different grades with an accuracy of 81% correctly sorted logs (Table 4). For spruce, 3D variables describing bow height and crookedness were most important, whereas for pine, X-ray variables describing the knot structure were more important.

It should be noted that the high hit rate observed for spruce is to some extent an effect of most logs having the same grade (VMF1), therefore the pine model can be said to work better, since the logs are spread out more between the different grades. For both species, the hit rates are better than those typically observed in manual log grading, meaning that the combination of X-ray and 3D scanning is a feasible technology for automatic log grading for payment.

However, some grade-determining log defects, such as forest rot and blue stain (Anon., 2007), are difficult or impossible to detect using X-ray scanning. Therefore, the work has continued in the direction of developing a methodology for semiautomatic log grading for payment based on the new VMR 1-07 grading rules (Anon., 2007). The idea is that the automatic system will make the manual grader's job easier by determining a base grade for each log. The manual grader will only be looking for defects not handled by the X-ray system and will downgrade any logs where excessive amounts of, for example, forest rot or blue stain are found. This will make log grading for payment easier for the manual grader, and the process will run both faster and more smoothly.

An important step is the verification of the models on a large amount of material representative of the whole of Sweden. Because many Swedish sawmills with X-ray scanners handle only Scots pine, it was decided to first develop X-ray-based grading models for pine. Furthermore, the number of spruce grades has been reduced to two in the new grading standard (Anon., 2007) with the most important property for spruce being crookedness. This means that simply using a 3D scanner to determine the crookedness of the logs will be enough to make spruce grading a simple and smooth process for the grader.

The X-ray models for grading pine based on VMR 1-07 (Anon., 2007) have proven stable, and this methodology is now in the final stages of verification. Hopefully, the Swedish Timber Measurement Council will be able to authorize the use of X-ray scanning for semiautomatic grading for payment of Scots pine sawlogs before the end of 2013.

The possibility to use X-ray scanning to make grading for payment more efficient can be a real breakthrough for the Swedish sawmill industry. For many sawmills, the log grading for payment is a bottleneck and if this bottleneck in the log sorting is removed, it would be possible for those sawmills to increase the productivity. This will make it easier to get return on investment and should encourage middle-sized sawmills to also invest in an X-ray log scanner. Moreover, with the equipment in place, these mills can then begin with quality sorting of their logs for the production of some special products. A large-scale introduction of X-ray scanning in the Swedish sawmills will make the industry more competitive in an international perspective and provide for a more efficient use of raw materials.

Table 3: Automatic grading of Norway spruce logs according to VMR 1-99. Comparison between log grade according to manual grading and log grade according to automatic grading based on X-ray and 3D scanning. Amount of logs given in percent of the total number.

Log grade according	Log grade according to X-ray and 3D					
to the manual grader	VMF1	VMF2	VMF8	VMF9		
VMF1	76	7	0	0		
VMF2	7	8	0	0		
VMF8	1	0	0	0		
VMF9	0	0	0	2		

Table 4: Automatic grading of Scots pine logs according to VMR 1-99. Comparison between log grade according to manual grading and log grade according to automatic grading based on X-ray and 3D scanning. Amount of logs given in percent of the total number.

Log grade according	Log grade according to X-ray and 3D						
to the manual grader	VMF1	VMF2	VMF3	VMF4	VMF5		
VMF1	6	0	1	0	0		
VMF2	0	33	3	3	0		
VMF3	1	3	30	3	1		
VMF4	0	3	3	9	0		
VMF5	0	0	0	0	4		

5.4 Industrial implementation of results

Sawmills

Most of the results presented in this thesis have been developed within the research project "Improved log sorting combining 3D and X-ray technology", which has been funded by WoodCenter North (TräCentrum Norr, TCN) from 2006 to 2013. TCN is a centre partly funded by industrial stakeholders, including many of the major sawmill companies in Sweden. The centre aims at increasing the competitiveness of the Swedish wood industry by promoting a deeper cooperation between research and industry (Schütze, 2008).

There has been a strong collaboration with the sawmill industry throughout the project. In a series of workshops, project results have been presented to the industry and new research activities have been outlined based on the research priorities of the participating sawmill companies. The industry has been following the project with a genuine interest and has come to realize the usefulness of the X-ray log-scanning technique. Over the course of the project, many sawmills have invested in X-ray scanners for their log-sorting stations. At the beginning of the project there were three installations of X-ray log scanners in Sweden and five in Finland, and at the time of writing this thesis (April 2013) there are nine installations in Sweden, thirteen in Finland and one in Estonia.

Currently, the Swedish sawmill industry is closely following the development of the rules for automatic grading of sawlogs for payment based on X-ray scanning. When the Swedish Timber Measurement Council adopts the new rules, making it possible to start using X-ray scanning for pricing of sawlogs, it is likely that more sawmills will make the decision to invest in X-ray equipment for their log sorting. Especially a cost-efficient one-directional X-ray system in combination with a 3D scanner may turn out to be a popular alternative for this kind of application.

Hardware manufacturers

There are two manufacturers of X-ray log scanners that have delivered installations on the Swedish market, RemaSawco (Anon., 2013*e*) with seven installations and Microtec (Anon., 2013*c*) with two installations. In Finland, another two manufacturers are active, Bintec (Anon., 2013*a*) and Inray (Anon., 2013*b*). The results presented in this thesis have however all been obtained using X-ray systems from RemaSawco (Anon., 2013*e*) and this manufacturer also has implemented most of the findings in their systems. The other companies have followed the development by reading publications from the project and all manufacturers now market systems offering various combinations of Xray and 3D scanning.

5.5 Discrete X-ray scanning versus industrial CT scanning

Both discrete X-ray log scanners and industrial CT scanners are equipment aimed at improving the value yield of sawing by predicting important properties of the sawn goods prior to actual sawing. The big difference between the two scanner types is the more exact positioning of the wood features that is possible using a CT scanner. Whereas an X-ray scanner can recognize the presence of many log features and give the longitudinal position, the CT scanner also gives the radial and tangential position of the defects. For instance, a two-directional X-ray scanner gives information on knot groups whereas a CT scanner is capable of measuring size and position of individual knots. This means that an X-ray log scanner is best equipped for optimizing the sawing by selecting suitable sawing patterns for each log, either by sorting the logs into different quality batches or by changing the sawing pattern on the fly if the scanner is positioned in a saw line capable of changing the sawing pattern for each log. The use of a CT scanner, on the other hand, enables not only the selection of suitable sawing patterns, but also provides the ability to optimize the positioning (rotation, parallel position and skew) of the logs with respect to the internal features (Rinnhofer *et al.*, 2003).

Consequently, X-ray and CT scanners are in general not competing systems. Rather, they could complement each other very well. If a CT scanner is being used in the saw line, an X-ray scanner would be a good choice for presorting of logs, making sure that the CT-equipped saw line is fed with suitable logs. Alternatively, a CT scanner in the log sorting could be complemented by an X-ray scanner in the saw line, which would help trace each log from the CT scanner to the saw line.

Still, it is relevant to compare the precision of X-ray and CT log scanners for log sorting purposes. The X-ray-based heartwood-diameter calculations presented in this thesis are very precise; for pine the measurements are within 5 mm and for spruce within 10 mm from the manual references taken in medical CT images. Using an industrial CT scanner, the precision will be even better, but for most applications, an X-ray scanner will provide high enough accuracy of heartwood-diameter detection.

For density, the CT system has the advantage of giving a direct measure of the green heartwood density. But just as in the X-ray system, the prediction of dry density will be based on measurement of the green density, meaning that the predictive power should be close to the values observed for the medical CT scanner in Figure 4 of paper V ($R^2 = 0.87$; RMSE = 16 kgm⁻³). This means that for both dry density and sapwood moisture content, the precision will be better using a CT scanner: but the improvement over an X-ray scanner will not be huge, because many of the same factors still limit the precision.

For the other two features described in this thesis, top ruptures and resin pockets, the difference will be greater. The CT scanner offers a good location of the pith and is also capable of identifying individual knots. Both these factors imply that more top ruptures can be detected with a lower risk of false positives. For resin pockets, it was concluded that a two-directional X-ray scanner is not feasible, but a four-directional scanner may be used to identify logs with many resin pockets. Using a CT scanner, however, resin pockets located in the heartwood can be detected with fairly high accuracy (Oja & Temnerud, 1999).

Chapter 6: Conclusions

The most important conclusions from this work are:

- 1) A good path-length compensation of the X-ray radiographs can be obtained using outer shape data from either a 3D scanner or an X-ray scanner with at least two measurement directions.
- 2) It is likely that better precision in the path-length compensation could be obtained from a system where the X-ray and 3D scanners are positioned closely together and run synchronously.
- 3) The combination of a one-directional X-ray scanner and a 3D scanner is a costefficient system for obtaining high-precision measurements of log properties.
- Path-length compensation generates green density images of the log, which have higher contrast between heartwood and sapwood than uncompensated X-ray images.
- 5) The higher contrast (conclusion 4) leads to great improvements in the calculations of heartwood diameter and dry density.
- 6) The combination of X-ray and 3D scanning can be used to detect logs with low sapwood moisture content.
- 7) Using path-length-compensated X-ray scanning, it is possible to detect top ruptures in some logs that look straight from the outside.
- 8) Using X-ray scanning, it is not possible to identify every individual resin pocket. However, it should be possible to detect logs with many resin pockets. For this task, at least four X-ray directions are recommended.
- 9) By the use of X-ray scanning, log grading for payment can be done more efficiently. This will make it easier to get return on the investment and should encourage more sawmills to invest in an X-ray log scanner.
- 10) Discrete X-ray scanning is a good choice for quality sorting of logs, whereas CT scanning provides the resolution necessary for optimization of the sawing position. Thus, X-ray scanning can in the future be a valuable complement to CT scanning.

Chapter 7: Future work

This project has resulted in many promising calculation models that have now been implemented in X-ray log scanner software and are ready for implementation at the sawmills. The project has also identified ideas that the machine manufacturers can implement in order to obtain higher precision in their equipment. Finally, a number of areas have been identified where more research is needed. This means that future work for the different sectors includes:

For the sawmills

Rethinking production strategies in order to take advantage of the improvements that are now becoming available:

- 1) Sorting of logs according to heartwood diameter allows the production of heartwood-rich products. Especially the potential of Norway spruce heartwood is today very little utilized (Sandberg, 2009).
- 2) The improved precision in the dry-density predictions now makes density sorting of logs for special products more attractive.
- 3) Logs likely to contain top rupture can be sorted out for use with products insensitive to top rupture, such as finger-jointed wood.
- 4) Drying schedules can be adjusted based on information on heartwood content, dry density and sapwood moisture content. Proper adjustment should lead to smaller variations in final moisture content and improved product quality.

For the machine manufacturers

Current scanning systems could be modified according to these concepts:

- 5) Combining one-directional X-ray scanning with 3D scanning will give a costefficient system.
- 6) Better integration of X-ray and 3D scanning by positioning the systems closely together and running them synchronously will likely yield higher precision.

For the research community

Some more verifications and modelling are needed in these areas:

- 7) The algorithms for detection of predried logs need to be evaluated for logs with various degrees of drying, and a proper indicator for predrying should be developed.
- 8) The models for dry-density prediction should be modified and evaluated for the calculation of the average density of the centre yield.

Important areas for future research projects include:

- 9) Build new models for X-ray-based strength grading based on the improved drydensity predictions.
- 10) Develop models and strategies that use automatic detection of top rupture and other defects in order to adjust parameters such as saw-blade thickness and feed speed.
- 11) Cooperation between discrete X-ray scanning and CT scanning for improved production strategies and traceability between the log sorting and the saw line.

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Improved log sorting combining X-ray and 3D scanning – a preliminary study

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ABSTRACT

Quality sorting of sawlogs is becoming more and more common. This is the result of increasing production of customer specific products in combination with high raw material prices.

Today, log quality sorting is being based on either 3D or X-ray scanning techniques. Previous research has shown that sorting accuracy is improved when using multivariate models to combine variables from both 3D and X-ray scanners. There is however a potential of further improving the sorting if 3D and X-ray data are combined at an earlier stage; from the measured 3D shape a better estimate of the X-ray path lengths through the log may be found, thus enabling the calculation of a log density profile from the measured X-ray attenuation.

The development and evaluation of such a technique is the topic of current research at SP Trätek and Luleå University of Technology in Skellefteå. Preliminary results show that the method is good at calculating large scale properties such as heartwood content and heartwood and sapwood densities. When looking for smaller geometric objects, e. g., knot whorls, extra care must be taken so that observational errors from the 3D scanner do not compromise the X-ray data.

Software simulating industrial X-ray scanner data from CT-scanned logs has also been developed. A very good agreement was found between simulated data and actual data from an industrial installation. This underlines that such a simulation tool is very valuable when developing algorithms for industrial X-ray scanners.

INTRODUCTION

Grounds for quality sorting of sawlogs

For a long period of time, sawmills have had a strong focus on productivity. The standard methods of improving profits has been either making efforts to improve volume recovery or increasing the volumes of sawlogs passing through the mill. Today, the competition for sawlogs is fiercer and raw material costs are rising, comprising an increasingly large amount of the total costs of the mill.

Consequently, it is has become ever more lucrative for sawmills to focus on value recovery and quality of sawn products rather than just outgoing volumes. One way of doing this is sawing products carrying specific combinations of dimension and grade, better corresponding to customer demands and thus yielding better value. In order to achieve this, keeping an efficient raw material use, it is important to get it right from the beginning, identifying the right sawlogs for each product; hence quality sorting of logs before sawing is becoming more and more common.

Quality sorting using optical 3D scanners

Quality sorting of sawlogs requires the ability to predict quality of sawn goods from log measurements. Many sawmills already sort the timber based on length and diameter measures obtained from optical three-dimensional (3D) surface scanners (Figure 1). These scanners also yield information about taper, bumpiness and other variables that may be used to estimate the log quality (e.g. Grace 1994, Jäppinen and Nylinder 1997, Oja et al. 1999). Such predictions, using partial least squares (PLS) modelling on 3D data in the quality sorting software Kvalitet On-Line (Anon. 2007*b*), has proven successful and become widely spread in Sweden.





Figure 1. Schematic description of an optical 3D surface scanner (Dashner 1993).

Quality sorting using X-ray scanners

Still the quality information obtainable from 3D scanners is limited, since it is based solely on outer shape properties of the log. An extensive evaluation (Grundberg et al. 1990) of different measurement techniques showed that inner properties of logs are best measured using X-rays.

X-ray scanning by computed tomography (CT) is too slow for industrial applications but may be used to obtain precise measurements of wood density (Lindgren 1991). The high quality images captured have proven very useful for research purposes, e.g., the Swedish pine stem bank, a collection of CT images gathered by Grönlund et al. (1995).

In order to improve speed, industrial X-ray scanners only use a limited number of fixed measurement directions (e.g. Aune 1995, Grundberg and Grönlund 1995). Many authors have developed algorithms analyzing images from such detectors, including calculation of knot structure (Pietikäinen 1996), annual ring width (Wang et al. 1997), outer shape (Oja et al. 1998, Skatter 1998) and strength of sawn products (Oja et al. 2005). Figure 2 shows the principle of a successful two-directional X-ray LogScanner for Scots pine (*Pinus sylvestris* L.) developed by Grundberg and Grönlund (1995), being in use at seven sawmills as of October 2007. Today the use of X-ray scanners is increasing and, likely, more installations will follow.



Figure 2. Schematic description of the X-ray LogScanner developed by Grundberg and Grönlund (1995), image from Oja et al. (1998).

Quality sorting combining X-ray and 3D scanners

Oja et al. (2004) made a comparison between the grading performances of X-ray and 3D scanning techniques and also investigated possible benefits from using a PLS model combining parameters from both methods. The study showed that 57% of sawn boards were correctly graded when using 3D scanning, 62% when using X-ray LogScanner and 66% when combining data from both scanning methods. The highest possible result, with ideal log grading, was 81%. The study concludes that the combination of 3D and X-ray scanning seems very promising and suggests that future studies should focus on fully utilizing the possibilities of combining the two techniques. The combination could also be expected to give better diameter measurements, joining the ability of the X-ray LogScanner to handle varying bark thickness with the ability of the 3D scanner to handle irregularly shaped cross-sections (Oja et al. 1998). Yet another reason for investigating the benefits of such a combination is that a 3D scanner is already present at most mills installing an X-ray LogScanner, and thus do not present any substantial extra investment costs.

By combining raw data from 3D and X-ray scanners at an earlier stage it would be possible to obtain improved density profiles of the logs. A density profile of the log can be obtained if the LogScanner signal is compensated for the varying travel path lengths of the individual photons through the wood (Grundberg et al. 1990). The best travel path compensation is found from the real shape of the log, which in practice is not known. Instead, algorithms developed should use the best shape information available, namely the shape measured by the 3D scanner. The hypothesis is that such a combined technique would lead to improved assessments of heartwood and sapwood densities and would allow for better identification of, among other things, heartwood content, knot whorls, annual ring distance and rot.

The aim of this study is consequently to develop algorithms combining X-ray and 3D data using travel path compensation and to evaluate whether the methods developed have a potential of improving quality sorting at sawmills.

MATERIALS AND METHODS

Data collection

In order to enable the development of quality sorting algorithms based on 3D and X-ray data, it was an essential first step to collect a well defined data set. A large sawmill in the north of Sweden, which had recently installed a one-directional LogScanner, was chosen as host for the project and a total of 435 Scots pine sawlogs, originating from 13 different diameter classes in the range of 150 to 300 mm, were picked out. Each log was individually ID marked and had its top heartwood diameter and annual ring distance manually measured. The logs were then sent through the log sorting station, where data from the RemaControl X-ray LogScanner and the MPM Engineering 3D surface scanner were recorded.

Once all available log data had been collected, the logs were sawn using suitable 2X-patterns, forming a total of 870 centre yield planks. The grades of the sawn planks with respect to knots were established manually by the mill's lumber grader as well as automatically using a FinScan Boardmaster equipment. Eventually, the dried planks were sent to a finger jointing facility where their knot free zones were determined.

Combining 3D and X-ray data using travel path compensation

The development of algorithms combining raw data from the 3D and X-ray scanners using travel path length compensation and was performed using MatLab 7 (Anon. 2007*c*) and Visual Studio 2005 (Anon. 2007*a*).

Data were combined on cross-section level according to the principle shown in Figure 3. For each X-ray cross-section, the corresponding 3D cross-section was located and inserted into a simulation model of the X-ray scanner. Since both scanners are located along a common carrier line, right next to each other, it was assumed that the rotational position of the logs did not change between the scanners.

Vibrations do however introduce an uncertainty in the exact horizontal and vertical position of each cross-section. Thus the positions of the 3D cross-sections are being individually adjusted in order to achieve best possible matching with X-ray cross-sections.

Once the 3D cross-section has been properly positioned in the simulation model, the travel path lengths through the wood for photons hitting each detector pixel are being calculated. With knowledge of the radiated X-ray spectrum as well as the absorption and travel length along each ray path, the average density at each ray path is being calculated (cf. Grundberg et al. 1990) and arranged together as a density profile of the cross-section.





Simulating an X-ray LogScanner from CT data

In order to validate the travel path algorithms and the density profiles calculated, as well as to allow for further algorithm development classifying knot whorls, rot and other internal artefacts, well defined source data is essential. A data set suitable for this purpose is the Swedish pine stem bank, a collection of more than 600 CT-scanned Scots pine logs. These logs are well defined regarding knot structure and other quality parameters and CT images are available for every 10 mm of the log.

When developing the X-ray LogScanner, Grundberg and Grönlund (1995) wrote algorithms that could simulate LogScanner data using CT images from the Swedish pine stem bank. The implementation however had become obsolete due to computer platform change and due to higher resolutions now being available for both CT images and LogScanners. Thus a new simulation code was written, better suited for the demands of this project.

