ONLINE ISSN 2069-7430
ISSN-L 1841-4737

PRO LIGNO
www.proligno.ro

Vol. 13 N° 4 2017
pp. 533-539

THE USE OF CT-SCANNING TECHNOLOGY IN WOOD VALUE-CHAIN RESEARCH AND IN WOOD INDUSTRY - A STATE OF THE ART

Magnus FREDRIKSSON
Luleå University of Technology, Wood Science and Engineering
Forskargatan 1, 93187 Skellefteå, Sweden
E-mail: magnus.1.fredriksson@ltu.se

Olof BROMAN
Luleå University of Technology, Wood Science and Engineering
Forskargatan 1, 93187 Skellefteå, Sweden
E-mail: olof.broman@ltu.se

Dick SANDBERG
Luleå University of Technology, Wood Science and Engineering
Forskargatan 1, 93187 Skellefteå, Sweden
E-mail: dick.sandberg@ltu.se

Abstract:

X-ray computed tomography (CT) is a powerful tool for the non-destructive measurement of dynamic processes in wood. After more than 25 years of research at Luleå University of Technology in the field of CT-scanning of wood material, the first industrial CT-scanners are now installed in sawmill production for the in-situ measurement of internal log features to steer of the sawmill process with the help of this information.

This paper provides an overview of the potential of CT-scanning in wood-material research and how this data can be used for the modelling and simulation of the wood value chain. A database of CT-images of trees is used to create a log model including the outer shape of the logs and their internal knot structure. Simulation software is used to saw these virtual logs in different positions relative to the sawblade, and also for the crosscutting of the sawn timber to components. The output is dimensions and grades of sawn timber, volume yield as well as an economic result based on real economic conditions. A specially designed climate chamber for CT studies of the drying of sawn timber is used to increase the knowledge of how the drying affects the response from the sawn timber during seasoning.

Key words: *CT scanning; sawmilling; simulation; modelling; drying.*

INTRODUCTION

X-ray computed tomography (CT) was introduced in the medical field in the early 1970s and uses X-rays to determine the density profile through a human body. Funt and Bryant (1987) were probably among the first to use medical CT images in the detection of internal log defects. They developed an automatic method for the interpretation of CT images to identify knots, rot, and cracks occurring in a log, but they also met the same problem as others at that time – the scanning time was about three minutes for a single 1 cm long disc or slice of the log. The technology was far from being realistic for industrial conditions. For more than 25 years, medical CT has been used in wood research at Luleå University of Technology (LTU). In wood science, CT is mostly used for steady-state studies of internal anatomical features of the wood material, but at LTU it is also possible to study processes such as drying, modification, water absorption, internal and external cracking, and material deformation in a temperature- and humidity-controlled environment (Fig. 1). This paper focuses however, on how CT-based information from logs (roundwood) can be used for simulation studies of the sawn timber value chain, both in research and for industrial purposes.

Computer simulation is an appropriate tool for studying the wood-value chain, for several reasons. Firstly, the complexity of both the raw material and the process itself means that it is diffcult to assess the possible effects of different decisions without a numerical model. Secondly, since the process of sawing and other machining operations is irreversible, the same material cannot be tested several times in a real system. This is possible however using a computer model, where the same log or board can be processed several times in different ways to study how different process parameters affect the outcome. Using a computer model, the effect of the raw material can be virtually neglected since only process parameters are changed between different tests. The opposite can also be done, even though this is also possible in a physical test. Time is also an important factor. In industrial tests, the lead time between the start and end of a test is quite long, and in the meantime the production units are occupied by the testing. This is avoided in simulation studies.

To realize a truly integrated approach to the wood-value chain, it is important to be able to predict the final result of a decision taken early in the chain. Preferably, this prediction should be made before a saw blade has even touched the log. To do this, there must be a way to link the properties of trees to the properties of end-products. Such an approach is presented in this paper. A short introduction to the X-ray CT principles is followed by a description of the different tools necessary for the modelling and simulation of the early stages in the wood value chain, i.e. (1) a 3D-description of properties in roundwood – the virtual stem bank, (2) a simulation program for the sawing of the virtual logs in the stem bank, and (3) a simulation program for the cross-cutting of sawn timber. Finally, progress in the development of industrial applications based on CT technology will be presented.

OBJECTIVE

The purpose of this paper is to give a comprehensive overview of the possibilities of using CT-scanning in wood-material research and of how these data can be used for the modelling and simulation of the wood value chain for industrial purposes.

