Dissertationes Forestales 70

The structure of Norway spruce (*Picea abies* [L.] Karst.) stems in relation to wood properties of sawn timber

Anu Kantola

Department of Forest Ecology, University of Helsinki, Finland
Finnish Forest Research Institute, Vantaa Research Unit, Finland

Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public examination in Lecture Hall B6, Building of Forest Sciences, Latokartanonkaari 7, on September 5th 2008, at 12 noon.

Title of dissertation: The structure of Norway spruce (*Picea abies* [L.] Karst.) stems in relation to wood properties of sawn timber.

Author: Anu Kantola

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Supervisors:
Prof. Annikki Mäkelä
Department of Forest Ecology, University of Helsinki, Finland

Dr Harri Mäkinen
Finnish Forest Research Institute, Vantaa Research Unit, Finland

Pre-examiners:
Dr Jennifer C. Grace
Ensis, New Zealand

Professor M. Paulina Fernández
Pontifica Universidad Católica de Chile, Chile

Opponent:
Dr Heli Peltola
Faculty of Forest Sciences, University of Joensuu, Finland

ISSN 1795-7389
ISBN 978-951-651-228-3 (PDF)

(2008)

Publishers:
The Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
Faculty of Forestry of the University of Joensuu

Editorial Office:
The Finnish Society of Forest Science
Unioninkatu 40 A, 00170 Helsinki, Finland
http://www.metla.fi/dissertationes

Kantola, Anu. 2008. The structure of Norway spruce (*Picea abies* [L.] Karst.) stems in relation to wood properties of sawn timber. Dissertationes Forestales 70. 42 p.
Available at http://www.metla.fi/dissertationes/df70.htm

ABSTRACT

An important challenge in forest industry is to get the appropriate raw material out from the forests to the wood processing industry. Growth and stem reconstruction simulators are therefore increasingly integrated in industrial conversion simulators, for linking the properties of wooden products to the three-dimensional structure of stems and their growing conditions. Static simulators predict the wood properties from stem dimensions at the end of a growth simulation period, whereas in dynamic approaches, the structural components, e.g. branches, are incremented along with the growth processes. The dynamic approach can be applied to stem reconstruction by predicting the three-dimensional stem structure from external tree variables (i.e. age, height) as a result of growth to the current state. In this study, a dynamic growth simulator, PipeQual, and a stem reconstruction simulator, RetroSTEM, are adapted to Norway spruce (*Picea abies* [L.] Karst.) to predict the three-dimensional structure of stems (tapers, branchiness, wood basic density) over time such that both simulators can be integrated in a sawing simulator.

The parameterisation of the PipeQual and RetroSTEM simulators for Norway spruce relied on the theoretically based description of tree structure developing in the growth process and following certain conservative structural regularities while allowing for plasticity in the crown development. The crown expressed both regularity and plasticity in its development, as the vertical foliage density peaked regularly at about 5 m from the stem apex, varying below that with tree age and dominance position (Study I). Conservative stem structure was characterized in terms of (1) the pipe ratios between foliage mass and branch and stem cross-sectional areas at crown base, (2) the allometric relationship between foliage mass and crown length, (3) mean branch length relative to crown length and (4) form coefficients in branches and stem (Study II). The pipe ratio between branch and stem cross-sectional area at crown base, and mean branch length relative to the crown length may differ in trees before and after canopy closure, but the variation should be further analysed in stands of different ages and densities with varying site fertilities and climates.

The predictions of the PipeQual and RetroSTEM simulators were evaluated by comparing the simulated values to measured ones (Study III, IV). Both simulators predicted stem taper and branch diameter at the individual tree level with a small bias. RetroSTEM predictions of wood density were accurate. For focusing on even more accurate predictions of stem diameters and branchiness along the stem, both simulators should be further improved by revising the following aspects in the simulators: the relationship between foliage and stem sapwood area in the upper stem, the error source in branch sizes, the crown base development and the height growth models in RetroSTEM. In Study V, the RetroSTEM simulator was integrated in the InnoSIM sawing simulator, and according to the pilot simulations, this turned out to be an efficient tool for readily producing stand scale information about stem sizes and structure when approximating the available assortments of wood products.