The new simulation code was verified by the X-ray scanning of a knot rich sawlog at the host sawmill. The sawlog was then brought to the tomography lab at Luleå University of Technology in Skellefteå where it was scanned with the same settings used for the Swedish pine stem bank. Rotational position of the log was kept track of, so that it could be scanned at the same position in both equipments. LogScanner data could then be simulated and compared to the data actually collected at the sawmill. The access to the full set of CT, X-ray LogScanner and 3D data for the same log also allowed for comparison between calculated density profile and actual density of the log.

RESULTS AND DISCUSSION

Travel path compensation

The study presented in this report has focused on the development of algorithms that combine raw data from 3D and X-ray scanners at an earlier stage in order to obtain improved density profiles of the logs. A comparison between raw X-ray LogScanner data and travel path compensated data is shown in Figure 4. A preliminary evaluation of the method show advantages as well as disadvantages of performing calculations on travel path compensated data rather than raw data.

Great advantages include the possibility to compensate for log shape irregularities and that the method enables direct reading of density from the images. This should make it easier to compare logs of different sizes and facilitate the development of general algorithms. It should also be easier to determine the heartwood border and the heartwood content and better measures of heartwood and sapwood densities can be expected.

The main difficulty lies in the step of finding the right 3D shape for a given X-ray cross-section. Firstly, there is some uncertainty in the identification of correct 3D cross-section and secondly there is also an uncertainty in the exact position of the log at the X-ray scanner. Furthermore the method transfers measurement errors from the 3D scanner into the X-ray data, e.g., an underestimate of the log diameter would cause an overestimate of the density profile of the cross-section. For this reason, extra care must be taken when looking for small artefacts ranging over a few slices, such as knot whorls, so that any localized measurement errors do not compromise the data.



Figure 4. (a), (b): Raw LogScanner data, X-ray absorption depends on density as well as travel path. (a) shows the full data range whereas (b) shows a zoomed data range, better exposing internal artefacts as well as the varying absorption along the log due to varying diameter. (c): Travel path compensated LogScanner data showing the density profile of the log. Uncertainty in the combination of 3D and X-ray data can be seen as bright or dark radial lines at the edge of the log, where the relative uncertainty of the travel path is greatest.

Density calculations

Figure 5*a* presents a density profile of a single cross-section within the log as well as an average over five neighbouring cross-sections. The average green density along a ray path in the sapwood area of the log is 1.0 g/cm³, which corresponds quite well to the true green density measurements obtained from the CT image (Figure 5*b*), ranging from 0.90 g/cm³ (inner sapwood) to 1.0 g/cm³ (outer sapwood).





Figure 5. (a): Green density profile of a log cross-section, the dotted line shows a single cross-section and the solid line shows an average over five neighbouring cross-sections. (b): CT image showing the corresponding log cross-section. Dark pixels represent low density while bright pixels represent high density.

The average green density, ρ_a , along rays passing through the heartwood area of the log is around 0.83 g/cm³. This figure is a combination of heartwood, ρ_h , and sapwood, ρ_s , densities along the rays:

$$\rho_a = h \cdot \rho_h + (1 - h) \cdot \rho_s$$

The difficulty lies in finding a good estimate of the percentage of path being travelled through heartwood, *h*. The algorithm finding this percentage is yet to be completed but preliminary calculations may be performed using estimated values. Looking at the density curve (Figure 5*a*), heartwood diameter can be estimated to be around 45% of the total diameter (90 pixels vs. 200 pixels). Thus, green density of heartwood close to the pith would be around 0.62 g/cm³. For a ray passing further out from the centre of the log, e. g., having an *h* value of 33%, heartwood green density would be about 0.48 g/cm³. Measurements within the CT image reveal a true heartwood density ranging from 0.50 g/cm³ close to the sapwood up to 0.60 g/cm³ close to the pith.

Although being performed only at a single position of a single log, these preliminary calculations suggest that green density values obtained by the method are not unreasonable. Further material for testing may be obtained by CT-scanning small parts of industrially scanned logs or by simulations from the stem bank (see below).

LogScanner simulations from CT

Figure 6 shows a comparison between industrially gathered and simulated X-ray LogScanner data, the agreement between the images being very good. This strongly supports the stance that simulation of LogScanner data from well defined CT images is a suitable method of obtaining source data for the development of X-ray LogScanner algorithms.



Figure 6. LogScanner data from an industrial installation (left). LogScanner data simulated from CT images (right).

CONCLUSIONS

This preliminary study has concluded that the combination of X-ray and 3D data using travel length compensation is a very promising technique for determining a density profile of the log. The technique will also facilitate the development of general algorithms for characterization of inner properties of sawlogs.

Preliminary green density values obtained for both heartwood and sapwood seem reasonable. However, more work need to be spent on development of rigorous methods for finding the heartwood density and final algorithms must be tested on a larger data material.

It has also been concluded that X-ray LogScanner data simulated from CT images well correspond to data from actual industrial installations. Even though being unaffected by vibrations and other disturbances experienced in industrial environment, such simulations constitute a very good tool for the development of X-ray LogScanner algorithms.

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Paper II



ORIGINAL ARTICLE

Heartwood diameter measurements in *Pinus sylvestris* sawlogs combining X-ray and three-dimensional scanning

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Abstract

Quality sorting of sawlogs based on three-dimensional (3D) or X-ray scanning or a multivariate combination of variables from both methods may be used to decrease the production of off-grade products carrying unwanted combinations of dimension and grade. There is, however, potential for further improving the sorting accuracy if 3D and X-ray raw data are combined at an early stage using path length compensation. From the measured 3D shape, a good estimate of the length of each X-ray path through the log can be made, enabling the calculation of a log density profile from the measured X-ray attenuation. The effect of this technique on heartwood diameter measurements of 423 Scots pine (*Pinus sylvestris* L.) logs was evaluated. By the addition of 3D data to the X-ray data it was possible to raise the predictability of the heartwood diameter from $R^2 = 0.84$ to 0.95 and to improve the root mean square error from 17 mm to 9.3 mm, primarily because of the enhanced contrast between heartwood and sapwood.

Keywords: 3D scanning, heartwood content, heartwood diameter, Pinus sylvestris, quality sorting, sawlogs, X-ray scanning.

Introduction

Reasons for quality sorting of sawlogs

For a long time, sawmills have had a strong focus on productivity. The standard methods of improving profits have been either making efforts to improve volume recovery or increasing the volume of sawlogs passing through the mill per time unit. Today, competition for sawlogs is fierce and raw material costs are rising, comprising an increasingly large amount of the total costs of the mill.

Consequently, it is becoming ever more important for sawmills to focus on value recovery and quality of sawn products rather than just outgoing volumes. One way of doing this is sawing products carrying specific combinations of dimension and grade that better correspond to customer demands and thus yield better value.

Heartwood content and wood quality

One of the most important wood quality parameters for Scots pine (*Pinus sylvestris* L.) is the heartwood content. Pine heartwood has a naturally low moisture content and low nutrient content, and contains toxic extractive compounds, giving the heartwood a better natural durability than sapwood (e.g. Taylor et al., 2002). Thus, for pine, heartwood is preferred to sapwood in applications where high durability and low water uptake are important, e.g. window frames. The durability of the heartwood may also eliminate the need for preservatives, making the heartwood an environmentally friendly alternative to impregnated wood.

Sorting based on heartwood content

The heartwood content of sawn goods may be measured using laser systems (Oja et al., 2006), near-infrared spectroscopy (Flæte & Haartveit, 2003), ultrasonics (Hyvärinen, 2007) and ultraviolet light (Oja & Berg, 2006; Skog, 2006). Such techniques allow grading of sawn goods according to heartwood content and may also help to adjust the wood-drying process. At this stage of the process, however, the lumber dimensions have already been

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determined, and a significant amount of off-grade products, goods carrying unwanted combinations of dimension and grade, may have been produced.

The problem with off-grade products may be addressed before sawing by the selection of suitable logs for each product. The selection of suitable logs can be made at the stand level using forest inventory data. Several authors have related heartwood diameter to parameters such as tree diameter, age, growth rate and climate (e.g. Sellin, 1994; Björklund, 1999; Wilhelmsson et al., 2002). However, since every tree is a unique individual, every batch of logs will contain a significant variation in log properties. Thus, forest inventory data alone may at best aid in choosing appropriate felling areas, but do not contain information accurate enough to guarantee of heartwood-rich the production products (Björklund, 1999).

To achieve high production rates of desired products while efficiently using raw materials, quality sorting of sawlogs must consequently be done at an individual level. In Sweden, quality sorting of logs at most large pine sawmills is performed using optical three-dimensional (3D) scanners, which are able to predict the quality of sawn goods from variables such as taper and bumpiness (e.g. Grace, 1994; Jäppinen & Nylinder, 1997; Oja et al., 1999). Still, the quality information obtainable from 3D scanners is limited, since it is based solely on outer shape properties of the log. Additional information about the heartwood content may be found by photographic inspection of log ends, with the heartwood elicited using infrared light (Arnerup, 2002; Gjerdrum & Høibø, 2004), ultraviolet light (David et al., 1993) or staining techniques (David et al., 1993). Alternatively, the inner properties of the whole log may be examined. This can be done using nuclear magnetic resonance, microwaves, ultrasound or gamma rays, but Grundberg (1994) concludes that the best technique for internal scanning of sawlogs is X-rays.

X-ray scanning of sawlogs

X-ray scanning of sawlogs by computed tomography (CT) is too slow for industrial applications. Instead, industrial X-ray scanners use a limited number of fixed measurement directions (e.g. Aune, 1995; Grundberg & Grönlund, 1995).

Oja et al. (2004) compared the grading performances of X-ray and 3D scanning techniques and found that grading could be improved further by the combination of variables from both methods in a partial least squares (PLS) model. It was also concluded that future studies should focus on fully

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utilizing the combination of data from 3D and X-ray scanning.

It was shown early on that path length compensation can be used to improve images from X-ray scanners and that the best compensation is obtained when using the true shape of the log (Grundberg et al., 1990). Since the true shape of the log is not known in practice, log shape data from a 3D scanner should be used instead as they provide the best approximation available. The combination of 3D and X-ray scanning using path length compensation was investigated by Skog and Oia (2007). X-ray path lengths through the log were estimated from the measured 3D shape. The path lengths were then combined with the measured X-ray attenuation yielding a green density profile of the log. The path-length-compensated X-ray technique (called 3D X-ray hereafter) was found to be promising for determining a density profile of the scanned log. From such a density profile it should be possible to locate the heartwood border with improved precision and to calculate a better estimate of the heartwood diameter than when using solely X-ray data (referred to as X-ray only method).

The aim of this study was to refine the 3D X-ray technique described by Skog and Oja (2007) and to investigate the possibility of improving heartwood diameter measurements by the use of this combination of 3D and X-ray data. A successful combination of 3D and X-ray scanning techniques would add extra value to the installation of an X-ray scanner at a sawmill, since most mills already have a 3D scanner present.

Materials and methods

Data collection

A large sawmill in the north of Sweden was chosen as host for the project, and a one-directional RemaLog X-ray scanner (Anon., 2008b) was installed next to the MPM Engineering 3D optical scanner (Anon., 2008a) in the log-sorting station (Figure 1). In total, 435 debarked green Scots pine sawlogs, originating from 13 different diameter classes in the range 150-300 mm, were picked out and individually ID marked. The top heartwood diameter of each log was manually measured in a direction selected to avoid extreme values in the case of oval or otherwise irregular heartwood shape. Subsequently, all logs were scanned and raw data from both log scanners were recorded. The 3D scanner measured the crosssectional shape of the log every 20 mm and the X-ray scanner measured the attenuation of X-rays through the log every 13 mm at a resolution of 576 pixels per cross-section (Skog & Oja, 2007).



Figure 1. Log scanners used when collecting log data: MPM Engineering 3D optical scanner (left) and a one-directional RemaLog X-ray scanner (right).

Combining 3D and X-ray data using path length compensation

The 3D X-ray algorithms combining raw data from the 3D and X-ray scanners using path length compensation were developed using the mathematical programming language Matlab (Anon., 2006). Data were combined on the cross-sectional level according to the principle shown in Figure 2. For each X-ray cross-section, the corresponding outer shape of the log, as measured by the optical 3D scanner, was identified and inserted into a simulation model of the X-ray scanner.

Since both scanners are located along a common carrier line, around 1 m apart (Figure 1), it was assumed that the rotational position of the log did not change between the scanners. Vibrations did, however, introduce an uncertainty as to the exact translational position of each cross-section. Thus, the position of every 3D cross-section was individually adjusted in the horizontal and vertical direction to achieve the best possible match with the X-ray cross-section. Once a 3D cross-section had been properly positioned in the simulation model of the X-ray scanner, the paths from the X-ray source to the centre of every detector pixel were intersected with the 3D cross-section, thus yielding the path length travelled through wood for photons arriving at every detector pixel (Figure 2a).

The mass thickness x of the log was obtained from the intensity I measured by the X-ray detector using the logarithmic relation $x = c_1 - c_2 \ln(I)$. This relation had previously been calibrated using data from a sawlog that had been scanned in the industrial X-ray log scanner as well as in a CT scanner, as described by Skog and Oja (2007). The mass thickness value for each detector pixel was then divided by the corresponding path length obtained from the 3D cross-section data, yielding the average green density along the X-ray path incident at that pixel (Figure 2b). Finally, the average densities along all rays in all cross-sections were arranged together as a green density profile of the log.



Figure 2. Principle for path length compensation of X-ray data using log shape information from an optical 3D scanner. (a) Simulation model of a one-directional X-ray log scanner, showing the measured X-ray attenuation through the log cross-section (grey line). The outer shape of the cross-section, as measured by an optical 3D scanner, is inserted into the simulation model and the path lengths through wood of X-rays hitting each detector pixel are calculated (black line). (b) The path-length-compensated X-ray cross-section (black line) is calculated by combination of the measured X-ray attenuation (grey line) and the calculated path lengths.

Calculating the heartwood diameter

The combined 3D X-ray data comprise average green density profiles for every cross-section of the log. Each such density profile was smoothed by an average filter, and derivatives were formed. The inflection points α of the smoothed profile, carrying the minimum derivative within region A and the maximum derivative within region B, were located. The heartwood border β in each region of the profile was then selected as the pixel where the tangent line through the inflection point equals the average sapwood density (Figure 3).

The heartwood content of each cross-section was then calculated as the ratio between the heartwood size and the log size. Subsequently, the heartwood content at the top of the log was calculated by linear extrapolation from the heartwood contents of all knot-free cross-sections within 250–2000 mm from the top end of the log.

Top heartwood content of the logs was also calculated using X-ray data only. These values were obtained using the existing software for the X-ray log scanner (Grundberg & Grönlund, 1995; Anon., 2008b).

The top heartwood diameter predictions for both the 3D X-ray and the X-ray only methods were calculated by multiplication of the top heartwood content by the top diameter obtained with the 3D optical scanner.



Figure 3. Path-length-compensated X-ray cross-section of a Scots pine log, describing an average green density profile of the log. A and B = valid regions when looking for the two heartwood borders of the cross-section; α = inflection point carrying the minimum derivative within region A and the maximum derivative within region B, respectively; β = heartwood border in each region, selected as the point where the tangent line through the inflection point equals the average sapwood density.

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The obtained top heartwood diameter predictions were compared with the manually measured top heartwood diameters, and linear models were developed, for which predictability (R^2) and root mean square error (RMSE) values were calculated.

Results

Of the total of 435 scanned logs, one (0.2%) had to be removed owing to a bad 3D measurement. The X-ray images of all logs for which both prediction methods reported errors greater than 25 mm compared with manual measurements were carefully inspected and 11 (2.5%) of these logs had to be removed from the study since the X-ray images made it certain that the manually measured heartwood diameters were incorrect. This left a total of 423 logs that could be used for further analysis.

When using only the top diameter from the 3D scanner in combination with the heartwood content from the existing X-ray log scanner software, it was found that the heartwood diameter could be predicted with an accuracy of $R^2 = 0.84$ and RMSE = 17 mm (Figure 4). When combining 3D and X-ray data using path length compensation, 421 of the 423 logs (99.5%) had their heartwood diameter predicted with a high accuracy, $R^2 = 0.95$ and RMSE = 9.3 mm (Figure 5). The remaining two logs (the outliers in Figure 5) were studied, and it was found that these measurements were affected by a poor match between 3D and X-ray data. These errors do not fall within the scope of Gaussian statistics and



Figure 4. Top heartwood diameters for 423 Scots pine logs, manually measured versus predictions using one X-ray direction (X-ray only method).

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Figure 5. Top heartwood diameters for 423 Scots pine logs, manually measured versus predictions using one 3D path-lengthcompensated X-ray direction. The two outliers (\times) were excluded when calculating R^2 and RMSE.

should not be used when calculating R^2 and RMSE. Yet, were the outliers included, accuracy would drop to $R^2 = 0.94$ and RMSE = 10.3 mm.

Discussion

This study has shown that combining X-ray and 3D data using path length compensation is a suitable technique for improving the accuracy of Scots pine heartwood diameter measurements when using a one-directional X-ray log scanner. When using only the X-ray log scanner, the minimum number of measurement directions is two; otherwise the scanner is not able to differentiate between a small object close to the X-ray source and a larger object farther away from the source. Receiving information on object size from the 3D scanner, the X-ray log scanner is, however, able to function with only one measurement direction, as shown in this study and by Oja et al. (2004). Whereas this study gives clear answers on the potential of combining 3D and X-ray data, possible benefits from using a second perpendicular X-ray direction have yet to be studied. The greatest advantages would, however, include the ability to detect irregularly shaped heartwood and better precision when positioning 3D cross-sections in the X-ray scanner simulation model. Any measurement uncertainty introduced by tree ovality can also be expected to decrease when the method is adapted for use with two measurement directions.

When predicting the top heartwood diameter the total RMSE was found to be 9.3 mm using the 3D

X-ray method and 17 mm using the X-ray only method. These errors are a combination of uncertainties originating from several sources, e.g. the manually measured reference values, the top diameter measurements of the 3D scanner, the use of a single X-ray direction and the location of the heartwood border in the X-ray data.

Eleven logs were removed owing to errors in the manually measured heartwood diameter. Some of the errors were typing errors, but most errors probably originated from difficulties in locating the exact heartwood border by eye. The manual heartwood diameter was measured in a direction avoiding extremes due to heartwood ovality and other shape irregularities, however, it is possible that some of the manual reference values used when developing the model contain relatively large errors. Thus, a significant part of the total RMSE can be assumed to stem from uncertainty in the reference values of the model.

The top diameter predictions of the 3D scanner can be assumed to be of high accuracy, with a standard deviation of less than 1 mm during repeatability tests (Grundberg et al., 2001). Thus, contributions from the 3D scanner are not significant to the total RMSE.

The use of a single measurement direction for the collection of X-ray data leads to a significant measurement uncertainty in the heartwood content when the heartwood shape is irregular. This error is of the same type as the error observed when measuring log diameter using a one-directional shadow scanner, which is reported to have a standard deviation of around 2–4 mm (Grundberg et al., 2001).

However, the greatest contribution to the RMSE values of both prediction methods can be concluded to originate from the heartwood border detection. This is also where the 3D X-ray method improves relative to the X-ray only method. It was found that the greatest reason for the improvement in the heartwood diameter predictions when adding the 3D data was an increased stability in the heartwood border detection due to the enhanced contrast between heartwood and sapwood. Manual examination of the X-ray images of the problem logs for the X-ray only algorithm reveals that most of these logs suffer from poor contrast between heartwood and sapwood, i.e. low moisture content gradient that may be caused, e.g. by dry sapwood or high density of the green heartwood.