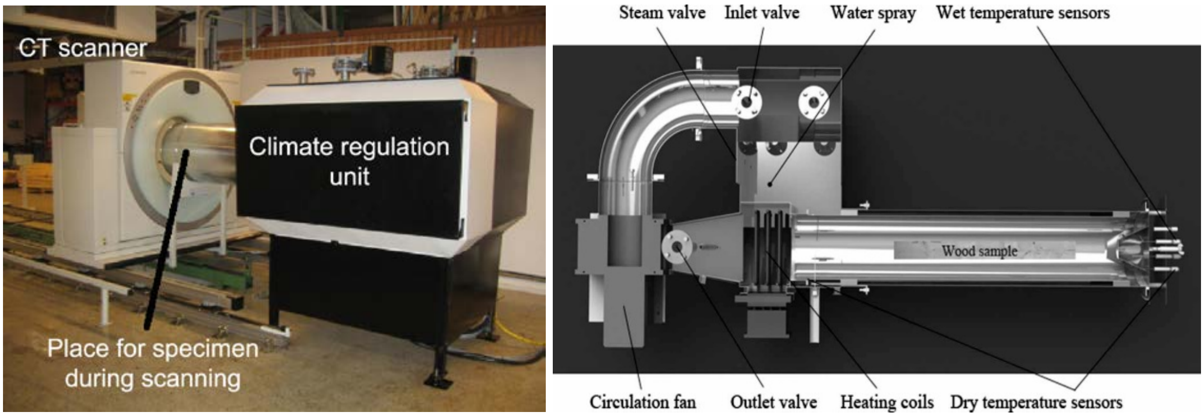

Fig. 1.
Siemens Somatom Emotion medical CT-scanner equipment at LTU with an integrated climate chamber for the non-destructive monitoring of dynamic processes within the wood material (left). Exploded drawing of the climate chamber (right).

X-RAY COMPUTER TOMOGRAPHY (CT-SCANNING)

X-ray scanners follow the theorem of Radon (1917) who theoretically demonstrated that the internal structures of an object can be reconstructed from single or multiple projections of the object, depending on the number of directions considered. In 1979, Cormack and Hounsfield received the Nobel Prize in medicine for the development of CT technology.

Whatever the number of directions, X-ray beams are sent and detectors measure the X-ray radiation transmitted through an object (Fig. 2). The intensity of the transmitted X-ray radiation can be related to the attenuation of the X-ray by the object by the Lambert–Beer exponential law under the assumption that the radiation is monochromatic and that the beam is propagated linearly in the object (Davis and Wells 1992):

$$I = I_0 e^{-\mu d} \qquad (1)$$

where: I is the intensity of the transmitted X-ray beam, I_0 is the intensity of the incident X-ray beam, d is the thickness of the object (length unit), and μ is the linear attenuation coefficient of the material along the transmission path (length unit^{-1}).

X-rays are emitted during rotation of the source around the object. At the same time detectors measure how many photons that have passed through the object. After complete rotation, the cross section is reconstructed showing a map of the attenuation coefficients. In medical CT-scanners, these values are normalized and compared to the coefficient of water, nowadays called the CT-number (Fig. 3).

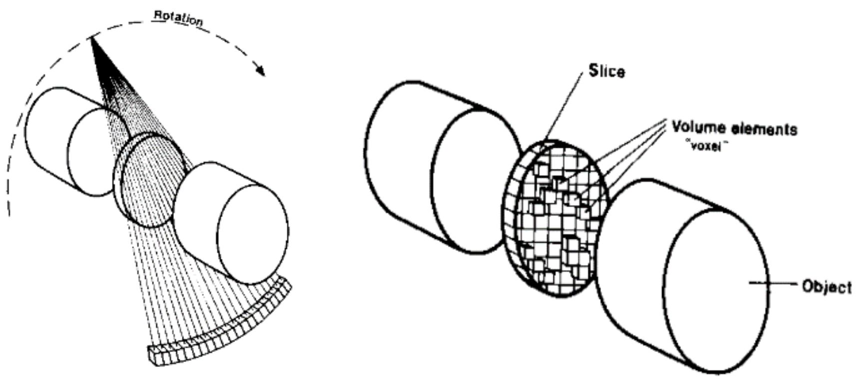

Fig. 2.
X-rays emitted during rotation are being detected and then calculated to give a map of attenuation coefficients.