Keywords: Branches, Crown, Norway spruce, PipeQual, RetroSTEM, Stem taper, Timber quality, Wood density

ACKNOWLEDGEMENTS

A years-long effort is about to culminate. I was inspired to take on this Ph.D. project mainly through the encouragement of Prof. Annikki Mäkelä of University of Helsinki, who intorduced me to wood quality simulators and suggested that developing them further for Norway spruce would constitute an interesting topic for a doctoral thesis. Dr Harri Mäkinen of Finnish Forest Research Institute (Metla) had varying roles during my Ph.D. project; first he kindly offered his help in data collection, then he became a co-author in two of my articles and finally my supervisor with Annikki. I deeply thank you Annikki and Harri for your encouragement and advice. You led my way to the field of science and trained me to be a researcher. Because of your clear guidelines, the work was a pleasure to carry out. I have also had the priviledge to co-operate with other skilled researches as co-authors: Sanna Härkönen of University of Joensuu, and Arto Usenius, Tiecheng Song and Antti Heikkilä of VTT Building and Transport. I also warmly thank the pre-examiners, Dr Jennifer Grace and Professor Paulina Fernández, for their valuable and constructive remarks on this thesis.

I had the great opportunity to work in the Vantaa office of Metla throughout the project in co-operation with several colleagues: Mikko Kukkola, Risto Ojansuu, Jari Hynynen, Aleksi Lehtonen, Marja-Liisa Herno, Hannele Saloseutu, Irmeli Virtanen, Sointu Nenola, Timo Siitonen, Tapio Huttunen, Tapio Nevalainen and all the field and laboratory personnel in the Salla office, particularly Pasi Aatsinki. I'd like to thank you Mikko for your advice in various details regarding the data bases in Metla, measuring and laboratory tasks, to begin with. Risto and Jari, you kindly offered me the opportunity to work in Metla. Aleksi, thank you for introducing me to the VAPU data base. Marja-Liisa, you edited my posters and gave me instructions for making graphic illustrations in general. Additionally, many thanks to all graphic designers who have helped me during this doctoral effort. Hannele and Irmeli, you converted the measured data to electronic form. Sointu, you designed several maps for me and together with Tapio H. took care of my computer facilities. Timo, you introduced me to the long-term experiments. Tapio N. you were a great help at the measurement sites in Punkaharju and Heinola. All my workmates in Metla who shared the coffee breaks with me (in addition to the above mentioned: Saija, Mervi, Tiina, Mikko V., Tuomo, Minna, Anja, Hilkka, Sauli, Risto S., Jari P., Kari, Antti I. and M., Simo), I have been very lucky to have you around during this Ph.D. project. Special thanks are due to to all who gave me a lift between Tikkurila and Viikki.

Above all, my dearest thanks go to Terhi Eskelinen, Saija Huuskonen, Tuula Jyske and Riitta Ryömä: you shared with me your friendship and experience as a Ph.D. student. Terhi and Saija, you gave me the strength to carry on. I owe warm thanks to my parents and Markus for supporting and encouraging me throughout the PhD project.

Finally, I would like to thank all those who funded this work: the Foundation for Research of Natural Resources in Finland first funded this study through a personal grant, then as part of the PURO research consortium. Additionally, Finnish Forest Research Institute, University of Helsinki (Innovood consortium), the Graduate School in Forest Sciences and Puumiesten Ammattikasvatussäätiö and Finnish Cultural Foundation have kindly financed my work.

Vantaa, July 2008

Anu Kantola

LIST OF ORIGINAL ARTICLES

This thesis consists of an introductory review followed by five research articles. These papers are reproduced with the permission of the journals in question.

I **Kantola, A.** & Mäkelä, A. 2004. Crown development in Norway spruce (*Picea abies* [L.] Karst.). Trees 18: 408–421. doi: 10.1007/s00468-004-0319-x.

II **Kantola, A.** & Mäkelä, A. 2006. Development of biomass proportions in Norway spruce (*Picea abies* [L.] Karst.). Trees 20: 111–121. doi: 10.1007/s00468-005-0018-2.

III **Kantola, A.,** Mäkinen, H. & Mäkelä, A. 2007. Stem form and branchiness of Norway spruce as a sawn timber—Predicted by a process based model. For. Ecol. Manage. 241: 209–222. doi:10.1016/j.foreco.2007.01.013.

IV **Kantola, A.,** Härkönen, S., Mäkinen, H. & Mäkelä, A. 2008. Predicting timber properties from tree measurements at felling: Evaluation of the RetroSTEM model and TreeViz software for Norway spruce. For. Ecol. Manage. 255: 3524–3533. doi:10.1016/j.foreco.2008.02.034.