Uncertainty in the 3D X-ray method arises when trying to combine 3D and X-ray cross-sections that do not match properly. This may be caused by a change in log rotation, errors in the axial positioning of the cross-sections or artefacts in the 3D shape of the log, possibly caused by bark or branches sticking out from the log. Mismatching data can cause a difference between actual and calculated ray path lengths, which in turn tends to cause peaks close to the edges of the calculated density profile, where the relative error is largest. To avoid such peaks being mistakenly identified as the heartwood border, the outermost 5% of the density profile was disregarded when looking for the heartwood border. This did not cause the algorithm to miss any true heartwood borders and at the same time eliminated most of the adverse effects at the edges. In some cases, however, it was found that peaks at the edges extended more than 5% into the log, which is why measurement errors tend to overestimate the heartwood content of individual cross-sections.

In the highly unlikely case of a poor match between 3D and X-ray data throughout the whole of a log, the heartwood content of most crosssections may settle close to an overestimated average. This is the case for the two outlier logs presented in Figure 5, which received poor heartwood diameter estimates from the 3D X-ray algorithm.

Future work includes expanding the algorithms for use with two X-ray directions. The possibility of using the developed algorithms for heartwood diameter measurements on Norway spruce and for improving the accuracy of other quality-sorting parameters, e.g. heartwood and sapwood densities and the detection of rot, needs to be investigated.

In summary, this study has shown that the combination of X-ray and 3D data using path length compensation is a successful technique for improving the accuracy of heartwood diameter measurements on Scots pine. For a one-directional X-ray log scanner, it was possible to raise the predictability of the heartwood diameter from $R^2 = 0.84$ to 0.95 and to improve the RMSE from 17 mm to 9.3 mm. This improvement was found to be primarily the result of the enhanced contrast between heartwood and sapwood, especially valuable for logs with a low moisture content gradient at the heartwood-sapwood border.

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Paper III

Combining X-ray and Three-Dimensional Scanning of Sawlogs – Comparison between One and Two X-ray Directions

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Abstract

In many sawmills, presorting of sawlogs is based on data from optical three-dimensional (3D) scanners. The use of X-ray log scanners is also becoming increasingly common and most sawmills installing an X-ray scanner already have a 3D scanner present.

It is in this paper demonstrated how data from oneand two-directional X-ray scanners can be combined with 3D scanner data using path length compensation. Examples show how the resulting images may be processed in order to predict quality parameters such as heartwood diameter and green heartwood density.

Using the proposed method, it is possible to improve the accuracy of these important quality sorting parameters using existing equipment. This will improve the presorting at sawmills, thus reducing the production of off-grade products carrying unwanted combinations of dimension and grade.

1. Introduction

Presorting of sawlogs according to dimension, e.g., using an optical three-dimensional (3D) scanner, may be used to make the sawing process more efficient. By presorting, the need of changing sawing pattern between individual logs is reduced and the handling of sawn goods is simplified since the number of board dimensions produced simultaneously decreases.

Using a 3D scanner, it is also possible to make some predictions on the quality of sawn goods from variables such as taper, crook and bumpiness [2, 5, 7]. However, since wood is a biological material, there may still be large variation between the properties of wood sawn from two logs of similar outer shape. In order to determine internal quality properties of the log, such as heartwood content [9], density [9], knot structure [3, 10], or annual ring width [1, 13] an industrial X-ray log scanner may be used.

Quality sorting of sawlogs helps the sawmill to produce more homogenous products. The ability to predict specific properties of sawn goods prior to Johan Oja

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sawing also makes it possible to reduce the production of off-grade products, carrying unwanted combinations of dimension and grade. For instance, logs with large heartwood diameter can be selected for sawing to window components or other products where the low water uptake of the heartwood is especially beneficial.

In Europe, 3D scanners are extensively used for the presorting of sawlogs. Recently, many sawmills have invested in X-ray log scanners, which are commonly being installed in conjunction with the 3D scanner. Thus, it is relevant to investigate potential gains by combining the two scanning techniques. Oja et al. [8] compared the grading performances of X-ray and 3D scanning techniques and found that grading could be improved by the combination of variables from both methods in a partial least squares (PLS) model.

Skog and Oja [11, 12] described how raw data from 3D and X-ray scanners can be combined using path length compensation. Since the mass attenuation coefficient is approximately constant throughout the log [6], the X-ray attenuation measured by the X-ray scanner depends almost exclusively on the mass thickness, i.e., the product of the ray path length travelled through wood and the average density along the path. The log shape measured by the 3D scanner can be used to estimate the path lengths, and so it is possible to calculate an average density profile of the log. The path-length-compensated X-ray (3D X-ray) 3D technique was tested with a one-directional X-ray log scanner in an industrial set-up and it was found that the method could be used to calculate the heartwood diameter in Scots pine (Pinus sylvestris L.) sawlogs with improved accuracy. The predictability was raised from $R^2 = 0.84$ to 0.95 when compensating the X-ray data with the 3D path lengths [12].

The aim of this study was to adapt the 3D X-ray method for use with two-directional X-ray log scanner data, since this is the most common scanner layout. The one- and two-directional 3D X-ray methods have been evaluated by comparison of the accuracy (R^2) in the calculation of two important quality sorting variables in Scots pine, heartwood diameter and heartwood density.

2. Materials and Methods

Data set

In previous studies, the 3D X-ray technique has been tested on industrial data from a 3D scanner and a onedirectional X-ray scanner and compared to manual heartwood diameter measurements [11, 12].

In this study, a dataset with well defined density was required. The Scots pine logs of the Swedish stem bank [4] were chosen for this purpose. For these logs, crosssectional computed tomography (CT) images are available every 40 mm, giving a good knowledge of the green density of the logs. There were however no industrial scanner data available for these logs, instead the 3D and X-ray log scanner data have been simulated from the CT images.

Outer shape data was derived from the CT images of the logs [4] and two-directional X-ray log scanner data was simulated from the CT images according to the principle described by Grundberg and Grönlund [3], using the implementation by Skog and Oja [11]. The log scanner images were simulated at 12 bit depth with 576 pixels per cross-section and a cross-sectional distance of 40 mm. In this study, ideal simulations without bark and artificial noise in 3D and X-ray data have been used.

Combination of 3D and X-ray data

Cross-sectional data from the 3D and X-ray scanners were combined according to the principle described by Skog and Oja [12]. For each X-ray cross-section, the corresponding outer shape of the log, as measured by the optical 3D scanner, was identified and positioned in a simulation model of the X-ray scanner, and so it was possible to calculate the path lengths through wood of X-rays hitting each detector pixel, Figure 1a.

In this study, X-ray log scanner data with one and two measurement directions have been used. The use of two X-ray directions constrains the position of the 3D cross-section, and thus simplifies the positioning. The border of the log in the X-ray data is defined as the outermost pixels where the X-ray intensity is below the maximum value and corresponds to path lengths through wood of approximately 55 mm, a figure that varies with the moisture content of the wood. When using two directions, the 3D cross-section is positioned so that the path length at all four X-ray borders is as equal as possible. When using one X-ray direction, the position of the log is only constrained in one dimension. In this case, the cross-section is placed so that the path length through wood equals 55 mm at both X-ray borders.



Figure 1. Principle for path length compensation of X-ray data using log shape information from an optical 3D scanner. (a) Simulation model of a two-directional X-ray log scanner, showing the measured X-ray attenuation through the log cross-section (grey line). The outer shape of the cross-section, as measured by an optical 3D scanner, is inserted into the simulation model and the path lengths through wood of X-rays hitting each detector pixel are calculated (black line). (b) The path-length-compensated X-ray attenuation (grey line) and the calculated path lengths. Similar calculations are being performed for detector 2.

The mass thickness x along any ray path through the log can be obtained from the intensity *I* measured by the X-ray scanner using the previously calibrated logarithmic relation $x = c_1 - c_2 \ln(I)$. By dividing the mass thickness by the corresponding path length calculated from the 3D shape, the average green density along that ray path is obtained, Figure 1b. Finally, the average green densities along all rays in all crosssections were arranged together as a green density profile of the log.

Locating the heartwood border

The combined 3D X-ray data comprise average green density profiles for every cross-section of the log, one for each measurement direction. At the edges of such a profile, the average density is high since the X-rays arriving at these pixels have been passing through moist sapwood only. In the centre of the profile, the average density is lower, since these rays have been passing through both sapwood and heartwood, see Figure 2 and Figure 3.

In order to locate the heartwood border β in such a profile, the profile was smoothed using an average filter and the inflection points α of the smoothed profile were located. The heartwood border β in the profile was then selected as the pixel where the tangent line through the inflection point equals the average sapwood density, as shown in Figure 2 [12].



Figure 2. Path-length-compensated X-ray cross-section of a Scots pine log, describing an average green density profile of the log. A and B = valid regions when looking for the two heartwood borders of the cross-section; α = inflection point carrying the minimum derivative within region A and the maximum derivative within region B, respectively; β = heartwood border in each region, selected as the point where the tangent line through the inflection point equals the average sapwood density [12].

Calculation of heartwood diameter

The heartwood content of an individual cross-section was then calculated as the ratio between the heartwood size and the log size and an average was formed for the two measurement directions. Eventually, the heartwood content at 1000 mm from the top end of the log was calculated by linear interpolation of the heartwood contents of all knot-free cross-sections within 300–2500 mm from the top end of the log. The heartwood diameter was then determined by multiplication of the heartwood content and the 3D diameter at this position.

The obtained heartwood diameter prediction was compared to the true heartwood diameter, which was obtained from the parameterized CT images of the logs [4]. The median of the heartwood diameters at 950, 1000 and 1050 mm from the top was used as reference, in order to reduce the uncertainty at knot whorls.

Calculation of heartwood density

In the region between the log border and the heartwood border, the rays pass only through sapwood, Figure 3. A quarter of this sapwood region (the rays situated within 45–70% of the region width, seen from the log border) was used to form an average sapwood density at every cross-section. Finally, the sapwood density was median filtered over ± 10 cross-sections.

For every cross-section, the heartwood border in both measurement directions was used to estimate an oval heartwood shape. In the case with only one X-ray direction, the heartwood was assumed to be centered and of the same size when being viewed from a second perpendicular measurement direction. From the estimated shape, the path length through heartwood was calculated for every ray and the share h of the path travelled through heartwood was then calculated by division by the previously calculated total path length through wood for the ray.



Figure 3. 3D cross-section of a log with an estimated oval heartwood shape inscribed. The dashed lines show example X-ray paths through sapwood only (1.) and through sapwood and heartwood (2.). The path length through wood of a ray is s and the path length through heartwood along the ray is $h \times s$.

A value for the green heartwood density ρ_h was then calculated for every ray passing through the heartwood. This value was calculated from the average green density ρ_a along the ray using the relation:

$$\rho_a = h\rho_h + (1-h)\rho_s \tag{1}$$

where ρ_s is the green sapwood density along the ray and h is the share of the path being travelled through the heartwood [11]. As an approximation for the local sapwood density ρ_s the median filtered average sapwood density of the cross-section was used.

An average green heartwood density $\rho_{h,avg}$ was calculated for the centermost third of the heartwood rays in each cross-section and a linear model was developed using the $\rho_{h,avg}$ values of all knot-free cross-sections. The predicted heartwood density $\rho_{h,pred}$ of the log was then determined by evaluation of the linear model 400 mm from the butt end of the log.

Finally, the predicted densities of all logs were compared to reference values measured in CT images. As reference, the average green heartwood density measured in a knot-free cross-section located around 400 mm from the butt end of each log was used.

3. Results and Discussion

Heartwood diameter

In the previous 3D X-ray study [12] the heartwood diameter predictions of the logs were compared to manual measurements at the top end. In this study, however, the reference heartwood diameter values were determined from CT images of the logs, which offer a sharp contrast between heartwood and sapwood of Scots pine in green condition. To avoid problems with drying at the log ends, the reference heartwood diameter was taken 1000 mm from the top end.

A total of 553 Scots pine sawlogs were evaluated and Figure 4 shows the relation between the reference values and the 3D X-ray predictions obtained using only one X-ray direction. With this setup, it was possible to predict the heartwood diameter of all logs except of one with high accuracy, $R^2 = 0.987$ and root mean square error RMSE = 4.5 mm. The problematic log was a large butt log with diameter around 400 mm throughout most of the log, causing the simulated X-ray detector to touch bottom. Since this log is out of the measurable range it should be disregarded. Yet, was this outlier included, accuracy would drop to $R^2 = 0.980$ and RMSE = 5.7 mm.

These values should be compared to the values previously obtained using industrial data, $R^2 = 0.95$ and RMSE = 9.3 mm, excluding outliers [12]. There are two main reasons for the improvement in accuracy observed relative to the industrial case. Firstly, there is a higher accuracy in the reference values for the heartwood diameter used in this study and secondly, in these ideal simulations the uncertainty associated with finding the matching 3D cross-section for every X-ray cross-section is eliminated. This suggests that predictions of the



Figure 4. Heartwood diameter 1000 mm from top end in 553 Scots pine logs, measurement in CT images versus predictions using one 3D path-length-compensated X-ray direction. The outlier (x) is an oversize butt log.



Figure 5. Heartwood diameter 1000 mm from top end in 553 Scots pine logs, measurement in CT images versus predictions using two 3D path-length-compensated X-ray directions.

measurement accuracy in an industrial application could be improved by adding artificial noise and uncertainty in the cross-section matching to these simulations.

When using two X-ray directions, the heartwood diameter of all logs could be predicted with an accuracy of $R^2 = 0.991$ and RMSE = 3.8 mm, as shown in Figure 5. These values include also the oversize butt log mentioned above, since it was possible to get a better view of it from the second measurement direction.

This means that, except for one outlier, the heartwood content of a sawlog as a whole could be predicted with similar accuracy using one or two X-ray directions. This was an unexpected result, since, for an individual cross-section, the uncertainty in heartwood content due to heartwood shape irregularities is higher when using only one measurement direction. It seems however, that this uncertainty becomes less important when inspecting a larger part of the log, probably because heartwood shape irregularities average out over a distance and do not affect the linear model that was used to predict the heartwood content.

Green heartwood density

The average CT density of the green heartwood was manually measured in 553 Scots pine logs. When using only one X-ray direction it was possible to predict the green heartwood density of 547 of the logs with an accuracy of $R^2 = 0.73$ and RMSE = 35 kgm⁻³, as shown in Figure 6. When using two X-ray directions, the accuracy improved to $R^2 = 0.80$ and RMSE = 30 kgm⁻³ for 548 of the logs. The logs failing to be predicted (circa 1%) were all large butt logs. This was an expected behaviour, since for too big log diameters the X-ray detector touches bottom and when this happens, density cannot be calculated.

It was found that the use of two X-ray directions greatly improved the accuracy of the calculated green heartwood densities. This was expected, since proper calculation of the heartwood density requires a good estimate of the share of the ray path travelled through heartwood, h in equation (1). As seen in Figure 3, the value of h for ray 2 very much depends on the heartwood content measured in the perpendicular measurement direction. Thus, the use of only one X-ray direction introduces significant uncertainty in the



Figure 6. Green heartwood density 400 mm from the butt end in 547 Scots pine logs, average values from CT images versus predictions using one 3D path-lengthcompensated X-ray direction.



Figure 7. Green heartwood density 400 mm from the butt end in 548 Scots pine logs, average values from CT images versus predictions using two 3D path-lengthcompensated X-ray directions.

density calculations. However, it should be noted that the density results obtained using the 3D X-ray technique with one X-ray direction are still of tolerable accuracy for many purposes and are comparable to results obtained using a two-directional X-ray log scanner without path length compensation [9].

4. Conclusions

It was found that the ideal simulations used in this study yield somewhat higher precision than corresponding measurements in an industrial set-up. Still, from these simulations it can be concluded that 3D path length compensation of X-ray data is a suitable technique for calculation of both heartwood diameter and green heartwood density.

The heartwood diameter of the log as a whole could be predicted with similar accuracy using one or two Xray directions, around $R^2 = 0.99$ and RMSE = 4 mm. Accuracy in heartwood density predictions on the other hand improved significantly when using two X-ray directions, from $R^2 = 0.73$ and RMSE = 35 kgm⁻³ to $R^2 = 0.80$ and RMSE = 30 kgm⁻³.

The 3D X-ray technique has potential for application with both one- and two-directional X-ray scanners and the possibility of determining dry density and moisture content in heartwood and sapwood are suitable topics for future studies.

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Paper IV



ORIGINAL ARTICLE

Density measurements in *Pinus sylvestris* sawlogs combining X-ray and three-dimensional scanning

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Abstract

Wood density is an important quality variable, closely related to the mechanical properties of the wood. Precise wood density measurements in the log sorting would enable density sorting of logs for products such as strength-graded wood and fingerjointed wood. Density sorting of logs would also give more homogeneous drying properties and thus improve the quality of the final products. By compensating the radiographs from an X-ray log scanner for the varying path lengths using outer shape data from a three-dimensional (3D) scanner, it is possible to make precise estimates of both green and dry density. Measurements on simulated industrial data were compared with densities measured in computed tomographic (CT) images for 560 Scots pine (*Pinus sylvestris* L.) logs. It was found that green sapwood density could be measured with predictability $R^2 = 0.65$ and root mean square error (RMSE) of 25 kg m⁻³. Green and dry heartwood densities were measured with similar precision: $R^2 = 0.79$ and RMSE = 32 kg m⁻³ for green density and $R^2 = 0.83$ and RMSE = 32 kg m⁻³ for dry density.

Keywords: Heartwood, log sorting, path-length compensation, quality sorting, sapwood, Scots pine, wood density.

Introduction

Wood density as an indicating property

Density is an important variable for the mechanical properties of the wood. In the European standard for strength classes of structural timber (EN 338; CEN, 2009), density is one of the three gradedetermining properties. The other two are bending strength and modulus of elasticity in bending, both related to density (e.g. Kollmann & Côté, 1968). Wood density is also important for determining the strength in joints using connectors such as screws, nails and nail plates (EN 1995-1-1; CEN, 2004). Thus, for sawmills that are strength grading the sawn wood, the ability to sort logs based on density would help to reduce the production of rejects, products not meeting the desired strength grade. Instead, wood of lower density could be sawn to other dimensions that are not being graded according to strength.

For softwoods such as Scots pine (*Pinus sylvestris* L.), the dry density of the wood is also closely

related to growth variables such as latewood percentage and annual ring width (Björklund & Walfridsson, 1993; Zhang, 1995; Wilhelmsson et al., 2002). For finger jointing, long internode length between knot whorls is a desired property, while at the same time, wood with large ring width sometimes need to be avoided because of reduced mechanical properties (Zhang, 1995). Thus, the dry density of the wood could be a suitable indicating property for avoiding logs inappropriate for finger jointing.

Density is also related to the drying properties of the wood. It is known that, below the fibre saturation point (FSP), high-density wood is more difficult to dry and requires longer drying times. Thus, variations in wood density can result in relatively large variations in the final moisture content of the planks (Esping, 1992). In the sapwood, most water is contained as free water, and the initial moisture content can vary considerably. The green sapwood density could be used as an indicator of the amount of water in the

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sideboards, and thus the time needed for the capillary drying phase.

Wood density and moisture content

The ratio between the mass of water, m_{water} , and the mass of wood substance, m_0 , is known as the moisture content, u:

$$u \equiv m_{\rm water}/m_0. \tag{1}$$

For green wood of Scots pine, the average moisture content is 35% in the heartwood and 105–160% in the sapwood (Esping, 1992).

At moisture content u, the total mass, m_u , of a piece of wood is the sum of the mass of wood substance, m_0 , and the mass of water, m_{water} :

$$m_u \equiv m_0 + m_{water} = (1 + u) \cdot m_0.$$
 (2)

Added water up to the FSP binds to the cell walls and causes swelling of the wood. Above FSP, the water fills cell cavities and does not cause any further swelling of the wood. The oven-dry volume of a piece of wood is V_{0} , and the volume V_u at moisture content u is given by:

$$V_u = (1 + \alpha_u) \cdot V_0, \tag{3}$$

where α_u is the volumetric swelling coefficient of the wood at *u*. Because the wood swells linearly up to the FSP, the swelling coefficient at any *u* can be calculated as:

$$\alpha_u = \alpha_{\max} \cdot u / u_{\text{FSP}} \text{ for } u < u_{\text{FSP}}, \tag{4a}$$

$$\alpha_u = \alpha_{\max} \text{ for } u \ge u_{FSP},$$
 (4b)

where α_{max} and u_{FSP} are the swelling coefficient and the moisture content at FSP. For Scots pine, the average value for α_{max} is 14.2% (Esping, 1992), and u_{FSP} is around 28% (Kollmann & Côté, 1968).