In the model presented by Tsai and Cho (1976), the linear attenuation coefficient µ is the sum of two absorption coefficients, each of them directly proportional to the material density. Several other authors (e.g. Davis and Wells 1992; Lindgren 1992) have suggested that the linear attenuation coefficient µ can be directly related to the material density. The other factors involved are the chemical composition of the material (Tsai and Cho 1976) and the incident beam energy that is related to the type of source used. These factors are not independent. The material density ρ is the main influence with high-energy X-ray beams, whereas the chemical composition has its main effect with low energy radiation (Macedo et al. 2002). The relationship between density and attenuation coefficient for green (wet) wood is close to linear with an accuracy of the order of ±6kg/m^3 (Fig. 3).

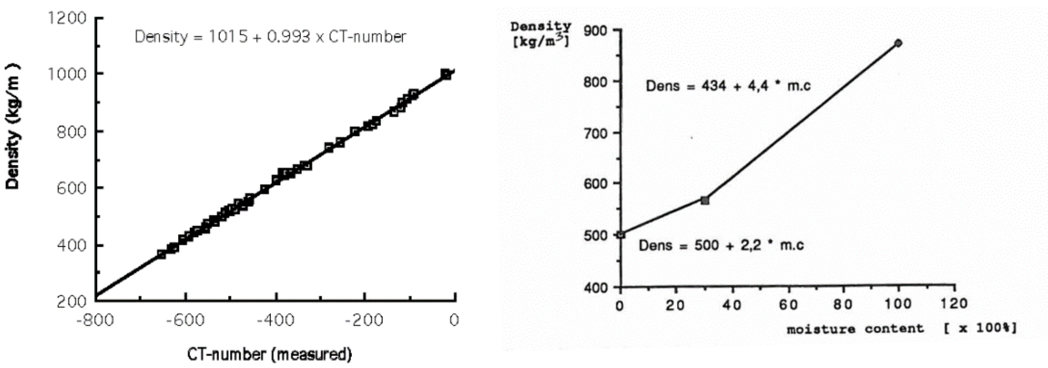

Fig. 3.
Relationship between green wood density and the CT-number /attenuation coefficient (left), and the relation between wood density and moisture content for a sample of wood with a dry density of 500kg/m^3.

Wood moisture is an important property to be measured and is highly related to the wood density that is a property that can be monitored using CT. One of the potential industrial applications of CT images is the monitoring of wood moisture during the drying process. Fig. 3 shows how the wood density increases with moisture content for a sample of wood with a dry density of 500 kg/m3. Wood swells from 0 to ca. 30% moisture content until the fibre saturation point (FSP) is reached. Above the FSP, the wood cell wall cannot absorb more water and wood stops swelling.

Since the correlation between density and attenuation coefficient is very high (Fig. 3), this relationship can be applied to evaluate “before and after” images using image processing, e.g. with the help of the software ImageJ developed at the National Institute of Health (ImageJ 2010). The data recorded by the CT scanner during the process is converted into a two- or three-dimensional image that, for instance, can show dynamic moisture behaviour during wood drying and crack formation.

THE VIRTUAL STEM BANK

The CT-scanner at LTU has been used to build up a stem bank of scanned trees that can be used for further studies such as anatomical studies, modelling of the sawmill process or the peeling of veneer, wood component processes, and for developing automatic applications for the sorting of logs and sawn timber. The stem bank contains information about 200 Scots pine trees from 33 permanent and well-documented sample plots at the Swedish University of Agricultural Sciences, 144 Norway spruce trees from 44 sample plots in Sweden, Finland and France, and a dozen oak logs. Some of the sample plots have been observed for up to 100 years and the databases include forestry data such as stand data, silvicultural treatments, images from the stand, images of the sampled trees etc.

To be able to use CT-scanned data in different simulations, the amount of data has to be reduced and pixels in the CT images need to be classified according to different types of wood such as knots, heartwood etc. A parametric version of the CT-data has therefore been developed. The outer shape of the logs and the sapwood/heartwood border are described by a radius every degree for a circumference at every 10 mm cross-section in the length of the log, and every knot is described by ten parameters describing volume extension, type of knot, and location in the stem. More details of the stem bank are given in Grönlund et al. (1995) and Nordmark (2005). An example of a log model with outer shape and knots is shown in Fig. 4. Some examples of how the stem bank has been used are:

- The development of stem models that describe how knot properties vary in the stem and how different parameters influence the knot properties.
- An analysis of relationship between log grade and the grade of sawn timber.
- The development of industrial X-ray log scanners, including simulations of X-ray signals and development of control algorithms.
- An analysis of measurement accuracy for different log diameter measurement principles.
- The development of a method for the measurement of spiral grain in CT-images.
- An analysis of different sawing strategies for sawmills.
- The measurement of bark thickness.
- An analysis of resin pocket frequency.
- The development of a heartwood distribution model.

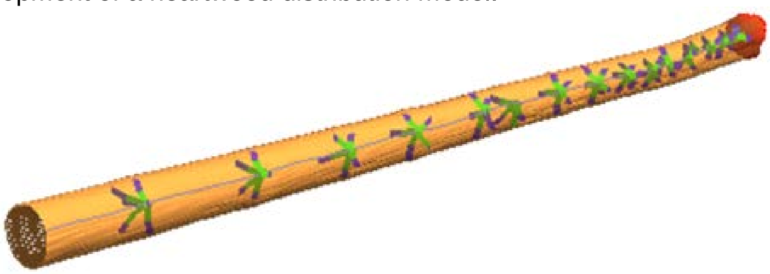

Fig. 4.
Example of log model based on the virtual stem bank.

SIMULATION OF THE SAWING PROCESS

In order to study the potential for recognizing the inner properties of logs, a specific simulation software has been developed for the sawing process, Saw2003 (Nordmark 2005). The input is log models, based on the CT scanned logs of e.g. the stem bank. Saw2003 models a sawmill that employs cant sawing with two sawing machines, with curve sawing in the second saw. It is also possible to control positioning of the logs during sawing, green dimensions, machinery etc. Boards are quality graded according to a user-specified grading system, based in principle on the Nordic Timber Grading Rules (Anon. 1997).The sawing simulation leads to virtual boards with information about knots, dimensions, quality, value etc. Saw2003 has been used extensively in earlier research (Nordmark 2005, Moberg and Nordmark 2006, Lundahl and Grönlund 2010, Berglund et al. 2013, Fredriksson 2014).

SIMULATION OF THE REFINING PROCESS

With modern scanning and optimization systems, there is a need to understand the interaction between the biological material and the process of turning it into a product. Otherwise there is a risk that the process will be inefficient with a large amount of waste along the way, especially at the end of a longer production chain when several machine grading decisions are involved before a consumer product is achieved. This understanding is difficult to achieve with high production speeds and automated grading, since there is little human interaction with the wood material. However, research tools capable of modelling the end result of a production process based on the raw material and quality rules would augment this understanding and help to achieve an integration of the forestry-wood chain.

A simulation tool developed and validated by Fredriksson et al. (2015) is one important step on the way to an integrated approach, since it can be used to link tree or log properties to cross-cut products. This is achieved by using virtual boards from sawing simulation as input. The tool is capable of crosscutting the boards, given a product specification with limits on the size of knots and wane for different board sides. The outcome is value-optimized and based on a value of each product set by the user. It is possible to define both fixed length and flexible length (typically finger-jointed) products, which can be considered simultaneously in the optimization.

Board features are classified as either accepted or rejected depending on a maximum length and width. If quality limits for both length and width are exceeded, the feature is considered as a defect and is cut away. The rest of the defect-free wood is considered accepted and is subsequently used to value-optimize the cutting of products.

Combined with a discrete event simulation tool, of which several are available commercially, the cross-cutting simulation tool can be used to predict how different decisions affect production costs in the entire forestry-wood chain. This can augment discussions between actors in the chain, since the cost involved in any decision can be quantitatively predicted beforehand. Other activities such as splitting, wood moulding and planing remain to be modelled in the same way as cross-cutting. If these were added, a wide range of end products could be considered at an early decision stage, making it possible to decide what to do with each individual log before sawing it. To this can also be added other end uses of wood, such as pulp and paper or energy conversion.

INDUSTRIAL USE OF THE CT-TECHNOLOGY

A sawmill's goal is to produce as much valuable wood as possible from roundwood. Due to natural variability, each log is different, although most of the distinguishing characteristics are visible only after sawing. As a result, the decision as to how best to saw the log is driven mainly by the log´s external appearance, which significantly reduces the ability to exploit the roundwood's true value. For this reason, knowing the real internal characteristics of a log before deciding its use has been only a dream for the sawmills. Tools that can use data from industrial scanning of real logs, where internal as well as external log features are represented in three dimensions, e.g. gamma-ray, X-ray, and CT scanners, have been developed since the 1970s, the first gamma-ray scanning equipment being installed in a sawmill in Sweden.