The changing mass and volume of wood have given rise to several common definitions of wood density. In this paper, dry density, $\rho_{0,0}$, and green density, $\rho_{u,w}$ are used and are defined as:

$$\rho_{0,0} \equiv m_0 / V_0, \tag{5a}$$

$$\rho_{u,u} \equiv m_u / V_u = \frac{1+u}{1+\alpha_u} \rho_{0,0}.$$
 (5b)

Density measurements using computed tomographic scanning

In a computed tomographic (CT) scanner, the transmission of X-rays through the object is measured in a large number of directions and a CT image of the X-ray attenuation μ throughout

the object is reconstructed using back-projection (Cormack, 1963; Hounsfield, 1972). In medical CT scanners, the linear X-ray attenuation coefficient μ in each reconstructed volume element (voxel) is normalized by the corresponding attenuation coefficient through water, μ_{w} . The normalized value is referred to as the CT number and is defined as:

$$CT number = 1000 \times (\mu - \mu_w)/\mu_w.$$
(6)

This value is closely related to the density in the voxel, since the linear attenuation coefficient μ is the product of the density $\rho_{u,u}$ and the mass attenuation coefficient μ_{m} , which is a material property:

$$\mu = \mu_{\rm m} \rho_{u,u}.\tag{7}$$

Lindgren (1991) showed that μ_m is approximately constant for dry wood and that μ_m of water is about 5% larger than $\mu_{\rm m}$ of dry wood. This means that $\mu_{\rm m}$ of green wood will vary slightly with moisture content. Lindgren (1991) also investigated the relationship between CT number and wood density and showed that density of wood can be measured with a 95% confidence interval of $\pm 4 \text{ kg m}^{-3}$ for dry wood and $+ 13 \text{ kg m}^{-3}$ for green wood using a CT scanner. The major contributor to the measurement error observed for green wood (at least + 6 kg m⁻³) was the uncertainty in mass attenuation of green wood caused by the difference in μ_m between dry wood and water. The accuracy when measuring the same set of samples using a balance and a vernier calliper was about 2.5 kg m^{-3} .

Density measurements using industrial X-ray scanning

To improve scanning speed, industrial X-ray scanners use only a limited number of fixed measurement directions (Aune, 1995; Grundberg & Grönlund, 1997). The most common solutions on the market are two-directional X-ray log scanners, producing two radiographic images perpendicular to each other as the log is fed through the scanner (Figure 1).

These X-ray radiographs are collected using photodiode arrays, detecting the intensity of the X-rays arriving at each pixel in the array. The intensity I_{tot} transmitted through the log along any given ray path is:

$$I_{\text{tot}} = \int_{E_{\min}}^{E_{\max}} I_0(E) \cdot e^{-\mu_m(E)\rho_{av}t} dE,$$
(8)

where E_{\min} and E_{\max} define the photon energy range of the X-ray source, $I_0(E)$ is the intensity of the incident beam, $\mu_m(E)$ is the mass attenuation coefficient of the wood at photon energy E, ρ_{av} is the average density along the ray path, and t is the path length through the wood. The integral in eq. (8) can



Figure 1. Schematic of the two-directional X-ray log scanner described by Grundberg and Grönlund (1997), producing two radiographs perpendicular to each other as the log is fed through the scanner.

be discretized to a sum of exponential equations, which can then be approximated with high accuracy by a single exponential. For a 160 kV tungsten X-ray tube, the transmitted intensity will be:

$$I_{\text{tot}} \approx \sum_{E=0}^{E=160\text{keV}} I_{0,E} \cdot e^{-\mu_m(E)\rho_{av}t} \approx I_{0,\text{eff}} \cdot e^{-\mu_{m,\text{eff}}\rho_{av}t}.$$
 (9)

where $I_{0,E}$ is the initial intensity of the photons within a narrow energy interval around the energy level *E*, and $I_{0,\text{eff}}$ and $\mu_{m,\text{eff}}$ are the effective initial intensity and mass attenuation, respectively.

The transmitted intensity is a function of the mass thickness x, which is the product of the average density ρ_{av} and the path length t. This means that the mass thickness corresponding to a measured intensity is found by solving eq. (9) for x:

$$x \equiv \rho_{\rm av} t = (\ln I_{0,\rm eff} - \ln I_{\rm tot}) / \mu_{\rm m,eff}. \tag{10}$$

Thus, it is possible to obtain an average density image of the log if the X-ray log scanner image is properly compensated for the varying path lengths through the log (Grundberg et al., 1990). The path lengths are calculated from the outer shape of the log, and an elliptical approximation of the outer shape can be estimated from the data of two- or three-directional X-ray scanners (Oja et al., 1998; Skatter, 1998). In this way, the average green density along each ray path can be calculated from the X-ray data.

Skog and Oja (2007), however, argued that pathlength compensation should be done using the best outer shape information available, namely log shape data from an optical three-dimensional (3D) scanner, which is frequently positioned right next to the X-ray scanner. The 3D path-length-compensated X-ray technique (3D X-ray) was found to be promising for determining an average density image of the scanned log. Such an image is made up of the average density profiles of each scanned cross-section of the log (Figure 2). From a 3D X-ray profile, the green sapwood density can be found by inspection of the pixels close to the edge of the log, where rays have passed only through sapwood. Green heartwood density cannot be found so easily, because



Figure 2. Three-dimensional path-length-compensated X-ray cross-section of a Scots pine log, describing an average green density profile of the log cross-section. α is the inflection point used to locate the heartwood border β in regions A and B, respectively (Skog & Oja, 2009).

all X-rays passing through the heartwood also travel through the sapwood. This implies that calculation of the green heartwood density requires knowledge of the green sapwood density and the heartwood content. It has been shown that high-accuracy measurements of the heartwood content in Scots pine sawlogs can be achieved using the 3D X-ray technique (Skog & Oja, 2009), meaning that this technique should also be suitable for density calculations in sawlogs.

Consequently, the aim of this study was to utilize the 3D X-ray technique for green density measurements of heartwood and sapwood and to apply these results in the calculation of dry density in Scots pine sawlogs, assuming a heartwood moisture content of 35%. All tests in this study were performed using simulated 3D and X-ray log scanners.

Materials and methods

Data basis

The development of density-calculation algorithms based on the 3D X-ray technique requires access to a set of sawlogs with well-defined green and dry densities. X-ray log scanner images and outer shape data from an optical 3D scanner must also be available for the logs.

The logs of the Swedish pine stem bank (Grundberg et al., 1995) meet the first of these criteria. The stem bank contains a total of 560 Scots pine sawlogs (165 butt logs and 395 upper logs), that have been CT scanned in green condition. Cross-sectional CT images are available every 10 mm within knot whorls and every 40 mm between whorls, giving a good knowledge of the green density of the logs. A disc was cut out from the butt end of every log, conditioned to 9% moisture content and then CT scanned again. From this CT image, the dry density of each log can be calculated.

For the stem-bank logs, there are no data available from industrial 3D and X-ray scanners. However, this problem can be sufficiently overcome, since data from both these scanner types can be simulated from the CT images. An overview of the study is given in Figure 3, showing how the stem-bank data have been used in each step of the described method.

Simulation of industrial scanner data

Outer shape data can easily be derived from the CT images of the logs (Grundberg et al., 1995). Because previous work (Skog & Oja, 2009) had been done on debarked logs, the bark was removed from the CT logs using a threshold filter before their outer shape was calculated. The outer shape was stored in standard 3D scanner format, with 72 radii per

cross-section and a cross-sectional distance of 40 mm. A normally distributed measurement error with 1.0 mm standard deviation was added to every radius.

Two-directional X-ray log scanner data were simulated from the CT images according to the principle described by Grundberg and Grönlund (1997) using the implementation by Skog and Oja (2007). The log-scanner images were simulated at 12-bit depth (4096 intensity levels) with 576 pixels per scan, each pixel corresponding approximately to 0.8 mm of log diameter. The distance between each cross-section measured was 40 mm. Artificial electronic noise, normally distributed with standard deviation of 0.8 times the square root of the intensity, was added to the signal. This noise level was chosen to correspond to the noise observed in industrial X-ray radiographs.

Calculation of reference values

The reference values for the green heartwood and sapwood densities were measured in CT images of the green logs. The average CT numbers were calculated over a segment of the heartwood and sapwood, respectively, and then converted to average densities using eqs (6) and (7). For each log, these measurements were done in a knot-free cross-section located 300–400 mm from the butt end of the log. This position was chosen to avoid drying at the log ends, but to be close enough to the butt end to enable comparison with the conditioned disc.

For each log, the average CT number was also measured in the CT image of the conditioned butt-end disc. The average was taken over a segment of the heartwood, avoiding cracks and other defects, and extending out to approximately 40% of the log radius. From this segment, the density at 9% moisture content was calculated using eqs (6) and (7) and then converted to the dry density using eqs (4a) and (5b).

Combination of three-dimensional and X-ray data

Cross-sectional data from the 3D and X-ray scanners were combined according to the principle described by Skog and Oja (2009). Because the incident intensity is constant and the mass attenuation coefficient is approximately constant, eq. (10) may be rewritten as:

$$x \equiv \rho_{av} t = c_1 - c_2 \ln I_{tot}, \tag{11}$$

where I_{tot} is the intensity level measured by the simulated X-ray log scanner and c_1 and c_2 are calibration constants relating the intensity to

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Figure 3. Overview of the study. Industrial scanner data were simulated from the stem bank data and then combined using the threedimensional (3D) X-ray method. Density predictions were calculated from the combined 3D X-ray data and compared with reference values taken directly from the stem bank. CT = computed tomography.

the corresponding mass thickness, as determined by a CT scanner.

For every X-ray cross-section, the matching 3D cross-section was identified and positioned in a simulation model of the X-ray scanner. The distance, *t*, travelled through wood was then calculated for every ray path, and by combining the mass thickness,

x, and the path length, t, according to eq. (11), the average green density, ρ_{av} , along each ray was obtained (Figure 4).

The 3D cross-section was positioned in the simulation model so that it matched the border of the log in the X-ray data, which is defined as the outermost pixels where the X-ray intensity is below



Figure 4. Principle for path-length compensation of X-ray data using log-shape information from an optical three-dimensional (3D) scanner. (a) Simulation model of a two-directional X-ray log scanner showing the measured X-ray attenuation through the log cross-section (grey line). The outer shape of the cross-section, as measured by an optical 3D scanner, is inserted into the simulation model, and the path lengths through wood of X-rays hitting each detector pixel are calculated (black line). (b) The path-length-compensated X-ray cross-section for detector 1 (black line) is calculated by combination of the measured X-ray attenuation (grey line) and the calculated path lengths.



Figure 5. Principle for calculation of the share h of the path length travelled through heartwood for X-rays passing through a cross-section of the log (black contour). (a) Estimated oval heartwood shape (grey) inscribed around the centre of the heartwood (cross). Solid lines = log borders from the X-ray data; dashed lines =heartwood borders from the three-dimensional path-length-compensated X-ray data. (b) Example X-ray paths passing through sapwood only (1) and through sapwood and heartwood (2). The path length through wood of a ray is s_s and the path length through heartwood is $h \times s$.

the maximum value. This border corresponds to path lengths through wood of approximately 55 mm, a figure that varies with the moisture content of the wood. In the paper by Skog and Oja (2009) a onedirectional X-ray log scanner was used. In this study, however, the use of an X-ray log scanner with two measurement directions was simulated. This simplified the positioning of the 3D cross-section, and it was placed so that the path lengths at all four X-ray borders were as equal as possible, but not necessarily 55 mm.

Density calculations

In the region between the log border and the heartwood border, the rays pass through sapwood only (Figure 5b). A quarter of this sapwood region (the rays situated within 45–70% of the region width, seen from the log border) was used to form an average sapwood density at every cross-section. Finally, the green sapwood density, $\rho_{\rm s}$, was median filtered over ± 10 cross-sections.

The heartwood border was calculated as described by Skog and Oja (2009). For every cross-section, the heartwood borders in both measurement directions were used to estimate an oval heartwood shape (Figure 5a), and the path length travelled through heartwood was calculated for every ray (Figure 5b).

A value for the green heartwood density, ρ_h , was then calculated for every ray passing through the heartwood. This value was calculated from the average green density, ρ_a , along the ray using the relation:

$$\rho_a = h\rho_h + (1-h)\rho_s,\tag{12}$$

where ρ_s is the green sapwood density along the ray and *h* is the share of the path being travelled through the heartwood (Skog & Oja, 2007). As an approximation for the local sapwood density, ρ_s , the median filtered average sapwood density of the cross-section was used.

An average green heartwood density, $\rho_{h,avg}$, was calculated for the centremost third of the heartwood rays in each cross-section, and a linear model was developed using the $\rho_{h,avg}$ values of all knot-free cross-sections in the log. The predicted green heartwood density, $\rho_{h,pred}$, of the log was then determined by evaluation of the linear model 400 mm from the butt end of the log, the position where the green reference values had been measured (Figure 6).



Figure 6. Top: Average density image of the log. For each crosssection, the average green heartwood density is calculated over the centremost third of the heartwood area. Knot whorls (black rectangles), butt end and top end of the log are excluded from the calculation areas (white). Bottom: Average green heartwood density in each cross-section (dots). The green heartwood density 400 mm from the butt end (circle) is calculated using a linear regression model (dashed) of the cross-sectional values.





Figure 7. Green sapwood density for 560 Scots pine sawlogs. Measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional log scanner data, including artificial noise. Separate linear regressions for butt logs and upper logs have been used.

Finally, a prediction for the dry heartwood density, $\rho_{0,\text{pred}}$, of the wood at this position was calculated. This value was obtained from eq. (5b) assuming the heartwood moisture content of all logs to be 35% and the volume swelling to be 14.2% (eq. 4b). No attempts to predict the dry density of the sapwood were made in this study.



Figure 8. Green heartwood density for 553 Scots pine sawlogs. Measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional log scanner data, including artificial noise. Separate linear regressions for but logs and upper logs have been used.



Figure 9. Dry heartwood density for 553 Scots pine sawlogs. Measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional log scanner data, including artificial noise. One common linear regression has been used for both butt logs and upper logs.

Evaluation of results

All calculated densities (from simulated X-ray and 3D log scanner data) were compared with the corresponding reference CT measurements and evaluated using simple linear regression models (Figures 7–10). Two modelling cases were evaluated. In the first case, all logs were included in one common regression, and



Figure 10. Dry heartwood density for 553 Scots pine sawlogs. Measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional log scanner data, including artificial noise. Separate linear regressions for butt logs and upper logs have been used.

in the second case, separate regressions were used for butt logs and upper logs. The precision of the density predictions was evaluated by calculation of coefficient of determination (R^2) and root mean square error (RMSE).

A sensitivity analysis was performed to determine how different sources of artificial noise and input errors affect the outcome of the density calculations. Four types of noise and errors were evaluated: electronic noise in the X-ray data (X), uncertainty in the cross-sectional 3D shape (3D), a positioning error with standard deviation of 60 mm in the lengthwise matching between the 3D and X-ray cross-sections (z), and increased distances between the 3D crosssections. All density calculations were performed without any artificial noise, using only X noise, using X and 3D noise and using X, 3D and z noise. The effect of increased distances in the 3D data was evaluated for the final two of these noise combinations by including only every second or every third 3D cross-section in the calculations. Three equivalent sets of 3D noise and three equivalent sets of z noise were tested, giving a total of nine equivalent noise combinations when using both 3D and z noise. More details on the properties of the X and 3D noise are given in the section Simulation of industrial scanner data.

Results

Green sapwood density

For all 560 logs, the mean value of the reference green sapwood density (measured in a CT crosssection 300–400 mm from the butt end of each log) was 1031 kg m⁻³ and the standard deviation was 43 kg m⁻³. The best prediction of the reference values was obtained when using the mean sapwood density of the log as an explanatory variable. When using the results from the 3D X-ray calculations without any artificial noise, the reference green sapwood densities of all 560 logs were predicted with a linear regression giving an R^2 of 0.64 and an RMSE of 26 kg m⁻³. The sapwood-density calculations behaved in a similar manner for butt logs and upper logs: when separate linear regressions were used for butt logs and upper logs, the precision only improved slightly, to $R^2 = 0.66$ and RMSE = 25 kg m⁻³.

The sensitivity analysis showed that the precision of the green sapwood density calculations was very stable for all types of noise evaluated: noise in the X-ray images, noise in the 3D shape, uncertainty in the matching of the 3D and X-ray cross-sections, and increased distances between the 3D cross-sections (Table I). The values in Table I are averages of the R^2 and RMSE values obtained using three equivalent sets of random 3D noise and three equivalent sets of poor lengthwise matching between the 3D and X-ray cross-sections. A representative example including all types of noise and using every second 3D cross-section is shown in Figure 7. The same set of noise is used throughout Figures 7–10.

Green heartwood density

For all 560 logs, the mean green heartwood density was 562 kg m⁻³ and the standard deviation was 70 kg m⁻³. When using no artificial noise and one linear regression for all logs, the green heartwood density, measured in a CT cross-section 300–400 mm from the butt end of the log, could be predicted with a precision of $R^2 = 0.81$ and RMSE = 30 kg m⁻³ for 555 (99.1%) of the 560 logs. The logs failing to be predicted were all large butt logs and upper logs, the precision improved slightly, to $R^2 = 0.82$ and RMSE = 29 kg m⁻³.

When noise was added to the simulations, the precision decreased slightly. Still, between 553 and 555 logs (98.9%–99.1%) could be predicted. The most severe types of noise were uncertainty in the 3D cross-sectional shape, increasing the average RMSE by 0.7 kg m⁻³, and the distance between 3D cross-sections, increasing the average RMSE by about 1 kg m⁻³ when every second 3D cross-section

Table I. Precision in green sapwood density calculation using separate models for butt logs and upper logs.

Artificial noise	All 3D c-s		Every 2nd 3D c-s		Every 3rd 3D c-s	
	R^2	RMSE (kg m^{-3})	R^2	RMSE (kg m $^{-3}$)	R^2	RMSE (kg m $^{-3}$)
None	0.657	25.1				
Х	0.655	25.1				
X+3D	0.655	25.1	0.655	25.2	0.656	25.1
X+3D+z	0.646	25.5	0.646	25.5	0.646	25.5

Notes: Noise types: X = electronic X-ray noise; 3D = uncertainty in cross-sectional three-dimensional (3D) shape; z = uncertainty in lengthwise matching of 3D and X-ray cross-sections. Values using all, every second and every third 3D cross-section (c-s) are tabulated. R^2 and root mean square error (RMSE) values including 3D noise and z noise are average values obtained using three equivalent sets of 2D noise (i.e. a total of nine equivalent combinations of 3D and z noise).
	All 3D c-s		Every 2nd 3D c-s		Every 3rd 3D c-s	
Artificial noise	R^2	RMSE (kg m $^{-3}$)	R^2	RMSE (kg m $^{-3}$)	R^2	RMSE (kg m $^{-3}$)
None	0.819	29.4				
Х	0.812	29.7				
X+3D	0.805	30.4	0.796	31.0	0.780	32.4
X+3D+z	0.802	30.6	0.788	31.6	0.779	32.5

Table II. Precision in green heartwood density calculation using separate models for butt logs and upper logs.