An X-ray scanning equipment for detecting the inner properties of logs was developed in Sweden in the 1990s, the X-ray LogScanner (Grundberg and Grönlund 1995). This technology was developed from the experience of developing the *virtual stem bank* and the simulation software described above. Nowadays, most advanced sawmills use X-ray scanning to determine the inner properties of logs. The X-ray scanners are typically based on discrete X-ray scanning in 1-4 directions while the log is fed through the scanner (Pietikäinen 1996; Grundberg and Grönlund 1997).

With the help of discrete X-ray scanning in an industrial environment, it is possible to measure properties such as: diameter under bark, amount of heartwood/sapwood, density, knot whorl parameters (volume and distance), average annual ring width, log type (butt, middle, top) and species (e.g. spruce, pine). With CT-scanning it is also possible to measure sawing position, quality of boards, strength and stiffness in-line with the production.

In 2008, the Microtec company developed the first prototype of a CT-scanner for log imaging, using a 180kV, 10mA X-ray source, rotating at 2.8rev/s, and implementing spiral tomography with a small cone angle of 0.5 degrees. An approximate algorithm by Feldkamp et al. (1984), the FDK algorithm, was implemented for the tomographic inversion, but the maximum scan speed was only 5m/min, much less than desired.

In most modern industrial and medical CT scanners, the X-ray is emitted from the source in a cone-beam geometry, instead of the fan-beam geometry that was previously used. The challenge is the reconstruction of a three-dimensional image from this cone-beam geometry because the object is typically moved through the beam, and either the object or the combination of the detector and the X-ray tube is turning (spiral CT). Several solutions have been proposed for the reconstruction of cone-beam geometries using different approaches (Feldkamp et al. 1984; Kachelrieß et al. 2000; Stierstorfer et al. 2002). Some of them are implemented in commercial medical spiral CT scanners, but all of these reconstruction algorithms are approximate in their nature (Kalender 2006). Although they work reliably for small cone angles, wider cone angles result in cone beam artefacts, blurring the image (Zhu et al. 2004).

The breakthrough by Katsevich (2001, 2002) was to find and implement an exact analytical reconstruction algorithm, widely known today as Katsevich's Algorithm. The algorithm was subsequently further refined (2004) and solved not only the cone-beam artefact problem, but was also clearly better suited for use in situations where a fast movement or a high pitch in spiral CT scanners is necessary (Zhu et al.

2004), which was an important prerequisite for a high-speed CT log scanner. Prof. Katsevich therefore laid the theoretical foundation for a fast industrial spiral CT scanning method and paved the way for the application of CT scanners operating at full speed in sawmills. This was realized by Microtec in 2012 when the first functional industrial CT log scanner was developed, together with researchers at LTU, the Forest Research Institute of Baden-Württemberg and the SP Technical Research Institute of Sweden. The CT log scanner from Microtec yields a continuous, qualitative and full 3D log reconstruction. The CT data is used to control and optimize the board output by cutting the logs in a way that increases the value of the sawn products by approximately 10% in practice. Under ideal conditions, a theoretical value increase of more than 20% is possible (Fredriksson 2014).

For the industrial CT-scanning technology a number of challenges regarding mechanical constraints, data transfer, safety regulations, image processing, and optimization algorithms have been addressed. Easily installable in any sawmill, the CT Log helps to get the most out of each sawn tree. Currently (spring 2017) five sawmills in Europe and the Americas have a CT Log equipment able to scan and optimize the processing of the logs at each mill.

The first Microtec CT Log equipment in Scandinavia and the first ever installed directly in the saw line for the direct control of the breakdown process will be installed at the Sävar sawmill in North Sweden in November 2017. It is an investment of approximately € 3 million and is associated with the rebuilding of the saw line. The precise scanning combined with the latest band-saw technology from Söderhamn Eriksson/USNR - focusing on thin saw kerfs and high speed - ensures maximum volume and value yield.

CONCLUSION

Many studies have demonstrated that scanning the internal characteristics of each log before breakdown in order to optimize the process would result in a significant increase in the sawmill yield.

The advances of X-ray source technologies and the exact cone beam algorithm developed in recent years have led to an industrial CT scanner for the analysis of each log in a modern sawmill. This new technology and its successful implementation mark the start of a new era in non-destructive roundwood scanning. Ground-breaking research and innovative implementation have opened new horizons, facilitating further optimization of the sawing process for the timber industry. Compared to the product value derived from existing technologies in modern European sawmills, where 3D scanning of the shape of the log is used, a 10-15% increase in value of the output can be achieved. If all the advantages of having access to the internal features of the logs were realized, a theoretical increase of the order of 20-25% is possible. For an average-sized sawmill, an investment in this kind of equipment should have a payback time of not much more than a year.