Notes: Noise types: X = electronic X-ray noise; 3D = uncertainty in cross-sectional three-dimensional (3D) shape; z = uncertainty in lengthwise matching of 3D and X-ray cross-sections. Values using all, every second and every third 3D cross-section (c-s) are tabulated. R^2 and root mean square error (RMSE) values including 3D noise and z noise are average values obtained using three equivalent sets of 3D noise and three equivalent sets of z noise (i.e. a total of nine equivalent combinations of 3D and z noise).

was used and another 1 kg m^{-3} when every third 3D cross-section was used (Table II). An example including all types of noise and using every second 3D cross-section is shown in Figure 8.

Dry heartwood density

For all 560 logs, the mean value of the dry heartwood density (measured in a CT cross-section at the butt end of each log) was 480 kg m⁻³ and the standard deviation was 78 kg m⁻³. The dry heartwood density was estimated using the same prediction value as the green heartwood density, rescaled assuming 35% moisture content. In the case with no artificial noise and one linear regression for all logs, the dry heartwood density could be predicted with a precision of $R^2 = 0.77$ and RMSE = 37 kg m⁻³. When using separate linear regressions for but logs and upper logs, the precision improved significantly, to $R^2 = 0.85$ and RMSE = 30 kg m⁻³.

When noise was added to the simulations, precision in the dry heartwood density also decreased slightly. The most severe noise types were the electronic X-ray noise and the use of every third 3D cross-section (Table III).

Examples including all types of noise and using every second 3D cross-section are shown in Figure 9 using one common linear regression for butt logs and upper logs and in Figure 10 using separate linear regressions for butt logs and upper logs.

Discussion

In this study, simulated X-ray and 3D scanner data were used. For the results presented here to be valid in an industrial setting, it is vital that the simulations are valid. Both simulation of X-ray scanner data (Grundberg & Grönlund, 1997) and calculation of outer shape data (Grundberg et al., 1995) from CT images are well-established techniques. However, the combination of both scanning techniques also needs to be simulated in a realistic way. Therefore, sparse 3D data and poor lengthwise matching between X-ray and 3D data were also included in the sensitivity analysis. The sensitivity analysis showed that the sapwood density calculations, being log averages, were almost impervious to all types of noise. The heartwood-density calculations, in contrast, were more sensitive to noise. Especially severe was the use of only every second or every third 3D cross-section, increasing the average RMSE by about 1 or 2 kg m⁻³, respectively. This is probably because the cross-sectional distance of the simulated data was 40 mm. If all 3D cross-sections are not used, the distance, and thus the shape difference, between neighbouring 3D cross-sections will be significant. In an industrial set-up, however, X-ray scanners

Table III. Precision in dry heartwood density calculation using separate models for butt logs and upper logs.

	All 3D c-s		Every 2nd 3D c-s		Every 3rd 3D c-s	
Artificial noise	R^2	RMSE (kg m $^{-3}$)	R^2	RMSE (kg m $^{-3}$)	R^2	RMSE (kg m $^{-3}$)
None	0.845	30.4				
Х	0.830	31.3				
X+3D	0.827	31.8	0.829	31.4	0.813	33.4
X+3D+z	0.827	31.8	0.826	31.7	0.812	33.5

Notes: Noise types: X = electronic X-ray noise; 3D = uncertainty in cross-sectional three-dimensional (3D) shape; z = uncertainty in lengthwise matching of 3D and X-ray cross-sections. Values using all, every second and every third 3D cross-section (c-s) are tabulated. R^2 and root mean square error (RMSE) values including 3D noise and z noise are average values obtained using three equivalent sets of z noise (i.e. a total of nine equivalent combinations of 3D and z noise).

typically have cross-sectional distance of about 10 mm and 3D scanners about 20 mm, meaning that the effect of the number of X-ray and 3D crosssections not being 1 to 1 can be expected to be less severe. This also suggests that the precision of the density calculations when used in an industrial setting should not be worse than the precision obtained when using simulated data with every second 3D cross-section and all types of artificial noise. The algorithms proposed in this study have not vet been evaluated for logs measured on bark. However, since measurement on bark increases the uncertainty in the outer shape measurement, the precision in the density measurements can be expected to decrease somewhat. The effect of scanning on bark is a parameter that should be evaluated further when the algorithms are tested industrially.

For calculation of heartwood density, the density model was evaluated at the butt end of the log, because this was the position where reference values were available. For about 1% of the logs, it was not possible to obtain a heartwood density prediction at the butt end. The logs failing to be predicted were all large butt logs, which was expected, because for very large diameters, the X-ray signal becomes too weak to be detected. For log-sorting purposes, however, an average heartwood density for the whole log would perform well as a sorting variable. For large butt logs, the average could instead be taken over the upper part of the log, where it is still possible to detect the X-ray signal.

The use of separate linear regression models for butt logs and upper logs was found to be especially beneficial for the prediction of dry heartwood density. This is due to the lower moisture content and higher dry density in the butt logs compared with the upper logs (Esping, 1992), which affects the relation between the measured green density and the actual dry density. This was compensated for by the use of separate models for butt logs and upper logs.

Surprisingly, it was found that the green heartwood density, evaluated 400 mm from the butt end, $\rho_{h,pred}$, could be used to predict both green and dry heartwood CT reference densities with almost equal precision. Because the density prediction uses a linear model, which filters away local deviations, the error made when predicting the green heartwood CT reference density is probably caused by the local difference between the CT reference density and the modelled density, for example caused by local drying of the log. The error made when predicting the dry CT reference density is the sum of local dry density variations in the butt end of the log and the error made when assuming 35% heartwood moisture content for all logs. Since green and dry density prediction errors are of equivalent size, this indicates

that, for this set of logs, the heartwood moisture content varies at least as much within a log as between the logs.

The green sapwood density 400 mm from the butt end was best predicted using an average value for the whole log. This means that there is a considerable standard deviation involved in trying to predict the local sapwood density, probably caused by uncertainty both in the reference values and in the predicted values. Local drying of the log results in difficulties obtaining proper reference values using only one CT image. Uncertainty in the 3D shape and mismatching between 3D and Xray cross-sections cause local deviations in the sapwood density prediction, which are being averaged out over the log as a whole. The RMSE of the green sapwood density predictions $(25-26 \text{ kg m}^{-3})$ was better than the RMSE of both the green and dry heartwood density predictions, even though the sapwood predictions were made using a log average. This was expected, since the heartwood density calculations are more complicated. The small variation in green sapwood density (Figure 7), however, causes the R^2 of the green sapwood density (0.65-0.66) to be lower than the R^2 of the heartwood densities (0.78-0.85) (Figure 8).

In this study, no attempts were made to predict dry sapwood density. Because of the great variation in sapwood moisture content between individual logs (Esping, 1992), the correlation between green and dry sapwood densities is very low. The correlation between dry heartwood density and dry sapwood density is also weak, but could be worth investigating when developing a prediction model for dry sapwood density. This topic is, however, beyond the scope of this paper.

In this study, X-ray and 3D data, combined using path-length compensation, were used to predict the sapwood and heartwood densities within single cross-sections of the logs. These results need to be compared with predictions made using X-ray data only. Such calculations, based on industrial X-ray log scanner data, have been reported for Scots pine (Bellander, 2001) and Norway spruce (Oja et al., 2001b). For both species, the average dry density of the centre planks was predicted with a precision of R^2 between 0.5 and 0.6 and RMSE between 28 and 33 kg m⁻³. However, since average densities are not influenced by local variations, they are easier to predict, and consequently, those results cannot be directly compared with the current study. Oja et al. (2001a) report that green heartwood density measured in a single cross-section of Norway spruce logs can be predicted with a precision of $R^2 = 0.73$ and RMSE = 26 kg m⁻³ using a simulated X-ray log scanner. In that study, 7% of the logs (two

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out of 29) had been excluded as outliers. The R^2 values obtained in the current study are significantly better than those obtained in previous studies using X-ray scanning only, whereas the RMSE values are very similar in all studies. This indicates that the contrast gained by 3D path-length compensation of the X-ray data reduces the number of outliers, which is in line with the results observed for the heartwood diameter (Skog & Oja, 2009). In addition, the fact that the dry density of an individual cross-section in this study is calculated with a precision equal to or better than that previously been obtained for the average dry density strongly suggests that the precision of the dry heartwood density calculations has improved. This is reasonable, since it has previously been shown that 3D path-length compensation improves the heartwood diameter calculations significantly (Skog & Oja, 2009), and because heartwood diameter is one of the key inputs for calculating heartwood density (eq. 12), the heartwood density predictions should also gain from this method.

The RMSE value obtained for the dry heartwood density prediction (32 kg m^{-3}) is significantly lower than the standard deviation of the population as a whole (78 kg m⁻³). This means that sorting of logs according to predicted dry heartwood density would result in batches of logs with considerably less variation in density. This would, in turn, lead to more homogeneous properties of the final products and make it possible for the sawmills to improve yield in the strength grading, for example.

In summary, this study has shown that the combination of 3D and X-ray data using path-length compensation can be used to measure green sapwood density with a precision of $R^2 = 0.65$ and RMSE = 25 kg m⁻³, green heartwood density with a precision of $R^2 = 0.79$ and RMSE = 32 kg m⁻³, and dry heartwood density with a precision of $R^2 = 0.83$ and RMSE = 32 kg m⁻³ (including artificial noise and using every second 3D cross-section). Comparison with previous studies, using X-ray data only, indicates a significant improvement in the prediction of heartwood density.

Future work includes testing of the developed algorithms for logs scanned on bark, which is common in Sweden. The algorithms should also be tested with Norway spruce [*Picea abies* (L.) Karst.]. For spruce, strength grading is more common and, consequently, proper density measurements will be even more valuable than for Scots pine. The described method could also be used for estimation of sapwood moisture content or detection of severe rot and other defects affecting the wood density.

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Paper V

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ORIGINAL ARTICLE

Measuring heartwood diameter and density in *Picea abies* using X-ray and three-dimensional scanning

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Abstract

For Norway spruce (*Picea abies* (L.) Karst.), heartwood diameter and dry density of the wood are two important quality variables. In this study, 48 green Norway spruce sawlogs were scanned using industrial X-ray and optical three-dimensional (3D) log scanners and algorithms predicting the heartwood diameter and dry density from the industrial scanner data were developed. Reference measurements were taken in computed tomography (CT) images of the logs, collected in both green and oven dry condition.

It was concluded that path-length compensation is the key to high precision measurements of heartwood diameter and dry density, and that similar precision can be obtained by using compensation based on the outer shape aquired from 3D scanning and the outer shape aquired from X-ray scanning. Heartwood diameter can be measured with a coefficient of determination (R^2) of 0.95 and root mean square error (RMSE) of 9 mm and dry heartwood density can be predicted with R^2 of 0.78 and RMSE of 20 kgm⁻³.

Keywords: Density, heartwood, log sorting, path-length compensation, Norway spruce, quality sorting, sapwood

Introduction

Norway spruce (*Picea abies* (L.) Karst.)) is one of the dominating softwood species in Europe. Because spruce is often being used for construction purposes, strength grading is common. The strength grading is typically being performed on sawn boards using a strength grading machine. Brännström *et al.* (2007), however, concludes that it is possible to predict the strength of the boards already before sawing by means of an X-ray log scanner, and that such a strength prediction is on the same R^2 level as strength grading on the sawn boards.

One of the most important variables for X-ray based strength grading is the dry density of the wood. This means that an improved precision in the dry density prediction will lead to improved predictability of the strength. Also for strength grading of sawn boards, a good density prediction on the sawlog level is valuable. In the European standard for strength classes of structural timber EN 338 (CEN, 2009), density is one of the three grade-determining properties. The other two are bending strength and modulus of elasticity in bending, both related to density (*e.g.* Kollmann & Côté, 1968). If sawlogs were pre-sorted based on predicted lumber density, this would lead to more homogenous mechanical properties in the sawn goods and would reduce the amount of rejects in the strength grading.

Furthermore, density is related to the drying properties of the wood. It is known that, below the fibre saturation point, high-density wood is more difficult to dry and requires longer drying times. Thus, variations in wood density can result in relatively large variations in the final moisture content of the planks (Esping, 1992). Therefore, density pre-sorting is also expected to create a more even moisture content distribution in the final products.

Another interesting variable that could be used to pre-sort Norway spruce for special products is the heartwood diameter. Today, the potential of Norway spruce heartwood is rarely taken advantage of, to some extent because it is visually similar to the sapwood and also because its properties are not well known. However, scientific studies show that Norway spruce heartwood has both a lower water uptake (Sandberg & Salin, 2012) and a higher resistance to fungi growth compared to sapwood (Bergström *et al.* 2005, Sandberg 2008), making it suitable for outdoor applications.

Both heartwood diameter (Anon. 2000, Longetaud et al. 2007) and green density (Lindgren 1991, Skog & Oja 2010) can be directly detected in CT images of Norway spruce logs. This has made CT scanning an excellent choice as reference method within the wood science. Recently, the first high-speed CT log scanner for the sawmill industry has been introduced on the market (Giudiceandrea *et al.*, 2012), making it possible for sawmills to use the CT technique for log sorting and other applications. For many purposes, however, it should be sufficient to use more simple discrete X-ray log scanners (e.g. Aune 1995; Grundberg & Grönlund 1995). For instance, this type of scanners can be used to measure heartwood diameter (Oia et al. 2001a: Skog & Oja 2009) and heartwood density (Oja et al. 2001a) in green sawlogs of Scots pine (Pinus sylvestris L.) and Norway spruce. It has been shown that the precision in these measurements can be improved by path-length compensation using the outer shape obtained from optical 3Dscanners, a method that enhances the contrast between heartwood and sapwood (Skog & Oja, 2009, 2010). X-ray log scanners have also been used for predicting the dry density of centre boards sawn from Norway spruce logs, the precision reported is however pretty low with a coefficient of determination (R^2) around 0.5 and a root mean square error (RMSE) around 30 kgm⁻³ (Oja et al. 2001b). Because of the existence of intermediate wood in Norway spruce (Hillis 1987), the moisture content transition between heartwood and sapwood is less distinct in Norway spruce (Figure 1b) than in Scots pine (Figure 1a), making it more difficult to measure the heartwood diameter and density in spruce.

The hypothesis is that the contrast gained by applying path-length compensation will improve the precision of heartwood diameter and density measurement in Norway spruce. Consequently, the aim of this study is to develop path-lengthcompensated algorithms for measuring the heartwood diameter and dry density in Norway spruce, and to evaluate the algorithms on data collected in an industrial setting.



Figure 1: a) CT cross-section of a green Scots pine log. b) CT cross-section of a green Norway spruce log, used for reference measurement of heartwood diameter. The dotted line shows the largest ellipse that can be inscribed in the heartwood. c) CT cross-section of the same Norway spruce log after drying, used for reference measurement of dry density.

Norway spruce heartwood measurements



Figure 2: Principle for path-length compensation of X-ray data using log-shape information from either an optical 3D scanner or an X-ray scanner. a) Simulation model of a two-directional X-ray log scanner showing the measured X-ray attenuation through the log cross-section (grey line). The outer shape of the cross-section is inserted into the simulation model, and the path lengths through wood of X-rays hitting each detector pixel are calculated (black line). b) The path-length-compensated X-ray cross-section for detector 1 (black line) is calculated by combination of the measured X-ray attenuation (grey line) and the calculated path lengths.

Materials and methods

Data basis

A total of 48 Norway spruce logs of varying diameter and ring widths were selected at the log sorting station of a sawmill in northern Sweden. These logs were then scanned using the log scanning equipment of the sawmill, a RemaLog Bark® 3D scanner and a RemaLog XRay® X-ray scanner (Anon. 2013*a*).

From each log, a 30 cm long piece was cut from the top end. The green log pieces were brought to Luleå University of Technology were they were scanned using a Siemens Emotion Duo® (Anon. 2013b) computed tomography (CT) scanner. For each piece, one cross-sectional CT image located 20 cm from the log end was collected (Figure 1b). The log pieces were then dried to 0% moisture content in a 103 °C hot kiln, according to the standard EN 13183-1 (CEN, 2002). Finally, the dry pieces were CTscanned again at the same location as before drying. In order to facilitate the drying process, thinner discs had been cut out around the crosssection of interest and a radial cut had been made from the surface to the pith in order to allow for tension-free drying (Figure 1c).

Calculation of reference values

Reference values for the heartwood diameter were calculated from the green CT cross-sections as the largest ellipse that would fit into the heartwood of the log, as marked by the dotted line in Figure 1b.

Reference values for the green and dry heartwood densities were calculated from the average CT number in the heartwood section of the green and dry CT images respectively. When calculating the averages, care was taken to avoid including areas with knots and checks. The average CT numbers were then translated to density values as described by Skog and Oja (2010).

Calculations from industrial X-ray and 3D scanner data

For each log, values of heartwood diameter and green heartwood density were calculated using four different algorithms, see Table 1. Algorithm I is the original X-ray log scanner algorithm by Grundberg and Grönlund (1995), this algorithm uses X-ray data only and no path-length compensation. Algorithm II combines data from the X-ray and 3D scanners using path-length compensation (Figure 2) and was specifically

Table 1: Description of the four algorithms used for calculating the heartwood diameter and dry density of the heartwood.

Algorithm Algorithm		Path-length	Тор
number	name	compensation	diameter
I	Original X-ray	No	X-ray
П	3DX pine	3D	3D
Ш	3DX spruce	3D	3D
IV	X-ray spruce	X-ray	3D

developed for Scots pine (Skog & Oja 2009, 2010). Finally, a new algorithm (III, IV) was developed in this study by modifying algorithm II for use with Norway spruce. Algorithm III uses the outer shape obtained from the 3D scanner whereas algorithm IV uses an oval outer shape deducted from the two X-ray scanner projections when performing the path-length compensation; otherwise III and IV are identical.

The new spruce algorithm (III, IV) is based on calculations in cross-sectional density profiles (Figure 2b) obtained by compensating the X-ray attenuation data with path lengths calculated from the outer shape (algorithm III: 3D outer shape, algorithm IV: X-ray derived outer shape) of the log, as described for Scots pine by Skog and Oja (2010). The main difference relative to the pine algorithm (II) lies in the determination of the heartwood/sapwood border. The pine algorithm assumes a distinct border between heartwood and sapwood and consequently uses the maximum derivative of the density cross-sectional profile when looking for the border (Skog & Oja 2009). This assumption is not valid for Norway spruce, however. Instead, the heartwood/sapwood border is found by adaptive thresholding of the density profile (Figure 2b). The border is chosen as the first position where the density exceeds the average heartwood density by a predefined percentage. Because the average heartwood density in turn depends on the heartwood/sapwood border, an iterative solution is being applied in order to find the correct border. Once the heartwood/sapwood border is found, the green heartwood density in the crosssection is calculated using the same algorithm as for pine (Skog & Oja 2010).

When the heartwood/sapwood border and green heartwood density has been found for all cross-sections in the log, linear models of the heartwood content and the heartwood density along the log are developed. For algorithm III, only cross-sections with a high agreement between the 3D outer shape and the X-ray border are included in the models, whereas for algorithm IV all cross-sections are used because the X-ray outer shape always agrees with the X-ray border. The models are then evaluated at the top end of the log in order to find the heartwood content and the green heartwood density at the reference measurement positions. The top heartwood diameter is simply calculated by multiplying the top heartwood content by the top diameter measured by the 3D scanner. Finally, a prediction of the dry heartwood density of the wood at the top end is calculated from the green heartwood density as described by Skog and Oja (2010), assuming the heartwood moisture content of all logs to be 35% and the volume swelling to be 14.2%.

Results

Heartwood diameter

The top heartwood diameter of the logs calculated using the four different algorithms are shown in Figure 3. It is clear that algorithm I, the original X-ray log scanner algorithm, does not perform well at all for spruce, having a coefficient of determination (R^2) of only 0.583 and a root mean square error (RMSE) of 25 mm. Algorithm II, the 3D path-length compensated pine algorithm. performs much better with $R^{\bar{2}} = 0.900$ and RMSE = 12.3 mm. The best performance is found in the two spruce algorithms, with near identical precision, with $R^2 = 0.945$ and RMSE = 9.2 mm for algorithm III (3D path-length compensation) and $R^2 = 0.948$ and RMSE = 8.9 mm for algorithm IV (X-ray path-length compensation). In average, algorithm III was using 35% of the cross-sections in the calculations, for which a high agreement between 3D and Xray outer shape was found.

Dry heartwood density

For all 48 logs, the mean value of the dry heartwood density (measured in a CT cross-section 200 mm from the top end of each log) is 373 kgm⁻³ and the standard deviation is 43 kgm⁻³. The dry heartwood density can be predicted with a precision of $R^2 = 0.87$ and RMSE = 16 kgm⁻³ from the green density measured in CT cross-sections at the same location prior to drawing, Figure 4.



Top heartwood diameter in Norway spruce, CT reference values vs. predictions calculated using four different algorithms

Figure 3: Top heartwood diameters for 48 Norway spruce logs, manually measured in CT images vs. automatic predictions from 3D and X-ray scanner data. a) Uncompensated X-ray log scanner algorithm (I), b) 3D path-length compensated pine algorithm (II), c) 3D path-length compensated spruce algorithm (III), d) X-ray path-length compensated spruce algorithm (IV).

The density predictions from the four different algorithms are shown in Figure 5. Algorithm I, the original X-ray log scanner algorithm, is able to predict the density of 47 of the 48 logs with a precision of $R^2 = 0.466$ and RMSE = 32 kgm⁻³. There is one outlier, a log with very small heartwood. When including the outlier, precision drops to $R^2 = 0.306$ and RMSE = 38 kgm⁻³.

Algorithm II, the 3D path-length compensated pine algorithm, shows a high precision, $R^2 = 0.466$ and RMSE = 32 kgm⁻³. The accuracy, however, is poor and there is a systematic overestimate of the density by 34 kgm⁻³.

The two spruce algorithms have the best precision, with a slight difference in favor of the 3D path-length compensated algorithm III which reaches a precision of $R^2 = 0.778$ and RMSE = 20 kgm⁻³. The precision of the X-ray path-length compensated algorithm IV is $R^2 = 0.751$ and RMSE = 21 kgm⁻³.

Discussion

The pine algorithm which is used as the basis for the new spruce algorithms was developed using simulated X-ray and 3D scanner data (Skog & Oja 2010). In this paper, the algorithms have been evaluated on real scanner data collected at full production speed in a sawmill log sorting station, using logs scanned on bark. The current study makes it clear that the proposed methodology works also in an industrial setting and that scanning on bark does not impose a problem. This was expected, because both the 3D scanner and the X-ray scanner used in this study are designed to work well also when scanning on bark (Anon. 2013*a*). Comparing the results from the path-length compensated algorithms (II, III, IV) to the original X-ray log scanner algorithm (I), it is clear that the path-length compensation greatly improves the accuracy both in the heartwood diameter and in the dry density calculations. This result is in line with previous studies on Scots pine (Skog & Oja 2009, 2010). Skog and Oja (2009) conclude that the primary reason for the improvement is the gain in contrast between heartwood and sapwood obtained by application of the path-length compensation and that this is especially valuable for logs with low moisture content gradient at the heartwood-sapwood border. Because Norway spruce often has a region of intermediate wood



Figure 4: Heartwood density 20 cm from top end for 48 Norway spruce logs, manually measured in dry CT images vs. manually measured in green CT images.



Dry heartwood density in Norway spruce, CT reference values vs. predictions calculated using four different algorithms

Figure 5: Dry heartwood density 20 cm from top end for 48 Norway spruce logs, manually measured in CT images vs. automatic predictions from 3D and X-ray scanner data. a) Uncompensated X-ray log scanner algorithm (I), b) 3D path-length compensated pine algorithm (II), c) 3D path-length compensated spruce algorithm (IV).

between heartwood and sapwood, this explains why the increase in precision observed for Norway spruce in this study (heartwood diameter R^2 from 0.58 to 0.95) is even greater than what Skog and Oja (2009) reported for Scots pine (R^2 from 0.84 to 0.95). The largest part of the improvement for spruce (R^2 from 0.58 to 0.90) was found simply by applying the path-length compensated pine algorithm (II) by Skog and Oja (2009). By modifying the algorithm to include the finding of smaller changes in density, the precision for spruce could successfully be raised to the same levels previously observed for pine ($R^2 \approx 0.95$, RMSE ≈ 9 mm). Similar behaviour is found for the improvement of the dry density prediction.

Some interesting conclusions can be drawn by comparing the results from algorithms III and IV, i.e., the spruce algorithm with path-length compensation based on either 3D outer shape (III) or X-ray outer shape (IV). For heartwood diameter the results are in practice equivalent, and for dry density the results are only slightly in favour of the 3D outer shape version. This suggests that the great improvement is found by application of the path-length compensation and that obtaining exactly the right path lengths when performing the compensation is less significant. Generating an oval outer shape from the two Xray projections will inevitably produce small errors in the outer shape, but will still yield clear crosssectional density profiles (Figure 2) where the heartwood border can be found with high accuracy. The level of the curve will on the other hand be slightly offset, thus affecting the density calculations, but only to a small degree. Using the 3D outer shape gives better path lengths but comes with the drawback that combining mismatching 3D and X-ray cross-sections can reduce precision greatly (Skog & Oja 2009). This is why algorithm III in average is using only 35% of the cross-sections in the calculations, for which it is sure that a high agreement between 3D and X-ray data exists. It is therefore likely that the precision of the 3D and X-ray combination could be improved further by a better matching of the X-ray and 3D data. This could be achieved by, e.g., positioning the 3D and the X-ray scanner closer together and running them synchronously as one integrated system. In this study, two separate scanners were used and matching of the cross-sections was done using only a lengthwise position collected using the rotary encoder.

Lundahl *et al.* (2009) concludes that it is possible to produce Norway spruce heartwood products both efficiently and profitably, given a method for selecting suitable logs. The pathlength-compensated heartwood diameter calculations presented in this paper should be well suited for this purpose. Suitable uses for the spruce heartwood could be, e.g., outdoor claddings and noise barriers. Since the 100% heartwood products are not common on the market today, the challenge remains, however, for the producers to market them as premium goods and sell them at a high enough price.

The clear improvement in the dry density prediction presented in this study also opens up interesting opportunities. For sawmills interested in pre-sorting logs based on dry density, it will be possible to sort out larger volumes of high-density logs, making such a production strategy feasible in practice. Because of the strong relationship between the density and the mechanical properties of the wood, it should also be possible to predict the strength grade of the sawn goods with higher precision.

It is also well worth noticing that the density predictions presented in this study are for single cross-sections of the logs. Because single crosssection predictions are influenced by local variations, this means that even better precision should be expected if the proposed method is applied for the prediction of an average dry density of, e.g., the centre planks of the log.

In this study, manual measurements in medical CT images were used as reference and these can be expected to be very exact. Recently, an industrial CT scanner has been introduced on the market (Giudiceandrea et al., 2012). Such a scanner has slightly lower resolution than a medical scanner and comes with automatic image processing algorithms that are also associated with some uncertainty; nevertheless precision in both heartwood diameter and dry density should be higher for a CT scanner than for an X-ray scanner. The prediction of dry density in an industrial CT scanner is also based on measurement of the green density, meaning that the predictive power should be pretty close to the values observed for the medical CT scanner used as reference in this study, $R^2 = 0.869$ and RMSE = 15.5 kgm^{-3} (Figure 4). This means that a CT scanner will vield higher precision in log sorting than an X-ray scanner with the path-lengthcompensated algorithms proposed in this study. However, Berglund et al. (2013) argues that the best location for a CT scanner is in the saw line, where it can be used for optimizing the sawing position. In such a configuration, an X-ray scanner would be a good choice for pre-sorting of logs, making sure that the CT equipped saw line is fed with suitable logs. Alternatively, a CT scanner in the log sorting could be complemented by an X-ray scanner in the saw line which helps tracing each log from the CT to the saw line. Different modes of cooperation between X-ray and CT scanners is however a topic for future research.

In summary, this study shows that path-length compensation is the key to high precision measurements of heartwood diameter and density. Heartwood diameter can be measured with a precision of $R^2 = 0.95$ and RMSE = 9 mm and dry heartwood density can be measured with a precision of $R^2 = 0.78$ and RMSE = 20 kgm⁻³. The path-length compensation can be done using only X-ray data, which gives a simple and robust

system but will cause some uncertainty in density measurements when the outer shape is irregular. Compensation with 3D scanner data can offer better precision but is highly dependent on a good matching between data from the two scanners.

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Paper VI



ORIGINAL ARTICLE

Sapwood moisture-content measurements in *Pinus sylvestris* sawlogs combining X-ray and three-dimensional scanning

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Abstract

Because today's sawmill processes are not fully adapted to the variability of the raw material, it is crucial to sort sawlogs according to material properties in order to process the wood efficiently and to obtain high-quality end-products. One material property that could be used for sorting is the moisture content (MC) of the sapwood, an important parameter for both the processing and the end-products. Most sawmills use three-dimensional (3D) scanners to sort logs and some have also invested in X-ray scanners. Previous studies have shown that, by combining raw data from 3D and X-ray log scanners, green sapwood density and dry heartwood density in Scots pine sawlogs can be estimated. In this study, the method was used to estimate sapwood MC in green logs. It was found that the MC estimate could be used to separate the logs into groups with high and low MC, correctly classifying all logs with MC below 100% as low MC logs. Out of all logs, 70% were correctly classified. The MC estimate could also be compared to the dry density-dependent maximum MC and used to identify logs that have actually started to dry.

Keywords: 3D scanning, green density, log sorting, MC, Scots pine, X-ray scanning.

Introduction

Wood is a biological material with great variations in material properties between individual logs and within the same log. The wood industry of today deals with large volumes in an almost automatic process, which is not fully adapted to the variability of the raw material. Thus, the sawn wood also shows a great variability in material properties, and a large share of the production carries combinations of dimension and grade that do not meet customer requirements (Grönlund, 1992). To reduce the production of off-grade products, the sawlogs may be sorted according to specific material properties or predicted grade of the sawn goods before sawing. This enables the sawmill to saw each log into dimensions where the grade of the log is best utilized, thus improving the value of the sawn wood.

Sorting of logs or sawn goods according to certain material properties also helps the sawmill to adjust the process so that the wood can be processed efficiently and the highest possible quality of the end-products can be obtained. Heartwood content, wood density and sapwood moisture content (MC) are examples of properties important to the drying process. Boards with similar density and moisturecontent distribution show similar behaviour during drying, and by sorting the boards according to these parameters before drying, well-adapted drying schedules can be constructed with respect to time, energy consumption and quality of the final products. If the initial MC in the batch is known, over-drying can be reduced when using fixed schedules, and the finishing time can be predicted more accurately when using adaptive schedules (Larsson & Morén, 2003).

In the green sorting, heartwood content can be measured using, for example, laser systems (Oja *et al.*, 2006), and wood density and average MC can be measured using microwave scanning (Johansson *et al.*, 2003). Using these techniques, it is possible to sort the sawn goods with respect to drying

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properties. By this approach, however, the volumes sorted into each class is not known in advance, and consequently the production cannot be planned to achieve optimum filling in the kilns. To avoid this problem, it would be desirable to perform sorting based on drying properties earlier in the process at the log-sorting station.

In the log sorting, inner properties of logs such as heartwood content (Skatter, 1998; Oja et al., 2001) and density (Oja et al., 2001) can be measured using an X-ray log scanner. Most sawmills installing an X-ray log scanner already have an optical threedimensional (3D) scanner present, and it has been shown that the combination of both scanners can be used to sort logs with improved precision (Skog & Oja, 2009). The combined 3D X-ray method has been used to measure heartwood diameter (Skog & Oja, 2009), green sapwood density and dry heartwood density in Scots pine sawlogs (Skog & Oja, 2010). However, so far no method for measuring MC in the log sorting has been presented. The hypothesis of this study is that it should be possible to use dry heartwood density to estimate the dry sapwood density, and that the dry and green sapwood densities can be combined to obtain the sapwood MC in the log. Sorting the logs based on this information would result in batches with more homogeneous material properties, which would be helpful when optimizing the processing of the logs.

The aim of this study was to develop a sapwood MC calculation model and to evaluate the feasibility of this method for the sorting of sawlogs.

Materials and methods

Calculation of reference values

The development of MC calculation algorithms requires a set of sawlogs with well-defined green and dry densities. In this study, the computed tomographic (CT) scanned logs of the Swedish pine stem bank (Grundberg *et al.*, 1995) were used. The stem bank contains a total of 560 Scots pine sawlogs (165 butt logs and 395 upper logs), for which cross-sectional CT images are available every 10 mm within knot whorls and every 40 mm between whorls, giving a good knowledge of the green density in the logs. For each log, a reference value for the green sapwood density, $\rho_{u,u}$, was calculated by taking the average over the sapwood of a knot-free cross-section approximately 400 mm from the log end.

In the stem bank, CT images of discs cut from the butt end of every log and conditioned to 9% MC are also available. In these pictures, the average sapwood density at 9%, $\rho_{9,9}$, was calculated and used to find a reference value for the dry sapwood density, $\rho_{0,0}$. This value was calculated using the relation between the density, $\rho_{u,u}$ at MC *u* and the dry density, $\rho_{0,0}$:

$$\rho_{u,u} = \frac{m_u}{V_u} = \frac{(1+u) \cdot m_0}{(1+\alpha_u) \cdot V_0} = \frac{(1+u)}{(1+\alpha_u)} \rho_{0,0}$$
(1)

where m_u is the mass, V_u is the volume, and α_u is the volumetric swelling coefficient at MC *u*. The swelling coefficient was calculated using:

$$\alpha_u = \alpha_{\max} \cdot u / u_{\text{FSP}} \text{ for } u < u_{\text{FSP}}$$
(2a)

$$\alpha_u = \alpha_{\max} \text{ for } u \ge u_{\text{ESP}}$$
 (2b)

where α_{max} and u_{FSP} are the swelling coefficient and the MC at the fibre saturation point, respectively. The average values for Scots pine were used, α_{max} =14.2% (Esping, 1992) and u_{FSP} =28% (Kollman & Côté, 1968).

By inserting the reference values of the green sapwood density and the dry sapwood density in eq. (1) and using the swelling from eq. (2b), the reference value for the green sapwood MC u was found:

$$u = (1 + \alpha_{\max}) \cdot \rho_{u,u} / \rho_{0,0} - 1 \tag{3}$$

Prediction of sapwood moisture content using the 3D X-ray method

Industrial 3D and X-ray data for the logs were simulated from the CT images (Skog & Oja, 2010). The simulated data files were then combined using the 3D X-ray technique, and the average green sapwood density of each log was calculated as described by Skog and Oja (2010).

The dry heartwood density 400 mm from the butt end of each log was also calculated from the combined data (Skog & Oja, 2010), and two linear models predicting the dry sapwood density from the dry heartwood density were developed, one model for butt logs and one model for upper logs.

Finally, a prediction of the green sapwood MC was calculated by inserting the average green sapwood density and the predicted dry sapwood density obtained using the 3D X-ray method into eq. (3).

Evaluation of results

A linear correlation between the predicted and the reference sapwood MCs was developed and predictability (R^2) and root mean square error (RMSE) were calculated. A threshold value at 145% predicted MC was used to separate the logs into two groups with lower and higher MC, respectively. Calculated MCs were also compared to the theoretical maximum MC for saturated wood (Esping, 1992):

$$u_{\max} = \frac{1560 \text{kgm}^{-3} - \rho_{0,u}}{1.56 \cdot \rho_{0,u}} \tag{4}$$

where $\rho_{0,u}$ is the dry mass divided by the green volume. Using eqs (1) and (2b), $\rho_{0,u}$ was expressed in terms of the dry density, $\rho_{0,0}$:

$$\rho_{0,u} = \rho_{0,0} / (1 + \alpha_{\max}) \tag{5}$$

valid for MCs above the FSP. The average value of the swelling coefficient at fibre saturation was used, $\alpha_{\rm max} = 14.2\%$.

Results

For all 560 logs, the green density of the sapwood was predicted with a precision of $R^2 = 0.65$ and $RMSE = 25 \text{ kg m}^{-3}$ (Figure 1). The dry density of the sapwood was predicted with a precision of $R^2 = 0.47$ and RMSE = 43 kg m⁻³ for 553 (98.8%) of the logs (Figure 2). The seven logs that failed prediction were all large butt logs. When combining the predicted green and dry sapwood densities, the sapwood MC could be calculated with a precision of $R^2 = 0.29$ and RMSE = 21% (Figure 3).

The result when using the predicted MC to separate the logs into two groups is shown in Figure 4. The separation between the two groups is not very clear, but all logs with MC below 100% were correctly classified as dry logs. Out of all logs, 70% were correctly classified.

If the MC is plotted against the dry density (Figure 5), it can be seen that most of the observed



Figure 1. Sapwood green density in 560 Scots pine sawlogs: measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional (3D) log scanner data.



3D X-ray sapwood MC measurements

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Figure 2. Sapwood dry density in 553 Scots pine sawlogs: measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional (3D) log scanner data.

variation in MC is caused by the varying dry density of the logs. The MC follows a curve of the same shape as the theoretical maximum value (eq. 4), as shown by the solid line in Figure 5.

By comparing the calculated MC to the theoretical maximum, it should be possible to identify logs that have low MC due to drying of the sapwood. Figure 6 shows the ratio between calculated MC and maximum MC. The reference ratio measured in the



Figure 3. Sapwood moisture content in 553 Scots pine sawlogs: measurements in computed tomographic (CT) images versus predictions from simulated X-ray and three-dimensional (3D) log scanner data.



Figure 4. Observed sapwood moisture content (MC) (value from computed tomographic images) for 553 Scots pine sawlogs, separated into two classes depending on the sapwood MC predicted from simulated X-ray and three-dimensional log scanner data.

CT images could be predicted with a precision of $R^2 = 0.39$ and RMSE = 0.036.

Discussion

For Swedish sawmills, measurement of the sapwood MC would be most useful during periods when the logs may have been stored for extended periods in the forest, e.g. in spring. When the frost goes out of the ground, the roads become very soft and logs may have to be stored *in situ* for several weeks after felling until transport to the sawmills is possible. Because the logs start to dry immediately after felling, sapwood MC may vary significantly between individual



The method developed in this study offers a way of estimating the sapwood MC in sawlogs as they arrive at the log-sorting station. The RMSE of the sapwood MC estimate in the logs, 21.4% (Figure 3), is





Figure 5. Predicted moisture content as a function of estimated dry density in the sapwood of 553 Scots pine sawlogs. The solid line represents the theoretical maximum moisture content of saturated wood.

Figure 6. Sapwood moisture content (MC) relative to the theoretical maximum MC of saturated wood: measurements in CT images versus predictions from simulated X-ray and threedimensional log scanner data for 553 Scots pine sawlogs.

significantly larger than the RMSE obtained when using the alternative method, measurement of the MC in green boards using a microwave scanner (15.9%) (Johansson *et al.*, 2003). However, sorting of logs rather than boards is desirable because it facilitates planning of the production towards batches of optimum size for the kilns. In addition, for sawmills that decide not to sort the logs according to MC, a continuous measurement of the sapwood MC in the arriving logs would be of value, as it provides an important indication about when it is time to start adjusting the drying schedules.

In most of the logs, the predicted and reference values of the green sapwood density follow a linear correlation (Figure 1). For two of the logs, however, the green sapwood density in the reference crosssection is much lower than the predicted log average. This is probably caused by a local drying of the log around the reference cross-section. These two logs are also seen as outliers in Figure 6, with reference values below 0.6.