For example, high-speed scanners will also be pivotal in the further integration of related scientific research into the sawing optimization process and will most certainly stimulate further research in the wood processing area.

ACKNOWLEDGEMENT

Support from the Swedish Research Council for Environment, the Agricultural Sciences and Spatial Planning (FORMAS), project Experimental studies of capillary phenomena in bio-based materials 942-2016-64, and the COST Action FP1407 “ModWoodLife” project, is gratefully acknowledged.

REFERENCES

Anon (1997) Nordic Timber: Grading rules for pine (Pinus sylvestris) and spruce (Picea abies) sawn timber: Commercial grading based on evaluation of the four sides of sawn timber. Föreningen svenska sågverksmän (FSS), Sweden.

Davis J, Wells P (1992) Computer tomography measurements on wood. Industrial Metrology 2(3–4):195–218.

Feldkamp LA, Davies LC, Kress JW (1984) Practical cone beam algorithm. Journal of the Optical Society of America A: Optics, Image Science, and Vision 1(6):612-619.

Fredriksson M (2014) Log sawing position optimization using computed tomography scanning. Wood Material Science and Engineering 9:110-119.

Fredriksson M, Berglund A, Broman O (2015) Validating a crosscutting simulation program based on computed tomography scanning of logs. European Journal of Wood and Wood Products 73:143-150.

Funt BV, Bryant EC (1987) Detection of internal log defects by automatic interpretation of computer tomography images. Forest Products Journal 37(1):56-62.

Grundberg S, Grönlund A (1995) The development of a LogScanner for Scots pine. Proceedings from the 2nd International Seminar/Workshop on Scanning Technology and image Processing on Wood. Skellefteå, Sweden, pp. 39-50.

ImageJ 2010 (http://rsbweb.nih.gov/ij/download.html)

Kachelrieß M, Schaller S, Kalender W (2000) Advanced single-slice rebinning in conebeam spiral CT. Medical Physics 27(4):754-772.

Kalender WA (2006) Computertomographie – Grundlagen, Gerätetechnologiue, Bildqualität, Anwendungen. Publicis Corporate Publishing, Erlangen.

Katsevich A (2001) An inversion algorithm for Spiral CT, in: A.I. Zayed (Ed.), Proceedings of the 2001 International Conference on Sampling Theory and Applications, May 13-17, Univ. of Central Florida, pp. 261–265.

Katsevich A (2002) Theoretically exactfiltered backprojection-type inversion algorithm for Spiral CT, SIAMJ. Appl. Math. 62:2012-2026.

Katsevich A (2004) An improved exact filtered backprojection algorithm for spiral computed tomography. Advances in Applied Mathematics 32:681-697.

Lindgren O (1992) Medical CT---Scanners for Non---Destructive Wood Density and Moisture Content Measurements , PhD thesis. Luleå University of Technology, Skellefteå Campus. Division of Wood Technology. Report No. 1992:111D.

Macedo A, Vaz CMP, Pereira JCD, Naime JM, Cruvinel P, Wei et al. (2002) Wood density determination by X- and gamma-ray tomography. Holzforschung 56(5):535–540.

Pietikäinen M (1996) Detection of knots in logs using x-ray imaging". Dissertation. Technical Research Centre of Finland, Espoo. VTT Publications 266, 88 pp. ISBN 951-38-4924-4.

Radon J (1917) Über die Bestimmung von Funktionen durch ihre Integralwerte längs gewisser Mannigfaltigkeiten. Ber. Verh. Sächsische Akad. Wissenschaften 69:262–277.

Stierstorfer K, Flohr T, Bruder H (2002) Segmented multiple plane reconstruction – a novel approximate reconstruction for multi-slice spiral CT. Physics in Medicine and Biology 47:2571-2851.

Tsai CM, Cho ZH (1976) Physics of contrast mechanism and averaging effect of linear attenuation coefficients in a computerized transversal axial tomography (CTAT) scanner. Phys. Med. Biol. 21: 544-559.

Zhu J, Zhao S, Yu H, Ye Y, Lee SW and Wang G (2004) Numerical Studies on Feldkamp-type and Katsevich-type algorithms for cone-beam scanning along nonstandard spirals. Proceedings of the International Society for Optics and Photonics (SPIE), Bellingham, WA. Pp. 558-565.