When predicting the dry sapwood density (Figure 2), seven (1.2%) of the logs failed prediction. These were all large butt logs, which was expected, because for very large diameters, the X-ray signal becomes too weak to be detected. In this study, the dry sapwood density was predicted from the dry heartwood density using linear correlation. Because this relation varies between butt logs and upper logs, two separate correlations were used. For the reference data used in this study, the predictability between dry heartwood and dry sapwood densities was found to be $R^2 = 0.57$. The dry heartwood density, in turn, can be predicted with $R^2 = 0.83$ using the 3D X-ray technique (Skog & Oja, 2010). This means that most of the observed uncertainty in predicting the dry sapwood density $(R^2 = 0.47)$ is due to the poor predictability between the dry heartwood and the dry sapwood densities.

When combining the predicted green and dry sapwood densities to find the sapwood MC, the predictability of the reference values was found to be quite low $(R^2 = 0.29, RMSE = 21\%)$ (Figure 3). Here, it should be noted that the reference values themselves contain some uncertainty. This is primarily because the reference MC was calculated by comparison of the dry density at the butt end and the green density 400 mm from the butt end. Dry CT images were only available at the butt end, but owing to local drying at the log ends, the green density reference could not be taken at the same position. Instead, a position 400 mm from the butt end was chosen for the green CT images to avoid the log end drying, but still to be as close to the end as possible. By choosing this position, the impact of local dry-density variations was minimized. However, especially for butt logs, there may still be a considerable dry density variation over the distance of 400 mm, causing some uncertainty in the reference values used.

The predicted MC was calculated by comparison of a dry sapwood density prediction evaluated 400 mm from the butt end of the log and the average green sapwood density of the whole log. The average sapwood density of the log was used because it was found to be the best available estimate of the green sapwood density 400 mm from the log end. This means that the prediction model tries to predict the average MC in the region around 400 mm from the log end, whereas the reference value is a mixture of two local values taken 400 mm apart. Thus, local variations at the log ends in both dry density and MC contribute to the uncertainty in the prediction of the sapwood MC presented in Figure 3.

Because the correlation between predictions and CT reference values is rather low, the method needs to be verified experimentally. If the green and dry reference densities were calculated for the same piece of wood, the MC references would be more precise, and so the actual amount of uncertainty in the predictions could be determined. Furthermore, testing the method on industrially scanned logs would show that the method is also applicable under industrial conditions.

Because the logs used in this study were all scanned directly after felling, the logs had not dried out, and most logs had an MC around the threshold value of 145% that was used for separation of the logs into groups in Figure 4. Thus, the separation between the two groups was not very clear. Figure 5 shows that most of the observed variation in MC was caused by varying dry density of the wood and not by drying of the logs. This means that sorting of the logs by MC, as illustrated in Figure 4, is not a good way to find logs that have low MC due to drying of the sapwood. Instead, the calculated MC could be compared to the theoretical maximum given by eq. (4), as shown in Figure 6. Comparing calculated and maximum MCs could prove to be a very useful way of identifying logs that have been stored for a long time before arrival at the sawmill. A proper evaluation of this method would require testing on a more diverse population of logs, containing both logs with full sapwood MC and logs with reduced sapwood MC.

In conclusion, by combining 3D and X-ray scanning in the log-sorting station, it is possible to measure the green sapwood density and to estimate the dry sapwood density and, accordingly, the MC in Scots pine sawlogs. Because the correlation with CT reference values is quite low and the reference itself contains some uncertainty, experimental verification of the simulation results is needed.

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The MC estimate could be used to separate the logs into two groups with high and low MC, correctly identifying all logs with low MC as dry logs. Out of all logs, 70% were correctly classified.

The estimate can also be compared to the dry density-dependent maximum MC and used to identify logs that have actually started to dry. However, this approach needs to be evaluated for a population of dry logs, because most logs in this study were of full MC.

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Paper VII

Detecting Top Rupture in Pinus sylvestris Sawlogs

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ABSTRACT

The quality of sawlogs is sometimes reduced by defects such as spike knots, cross grain and compression wood, which have been formed in the growing tree after rupture of the main stem. The hypothesis is that such damages can be found prior to sawing by using the straightness of the log as an indicator. If top ruptures can be detected already on the logs, then it is possible to treat these logs in a specific way, for instance, using lower speed or thicker blades than when sawing normal logs. This also means that, for the large volume of material, the sawing process can be optimized without problems caused by logs with top rupture.

In this study, data from optical three-dimensional log scanners and X-ray log scanners were used to determine the outer shape and the heartwood/sapwood border of the logs. Indicator values based on sharpness of the crook in outer shape and heartwood shape were calculated and the logs were sorted by decreasing top rupture indicator value. The result was compared to the number of top ruptures noted in manual grading of the sawn boards. Two sets of data have been used, scanner data simulated from computed tomography images of 540 Scots pine (*Pinus sylvestris* L.) logs were used for algorithm development and data obtained by industrial scanning of 508 Scots pine logs were used for algorithm validation. The results show that both outer shape and heartwood shape can be used as indicator of damages from top rupture and that the heartwood shape indicator is capable of detecting logs with severe top rupture without making any false identifications.

INTRODUCTION

When the top of a growing tree is broken, e.g. by moose browsing, strong winds or by a snow load, one of the branches will bend upwards and form a new leading shoot [1]. This reduces the growth and cause a deformation, especially if the main stem is broken and not just the apical leading shoot. It is also possible that two or more branches compete for several years until one of them dominates enough to form a new top. Wind and snow may cause breakage at any height while moose browsing only affects the butt log. The most common type of browsing damage is apical leader loss and is most frequent at stem heights of around 1 m. The more severe browsing damages, main stem breakage and bark stripping, are most frequent at heights of 2–3 m [2]. This means that such damages are close to the mid part of the butt log. The Swedish moose population peaked during 1981–1982 and it can be expected that this has caused a peak in browsing damages to young trees during that period [3, 4]. As the tree grows, the damage will remain inside the stem even when it has been hidden by new wood. Therefore logs with large bark strips should be removed in early thinning while the damage is still visible [5].



Figure 1. Board sawn from a Scots pine log where the top was broken in the growing tree.

The crook caused by top rupture also gets less sharp as the tree grows and overgrown ruptures cannot always be detected from the outer shape of the stem. The strength of centreboards sawn from such logs will however still be reduced by cross grain and compression wood [6]. Variations in density and grain direction will induce lateral forces on the saw blade [7], which put a constraint on feeding speed and minimum saw blade thickness. Furthermore, such variations will cause deformations and stress in the wood during drying and there will be more visible defects on the sawn goods, e.g. vertical, bark-ringed and decayed spike knots. Figure 1 shows a board from a log where the top was broken when the tree was young and one of the branches formed a new leading shoot. The remaining defect is more pronounced in the heartwood shape than in the outer shape of the stem, where the crook has been reduced by formation of new wood.

Today, optical three-dimensional (3D) scanners are used by many sawmills to measure the outer shape of logs and can be used to calculate various variables describing the crook, such as bow height, angle and sweep [8]. Even though attempts have been made to classify logs by different types of crook [9], sweep is normally the only variable being used to describe straightness of the logs. The introduction of X-ray scanners has made it possible to include also interior properties in log sorting [10, 11]. The low moisture content in heartwood relative to sapwood gives a high contrast in the radiographic images obtained by X-ray scanning of green logs, meaning that the amount of heartwood can be measured. It has also been shown that the accuracy in measurements of the heartwood/sapwood border can be improved by combining the X-ray images with outer shape data from a 3D scanner using path length compensation. This makes it possible to obtain detailed information about the heartwood shape by means of industrial X-ray scanning [12].

The aim of this study is to develop algorithms for automatic detection of top rupture. The algorithms will be based on the outer shape and heartwood shape information available from industrial 3D and X-ray log scanners.

MATERIALS AND METHODS

The Swedish Pine Stem Bank

During the development of the algorithms for automatic detection of top rupture, 3D and X-ray data generated from computed tomography (CT) images was used. The algorithms used for simulation of log scanner data from CT images are described by Grundberg and Grönlund [13] and Skog [14].



Figure 2. X-ray image of a Scots pine log where log shape (solid), heartwood shape (solid), filtered centre of the log (dashed) and centre of the heartwood (dash-dotted) have been marked. Low density values appear dark in the figure.

The top rupture algorithms are based on observations from 540 logs in the Swedish pine stem bank [15] with top diameters in the range from 137 to 350 mm. This is a database containing detailed information about logs from 200 Scots pine trees. All logs have been scanned in a medical CT scanner (Siemens Somatom AR.T, [16]). After scanning, the logs were sawn using a normal sawing pattern and dried to 18 % moisture content. The centreboards were manually graded by a skilled grader according to the Nordic Timber grading rules [17]. About 80 % of the boards were also graded by a second grader as a reference. Visible defects on the boards were noted by both graders, but normally only the worst defect was noted if there was more than one kind of defects in a board. Because the grading did not explicitly focus on defects caused by top rupture, the number of boards noted as containing such defects may be too low.

Data For Industrial Validation Of Algorithms

The algorithms were validated by a second set of data obtained by industrial scanning of 508 Scots pine logs with top diameters in the range from 160 to 300 mm. These logs were scanned using a two-directional RemaLog XRay scanner [18] in line with a RemaLog Bark 3D scanner [18] in the log sorting station of a Swedish sawmill. 39 of the logs were manually selected because their outer shape revealed that they were damaged by top rupture and another 469 logs were taken from the normal production. The sawn boards were manually graded in the green sorting and top ruptures were noted.

Detection Of Top Rupture Using Heartwood Shape

3D and X-ray log scanner data are combined using path length compensation. For each crosssection of the log, the 3D scanner measures the outer shape of the log and the X-ray scanner measures the attenuation of X-rays passing through the cross-section. The 3D cross-section is then used to calculate the path lengths travelled through wood for X-rays arriving at each detector pixel. By combining the measured attenuations and the calculated path lengths, the average green density along each individual X-ray path is calculated. The final result is a green density image of the whole log with good contrast between heartwood and sapwood [12]. Because a twodirectional X-ray scanner is being used, two perpendicular images are obtained for each log.

The outer contour and heartwood contour of the logs are obtained from the green density images [12] and a short smoothing filter is applied to the contours. Log and heartwood centre lines are calculated from the detected contours and a long averaging filter is used to even out variations in the log centre line (Figure 2). A signal containing local heartwood shape irregularities is then extracted by subtraction of the filtered log centre line from the heartwood centre line. For each point in the irregularity signal, the gradient of the signal is calculated over a window to the left and to the right of the point respectively. In positions where the two gradients have opposite

signs, their absolute values are summed and used to indicate a sharp deviation in the shape. Finally, a filter is applied to reduce indications close to the ends of the log because of the higher uncertainty in measured shape at the log ends. Because a two-directional X-ray log scanner is being used, this process is repeated for both measurement directions and the maximum irregularity indicator value found in any of these two directions is being used as a top rupture indicator of the log.

Top Rupture Detection Using Outer Shape Only

Two different indicators for detection of top rupture using outer shape only are also evaluated. In the first approach, outer shape from the X-ray scanner is being used. The algorithm for heartwood shape irregularities described above is being used, but applied to the outer shape instead of the heartwood shape. In this case, the unfiltered log centre line is used in place of the heartwood centre line, meaning that the irregularity signal will describe local deviations in the outer shape rather than in the heartwood shape.

In the second approach, the outer shape measured by the 3D scanner is being used. Still, the same algorithm is being applied. In this case, the 3D shape is simply projected onto a plane along the main axis of the log, yielding an outer contour similar to the one in Figure 2. The centre line of this contour is then used in place of the log centre line measured by the X-ray scanner and the rest of the calculation proceeds as described above. In order to find the worst shape irregularities, the process is repeated eight times using different projections of the 3D shape. The planes being used for the projection are rotated 0, 22.5, 45, 67.5, 90, 112.5, 135 and 157.5 degrees around the main axis of the log respectively. The maximum irregularity indicator value found in any of these eight directions is being used as the top rupture indicator of the log.

Evaluation Of Results

Logs where the graders had found top rupture on any of the sawn boards are considered being top rupture logs. Each of the three top rupture indicator values, based on deviations in the heartwood shape, outer shape measured by X-ray and outer shape measured by 3D respectively, are then graphically compared to the top rupture notation (yes/no) from the graders. Suitable threshold values for finding logs with top rupture are chosen for all three indicators and logs with high indicator values but no noted top ruptures are examined more closely. The different top rupture indicators are also pair wise compared to each other in order to find any differences in which logs the methods tend to find.

RESULTS

The heartwood-shape and outer-shape top rupture indicator values of the logs from the Swedish pine stem bank are plotted in Figure 3. For all three methods, it was found that the highest values correctly correspond to logs where the sawn boards had been graded as top rupture boards. In order to facilitate comparison between the methods, each series was normalized so that the highest indicator value of any log not marked with top rupture by the board graders corresponds to a value of 10. For each method, the 15 logs with the highest indicator values that had not been graded as top rupture logs were investigated further. This was done by inspection of the CT images from the stem bank. It was found that two logs (squares in Figure 3) were severely damaged by scars, over a large portion of the log the sapwood was completely missing. This type of logs is not suitable for sawing and should thus never appear at a sawmill, therefore these two logs were excluded from further analysis. The CT image inspection also showed that, for each of the three methods, at least the top 10 logs that had not been graded as top rupture logs actually did contain top rupture (diamonds in Figure 3).



Figure 3. Top rupture in 540 Scots pine logs from the Swedish pine stem bank. The graphs show manual top rupture notation versus automatic top rupture indicator values based on heartwood shape from X-ray and 3D log scanner, outer shape from X-ray log scanner and outer shape from 3D log scanner respectively. Circles are top ruptures noted during board grading, diamonds are top ruptures found when investigating computed tomography (CT)

images of the logs and squares are logs with big scars. The dashed lines are suggested threshold values for separation between logs with and without top rupture. The calculations are based on X-ray and 3D log scanner data simulated from CT-scanned logs.



Figure 4. Top rupture in 508 Scots pine logs from a Swedish sawmill. The graphs show manual top rupture notation versus automatic top rupture indicator values based on heartwood shape from X-ray and 3D log scanner, outer shape from X-ray log scanner and outer shape from 3D log scanner respectively. Triangles are logs presorted as top rupture logs and circles are top ruptures noted during board grading. The dashed lines are suggested threshold values for separation between logs with and without top rupture. The calculations are based on industrial X-ray and 3D log scanner data.

The value 10 was chosen as a threshold for separation between logs with and without top rupture. This value is the highest value of a log not noted with top rupture during board grading, and the CT image inspection revealed that all logs with values close to 10 did contain top rupture. Therefore, this choice of threshold value left a margin between the threshold and the first logs without top rupture, see Figure 3. The feasibility of this threshold was then evaluated by comparison with the corresponding industrial measurements, see Figure 4. Table 1 shows the number of logs being correctly and incorrectly sorted as top rupture logs when using different threshold values.

Table 1. Number of logs being correctly and incorrectly sorted as having top rupture (TR) when applying different threshold values to the top rupture indicators obtained using the algorithms based on heartwood shape (Heart), outer shape from X-ray (OuterX) and outer

shape from 3D (Outer3D). The total number of logs in the stem bank data set is 540, whereof 66 with top rupture (including the top ruptures from grading and from inspection of CT images). The total number of logs in the industrial data set is 508, whereof 76 with top rupture.

		Stem bank data		Indust	rial data
Algorithm	Threshold	Correct TR	Incorrect TR	Correct TR	Incorrect TR
Heart	8	9	0	27	7
Heart	10	6	0	19	3
Heart	12	4	0	11	1
OuterX	8	8	0	9	2
OuterX	10	4	0	5	2
OuterX	12	1	0	3	1
Outer3D	8	4	0	23	25
Outer3D	10	4	0	18	9
Outer3D	12	2	0	14	5



Figure 5. Automatic top rupture indicator values for 540 Scots pine logs from the Swedish pine stem bank. The left figure shows indicator values based on heartwood shape from X-ray and 3D log scanners, versus indicator values based on outer shape from an X-ray log

scanner. The right figure shows indicator values based on outer shape from a 3D log scanner, versus indicator values based on outer shape from an X-ray log scanner. Circles are top ruptures (TR) noted during board grading, diamonds are top ruptures found when investigating computed tomography (CT) images of the logs, squares are logs with big scars and crosses are logs without top rupture. The calculations are based on X-ray and 3D log scanner data simulated from CT-scanned logs.



Figure 6. Automatic top rupture indicator values for 508 Scots pine logs from a Swedish sawmill. The left figure shows indicator values based on heartwood shape from X-ray and 3D log scanners, versus indicator values based on outer shape from an X-ray log scanner. The right figure shows indicator values based on outer shape from a 3D log scanner, versus indicator values based on outer shape from an X-ray log scanner, versus indicator values based on outer shape from an X-ray log scanner. Triangles are top ruptures found in log sorting, circles are top ruptures found on the boards in green sorting and crosses are logs without top rupture (TR). The calculations are based on industrial X-ray and 3D log scanner data.

In Figure 4 it can be seen that many of the logs that were presorted as containing top rupture get high indicator values from both the heartwood indicator and the outer shape indicators. However, a number of logs not containing any top rupture also get high values from the two outer shape indicators, making it difficult to use the outer shape methods to separate between logs with and without top rupture. The relationship between the different top rupture indicators is being shown in Figure 5 for stem bank data and in Figure 6 for industrial data.

DISCUSSION

Images that are produced by an X-ray log scanner contain a lot of information and a requisite for successful application of the technique is the ability to extract and handle the most useful parameters. The heartwood shape is one such parameter and the results show that it can be used to detect top ruptures that cause crooking of the heartwood. For the stem bank data, the heartwood method as well as the methods based on outer shape, measured either by the X-ray scanner or the 3D scanner, were all capable of detecting a fair amount of the logs with top rupture without giving false alarms. The highest indicator values corresponded to top ruptures noted in the grading and inspection of the CT images of the logs with high indicator values but no notes about top rupture on the boards showed that most of them contained top rupture. The reason that these top ruptures had not been noted could be that some of these boards had other defects that were being noted instead or, more likely, that the top ruptures were not visible or hardly visible on the boards. This means that the top rupture indicators also give information on the severity of the top rupture, and by tuning the threshold value, it will be possible to identify only logs with severe top rupture or also logs with less severe top rupture.

The industrial validation of the algorithms shows that the heartwood shape algorithm works fine also on industrial data. The algorithms based on outer shape did however not behave very well in the industrial validation because some logs without top rupture gives rise to high values (Figure 6). Especially the algorithm based on outer shape from the 3D scanner proves useless as the highest values are caused by logs without top rupture. The reason for this could be that the logs have been turning or bouncing around on the conveyor as they were passing through the 3D scanner.

The only other log defect found in this study that can cause a strong top rupture signal in the heartwood shape algorithm is the scars. However, because these scars are so big (up to one third of the log cross-section is missing), these logs would normally have been sent directly to a pulp mill or sorted out as soon as they arrive at the log sorting of a sawmill. Smaller scars could also be expected to give a signal in the heartwood shape irregularity algorithm; but because scars usually only affect one side of the log, the centre line will not be strongly affected and the signal from a scar should be expected to be weaker than that of a top rupture with a well-defined heartwood crook. The conclusion is that the algorithm based on irregularities in the heartwood shape should be a good candidate for the automatic detection of top rupture, with very low risk of making false positives.

Implementing top rupture identification in a sawmill would be a great tool for avoiding the problem logs when making products that are sensitive to top rupture. It will however not be desirable to completely remove the detected logs from production, instead, the top rupture logs could be used for alternative products that are not sensitive to top rupture, one example being wood for finger-jointing.

Because of the rapid variations in density and grain direction near the top rupture, it is one of the factors limiting feeding speed and saw blade thickness. Therefore, an algorithm for automatic detection of top rupture can be expected to play an important role in a system optimizing the sawing to the raw material. An important task for the future will be the development and implementation of such strategies.

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Paper VIII
Automatic Detection of Resin Pockets in Norway Spruce by X-ray Scanning

Johan Skog and Johan Oja

Abstract

Resin pockets are small lenses of resin oriented along annual rings. They are common in Norway spruce (*Picea abies* (L.) Karst.) but vary much both in size and numbers between and within stands and also within the same tree. The existence of resin pockets is a defect making it difficult to use spruce wood for, e.g., joinery products whereas resin pockets have very little effect on other products. Finding a method allowing automatic selection of sawlogs free from resin pockets would thus enable the use of spruce wood in sensitive products such as furniture, panels and floors.

The development of such a technique has been the aim of several research projects throughout the years. Detecting resin pockets using an industrially applicable technique has however proven to be very difficult. One technology that has been proposed is an industrial X-ray scanner using 7-9 fixed measurement directions. Today X-ray scanners with higher resolution are available. Using simulation software and the CT scanned logs of the Swedish stem bank it is possible to simulate these high resolution scanners with an arbitrary number of measurement directions.

A study has been conducted, investigating to what extent resin pockets of varying sizes are visible in industrial X-ray images. It was found that resin pockets in heartwood, whose width exceeds 10% of the log diameter, are identifiable from an appropriate viewing direction. It is not possible to reliably detect individual resin pockets but it should be possible to automatically detect logs with many resin pockets. The probability to detect resin pockets in a log with 10 measurable resin pockets is at least 69% when using a four-directional scanner and at least 92% when using an eight-directional scanner.

Introduction

Resin pockets are small lenses of resin oriented along annual rings. They are common in Norway spruce (*Picea abies* (L.) Karst.) but vary much both in size and quantity between and within stands and also within the same tree. In a study including a great number of Norway spruce logs from five geographic regions in Sweden it was shown that the average width (tangential measure) of resin pockets in heartwood is approximately 16 mm for butt logs as well as upper logs (Temnerud, 1999). The width distribution of the resin pockets in this study is shown in **Figure 1**.

The existence of resin pockets is a defect making it difficult to use spruce wood for, e.g., joinery products whereas resin pockets have very little effect on other products. Finding a method allowing automatic selection of sawlogs free from resin pockets would thus make it possible to increase the use of spruce wood in sensitive products such as furniture, panels and floors.

The development of such a technique has been the aim of several research projects throughout the years. Oja and Temnerud (1999) showed that in computed tomography (CT) images of green Norway spruce logs it is possible to detect resin pockets in the heartwood with high accuracy and that it is possible to detect at least larger resin pockets in the sapwood. These high resolution images of the

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Figure 1.—Histogram showing the width distribution of 255 resin pockets in innerwood of Norway spruce upper logs and butt logs. The average resin pocket width is 16 mm for both log types. Compiled from Temnerud (1999), with permission.



Figure 2.—Schematic of X-ray log scanners with two measurement directions (spacing 90°), four measurement directions (spacing 45°) and eight measurement directions (spacing 22.5°). The open circles depict X-ray sources, the dashed lines are the centres of the emitted fan beams and the solid lines are the X-ray sensors. The grey circle is the log cross-section being imaged.

density distribution within the log were gathered using a medical CT scanner, a technique well suited for research purposes (Grundberg et al., 1995) but much too slow for industrial applications.

A faster measurement of the internal properties of a sawlog can be achieved using an industrial X-ray scanner equipped with a limited number of fixed measurement directions arranged according to the schematic in **Figure 2** (e.g. Aune, 1995; Grundberg & Grönlund, 1995). Grundberg and Grönlund (1995) and Oja (1999) developed algorithms for an X-ray log scanner using two fixed measurement directions. With this scanner it is possible to measure internal properties such as heartwood content and knot parameters but it has so far not been possible to detect objects as small as resin pockets.

Hagman (2003) investigated noninvasive measurement techniques based on X-ray, microwaves, IR, laser, radar and thermography and found that no available technique was up to the task of detecting resin pockets in sawlogs. The study proposed that a technique based on an industrial X-ray scanner with seven to nine measurement directions should be able to perform the task.

Today industrial X-ray scanners with higher resolution are available. Simulation software has also been developed by SP Trätek, allowing the simulation of these high resolution scanners with an arbitrary number of measurement directions (Skog & Oja, 2007). Using the CT scanned logs of the Swedish stem bank (Grundberg et al., 1995) this simulation software makes it possible to investigate to which extent resin pockets of different sizes are visible in industrial X-ray images.

The aim of this study is consequently to determine whether industrial X-ray scanning is a feasible technique for the detection of resin pockets in sawlogs and to estimate how many measurement directions such equipment requires in order to provide sufficient accuracy.

Material and Methods

A number of resin pocket rich Norway spruce logs of varying diameter and log type were selected from the Swedish stem bank. These CT images were studied and a total of 18 resin pockets located in the heartwood were selected for further study. For each resin pocket, thickness and width was measured in the cross-section with maximum intersected area, see **Figure 3**, and the length was determined by counting the number of CT cross-sections where the resin pockets is visible.



Figure 3.—Definition of the intersected area, width and thickness of a resin pocket (Weslien 1993, translated with permission).

Using the simulation software by Skog and Oja (2007), the selected logs were converted to industrial X-ray images with a resolution of 1152 pixels per cross-section and 5 mm spacing between cross-sections. Each log was simulated in 16 different measurement directions with spacing of 11.25°. The positions in the simulated X-ray images where the resin pockets should appear were investigated by eye. Each resin pocket was categorized according to its contrast to the surroundings as not visible (0), barely visible (1) or readily visible (2, 3) to a human eye. Category 3 represent resin pockets that could certainly be detected using an automatic algorithm whereas category 2 represent the resin pockets that may or may not be detected automatically. Eventually, the probabilities of detecting the resin pockets in a scanner with two (2X), four (4X) or eight (8X) measurement directions, arranged according to the schematic in **Figure 2**, were calculated.

Results and Discussion

The visibility of the resin pockets were analyzed together with the resin pocket sizes and the cross-sectional diameters of the logs. It was found that the resin pocket width was the critical variable for the detection of the resin pockets. In order for the resin pocket to cause a visible contrast in the X-ray image, it is necessary that a large enough share of the ray path is travelled through the resin pocket and this is only the case when the ray passes through the resin pocket in an almost tangential direction, see **Figure 4**. The size of the resin pocket when depicted in the X-ray image will consequently be determined by its thickness and length and the contrast of the imaged resin pocket will be determined by its width.

The requirement that the resin pocket must be radiated in an almost tangential direction in order to cause visible contrast implies that it will only be detectable from a limited range of viewing directions. It was found that the ratio between the resin pocket width and the log diameter is a good measure for estimating the size of the visibility range, the set of viewing directions from which the resin pocket is visible, **Figure 5**. In the middle of the visibility range the contrast is high and it should be possible to identify the resin pocket automatically. Because the resin pockets were studied by eye only, it was not possible to state the exact border where the resin pocket becomes automatically detectable. Thus, both a range within which the resin pockets with certainty can be detected automatically and a range where resin pockets may or may not be detected automatically by a final algorithm is presented in **Figure 5**.



Figure 4.—Left: Cross-sectional CT image of a Norway spruce with a large resin pocket. A tangential ray path through the resin pocket is illustrated by the dotted line. Right: X-ray image of a portion of the log around the resin pocket, simulated in the direction specified in the CT image. The clearly visible resin pocket is enclosed by a rectangle. The white horizontal lines in the image are knot whorls and single knots.



Figure 5.—Visibility range of resin pockets (the set of viewing directions from which the resin pocket is visible) of varying size in X-ray log scanner images. The outlier is a resin pocket within a swarm of 30 resin pockets. Category 1-3 includes the whole interval where resin pockets are visible to the human eye. Category 2-3 is the interval where resin pockets may be automatically detectable. Category 3 is the interval where resin pockets with certainty are automatically detectable.

Probability of identifying an individual resin pocket

The probability of identifying an individual resin pocket using a certain type of X-ray scanner can be calculated by dividing the angular width of the visibility range by the angular spacing between two adjacent measurement directions. A resin pocket with a width corresponding to 10% of the log diameter, e.g., is clearly detectable from a 5° wide range and possibly detectable from a 10° range. Consequently, the probability that this resin pocket is clearly detectable using a 2X scanner is $5^{\circ}/90^{\circ} = 5.6\%$, using a 4X scanner $5^{\circ}/45^{\circ} = 11\%$ and using an 8X scanner $5^{\circ}/22.5^{\circ} = 22\%$. Similarly, the probability that the resin pocket is located within the possibly detectable interval is around twice the above calculated figures. A very large resin pocket, with a width corresponding to 15% of the log diameter, is clearly detectable within a 13° range and possibly detectable using a 2X, 4X or 8X scanner is 14\%, 29\% and 58\% respectively. The probability that the resin pocket lies within the possibly detectable ranges is 1.7 greater.

A complete algorithm for automatic detection of resin pockets can be expected to deliver somewhere in between the above mentioned figures for the clearly detectable and the possibly detectable ranges. In practice, this means that an industrial X-ray scanner, regardless of the number of measurement directions, cannot be used for a 100% certain identification of individual resin pockets.

Probability of identifying a resin pocket rich log

Whereas an industrial X-ray scanner cannot be used for a certain identification of individual resin pockets, the chances of identifying logs with a large number of resin pockets are better. If the probability that an individual resin pocket is located within the detectable range is p and the number of resin pockets of this size is n, the probability to detect at least one of these resin pockets is

$$p_n = 1 - (1 - p)^n$$
. [1]

Figure 6 shows the probabilities that at least one resin pocket lies within the clearly detectable interval for varying total number of resin pockets of widths 10% and 15% of the log diameter respectively. According to Temnerud (1999), around 34% of the resin pockets in the heartwood of upper logs are wider than 18 mm and 21% are wider than 22 mm. For butt logs, 17% of the resin pockets in the heartwood are wider than 22.5 mm and 5% are wider than 31.5 mm. This means that, at least for upper logs, it is probable that resin pocket rich logs will contain a fair number of resin pockets with sizes corresponding to 10 - 15% of the diameter.



Figure 6.—Probability to detect at least one resin pocket as a function of the number of resin pockets of widths 10% or 15% of the log diameter, using X-ray log scanners with two (2X), four (4X) or eight (8X) measurement directions respectively. The probabilities refer to at least one resin pocket being situated within the interval where resin pockets with certainty are automatically detectable.

Difficulties when identifying resin pockets

The major difficulty when identifying resin pockets using an industrial X-ray scanner is, as already mentioned, that the X-rays must penetrate the resin pockets in the right direction in order to produce a measurable contrast. It is also necessary that no other areas of high density, such as knots, sapwood or wetwood lie adjacent to the resin pockets, since such objects are likely to cover the image of the resin pocket. For a resin pocket to be detected by the scanner it must accordingly be large enough, located in the heartwood, away from sapwood and knots and also correctly oriented in relation to the scanner.

The risk that other internal structures in the log are mistaken for resin pockets is small, since the resin pockets have a distinctive round shape when imaged by an X-ray log scanner. Pebbles stuck in the bark may however be confused with resin pockets since they give a similar imprint in the X-ray image. Yet, in most cases it should be possible to separate pebbles from resin pockets since a pebble in average is depicted as shorter longitudinally, wider tangentially and with a sharper contrast than a resin pocket. Furthermore, pebbles are visible from a wider range of viewing directions than resin pockets and consequently, it should be possible to differentiate between pebbles and resin pockets with high accuracy when using at least four measurement directions. Under rare circumstances, other external features of the log, such as holes or uneven bark scrapings could also give rise to bright spots in the X-ray image, which may not be possible to differ from resin pockets.

Conclusions

This study has concluded that it by means of industrial X-ray log scanning is possible to, from the right viewing direction, detect a resin pocket in the heartwood if its width is at least 10% of the log diameter. Resin pockets in sapwood cannot be detected.

It has also been concluded that it should be possible to automatically detect upper logs with many resin pockets. For a log with ten detectable resin pockets, the probability to detect at least one resin pocket is no less than 44% with a 2X log scanner, 69% with a 4X log scanner and 92% with an 8X log scanner.

Thus, it is not possible to ascertain that a log is completely free from resin pockets. However, it should be possible to detect logs with many resin pockets. For this task, a log scanner with at least four measurement directions is recommended. The use of eight measurement directions would improve the detection rate greatly but would also represent a substantial extra investment cost.

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Paper IX

Deciding log grade for payment based on X-ray scanning of logs

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Abstract

In Sweden, the payment for a large part of the saw logs is based on both grade and volume. The volume is measured automatically using optical 3D or shadow scanners. The log grade is decided manually by visual inspection. The manual inspection is expensive and often limits the production speed. This makes it interesting to find an automatic method of grading logs for payment.

X-ray scanning of logs is today used at some sawmills for measuring inner properties of logs and based on this information choose the best logs for different products. Hence, this paper aims at studying if X-ray scanning of logs also can be used to decide grade for payment.

The study is based on 160 Norway spruce logs (*Picea abies* (L.) Karst.) and 160 Scots pine logs (*Pinus sylvestris* L.), all with a top diameter of around 180 mm. The logs were scanned with an industrial X-ray scanner and an optical 3D scanner, and then graded by a skilled log grader. Models for prediction of log grade based on X-ray and 3D data were calibrated using partial least squares (PLS) regression.

The log grade was correctly predicted for 86 % of the spruce logs and 81 % of the pine log. For spruce, bow height was the only significant variable while knot parameters were also important for pine logs.

The results are very promising, but must be tested on a larger and more representative material.

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1 Introduction

At Swedish sawmills, logs are measured and graded for two different reasons. One objective is to sort the logs based on dimension and quality, in order to fit each individual log to the right product. The other objective is to collect information for payment.

The log sorting for process control is based on automatic measurements of dimension and properties such as knot structure and heartwood diameter. The length and diameter are in most cases measured using a 3D scanner (Grundberg et al. 2001). The idea of this is to fit each log to the sawing pattern that produces the highest yield. But today, an increasing amount of customers is asking for sawn products with a specific combination of thickness, width, length and other properties such as heartwood content, distance between whorls and high strength. To produce this type of products in an efficient way, it is necessary to choose the right logs already before sawing. Otherwise, the sawmill will produce a large amount of products with low value due to unwanted combinations of dimension and wood properties.

When sorting the logs based on properties of the sawn wood, one alternative is to use data describing the external shape of the log to predict the properties of the sawn wood (Grace 1994). For more detailed non-destructive measurements of inner properties of saw logs, most industrial applications are based on X-ray scanning (Fig. 1). Industrial X-ray scanning of logs makes it possible to measure properties such as heartwood content (Skog & Oja 2009a), density (Oja et al. 2001), knot structure (Pietikäinen 1996; Grundberg & Grönlund 1997), or annual ring width (Wang et al. 1997; Burian 2006). X-ray scanning of logs can also be combined with 3D scanning for improved measurements of heartwood and density (Skog & Oja 2009b) and combined with acoustic measurements to improve the predictions of strength and stiffness (Lycken et al. 2009).

The payment of logs is at all large sawmills in Sweden based on a combination of automatic measurements of volume and manual grading. For most loads of logs, each log is individually graded. This means that the grader has to make decisions about species, amount and thickness of bark and log grade according to the rules defined by the Timber Measurement Council (Anon. 1999). The large number of decisions that have to be made by the grader limits the speed at the log sorting. At many sawmills this fact makes the log sorting, i.e. the manual grading, a bottle neck in the production chain.

Consequently, an automatic grading for payment would be a significant improvement and much work has been done to make this possible. Oja et al. (1998) describe a system that helps the grader by taking high quality pictures of the log ends and combines this information with an automatic log grade based on the external shape of the log. Edlund (2004) presents further development of

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the automatic grading based on log shape, while Norell & Borgefors (2008) have developed algorithms for automatic analysis of images of log ends.

So far, none of these methods have been implemented for automatic grading for payment. The reason is of course that grading for payment is a very critical process. Before implementing a new method, there must be no doubt that a sawmill using the new, automatic grading will pay the same price for the logs as if manual grading was used. This makes the robustness of the method important and therefore, X-ray scanning becomes interesting as it is little affected by external factors such as seasonal variation in bark or the existence of snow on the logs.

Thus, it is of interest to study the possibility of automatic grading of logs for payment based on industrial X-ray scanning.



Figure 1: Schematic of the industrial X-ray scanner described by Grundberg & Grönlund (1997).

2 Material and method

The study was made as an extension of a larger project (Lycken et al. 2009) and the material was because of this selected primarily for that larger study. The study is based on 160 Norway spruce logs (*Picea abies* (L.) Karst.) and 160 Scots pine logs (*Pinus sylvestris* L.), all with a top diameter of around 180 mm. The logs come from a sawmill in northern Sweden and were selected randomly from a pile of logs sorted according to top diameter.

The logs were scanned with an industrial X-ray scanner and an optical 3D scanner at normal speed (approximately 120 m/min), and then graded by a skilled log grader according to the rules defined by the Timber Measurement Council (Anon. 1999). For Norway spruce the logs were graded as VMF1, VMF2, VMF8 or VMF9, where VMF1 is the good logs while VMF8 and VMF9 are the worst logs. The Scots pine logs were graded as VMF1, VMF2, VMF4 or VMF5. VMF1 are high quality logs with small knots and VMF2 are high quality logs with larger sound knots. VMF4 indicates low quality and VMF5 are the worst logs.

Models for prediction of log grade based on X-ray and 3D data were calibrated using partial least squares (PLS) regression. For Norway spruce, two models were calibrated, one model for separating between VMF1 and VMF2 and another model for separating VMF8 and VMF9-logs from all other logs. For Scots pine one model with five Y-variables was calibrated, one Y-variable representing each of the grades VMF1 to VMF5.

3 Results

For Norway spruce, the log grade was correctly predicted for 86% of the logs (Table 1). But it is important to note that the high percentage to a large extent is reached due to a high percentage of the logs having the same grade (VMF1). For logs predicted as VMF2 according to X-ray and 3D, almost 50% were graded VMF1 by the manual grader. For Norway spruce the variables describing bow height and crookedness based on 3D scanning were the most important.

For Scots pine, the log grade was correctly predicted for 81% of the logs (Table 2). Even though the value is less than for spruce, the model can be said to work better since the logs are spread out more between the different grades for pine compared to spruce. In the model calibrated for Scots pine, variables describing the knot structure are more important than in models calibrated for spruce, but for the worst logs (VMF5), bow height is important also for pine.

Table 1: Automatic grading of Norway spruce logs. Comparison between log grade according to manual grading and log grade according to automatic grading based on X-ray and 3D scanning. Amount of logs in percent.

_		Log grade accord	ade according to X-ray and 3D (%)		
Log grade according to the manual grader	VMF1	VMF2	VMF8	VMF9	
VMF1	76	7	0	0	
VMF2	7	8	0	0	
VMF8	1	0	0	0	
VMF9	0	0	0	2	

Table 2: Automatic grading of Scots pine logs. Comparison between log grade according to manual grading and log grade according to automatic grading based on X-ray and 3D scanning. Amount of logs in percent.

-	Log grade according to X-ray and 3D (%)						
Log grade according to the manual grader	VMF1	VMF2	VMF3	VMF4	VMF5		
VMF1	6	0	1	0	0		
VMF2	0	33	3	3	0		
VMF3	1	3	30	3	1		
VMF4	0	3	3	9	0		
VMF5	0	0	0	0	4		

4 Discussion

The study is based on a very limited material but indicates that the combination of X-ray and 3D scanning can be a possible method to reach a system for automatic grading for payment. For Norway spruce it is possible that only 3D scanning is enough but for Scots pine the results indicate that X-ray scanning is a necessary addition.

Future work should focus on studies based on a more representative material. The material must be representative with respect to dimension and properties of logs as well as geographic origin of the material. It is also important to register the exact reason for downgrading for each log. This would make it possible to develop specific algorithms for defects such as rot or spike knots.

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