V **Kantola, A.,** Song, T., Usenius, A. & Heikkilä, A. 2008. Simulated yield and quality distribution of sawn timber from final felling in a Norway spruce (*Picea abies* [L.] Karst.) stand with varying thinning regimes — a case study. (Submitted to Wood Material Science and Engineering).

AUTHOR’S CONTRIBUTION

I am fully responsible for the text of this doctoral thesis, and all of the following five articles as a corresponding author. I was responsible for the field measurements in studies I, II, III (data set 1) and V. I carried out all the data analysis and wrote all the manuscripts by myself for the first lay-outs, after which the other authors reviewed and complemented my text. The PipeQual and RetroSTEM simulators, which I tested in studies III and IV, were parameterised by Annikki Mäkelä. In study III, appendix A was written by Annikki Mäkelä and appendix B by Harri Mäkinen. In study IV appendix A was written by Annikki Mäkelä and appendix B by Sanna Härkönen. In study V, the sawing simulations were run in VTT Technical Research Centre of Finland by Antti Heikkilä.

CONTENTS

1 INTRODUCTION

1.1 Norway spruce as raw material

Norway spruce (*Picea abies* [L.] Karst.) is a globally and locally important raw material for paper products, sawn goods and wood-based panels (Finnish Statistical Yearbook... 2006). The Finnish forest industry uses mainly softwood (ca 80% of the total wood consumption in the 2000s), recently favouring Norway spruce in sawn goods and wood-based panels (Fig. 1) (Metinfo database 2008). Since 2000, the annual growth of Norway spruce stands in Finland is approximately 27 million m^3, and the average annual removal of commercial roundwood 25 million m^3, of which around 60% is used as sawn timber and wood-based panels (Fig. 1) (Finnish Statistical Yearbook... 2006, Metinfo database 2008).

The visual and strength properties of sawn timber determine its suitability for wooden products (Hanhijärvi 2005, Lycken 2006). The properties are primarily quantified by the knottiness (number, size, quality and distribution) and wood density of the board, controlled by grading rules (Fig. 2) (Hanhijärvi 2005, Lycken 2006). High quality sawn timber of Norway spruce is mainly used in interior decoration; e.g. window and door frames, panels and load bearing constructions, while low quality boards are used e.g. as packaging materials (Nordic timber grading... 1997). The quality requirements of sawn goods vary as new products are introduced into the market, challenging the grading rules (Johansson et al. 1994).

The properties of sawn timber are dependent on stem structure: stem size, taper, branchiness, and wood density (Verkasalo and Leban 1996, Jäppinen and Beauregard 2000, Todoroki et al. 2001, Lycken 2006). Stem structure is dependent on the tree's rate of growth, which can be managed by silvicultural treatments. In Norway spruce stands, heavy thinning that favours dominant trees results in large stems with pronounced tapering (Brüchert et al. 2000, Mäkinen and Isomäki 2004ab), large branches (e.g. Mäkinen et al., 2003) and low wood density (e.g. Pape 1999ab). Knot-free timber can rarely be obtained from Norway spruce stems. Compared to Scots pine (*Pinus sylvestris* L.), however, the knots are smaller and the proportion of sound knots in a stem is larger (Hakkila 1969, 1972, Kärkkäinen 1986).

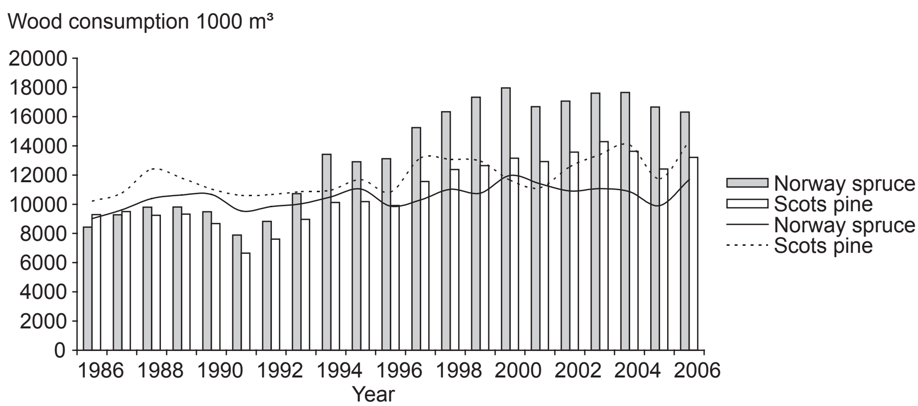

Figure 1. Softwood consumption in sawmilling and wood-based panel industry (blocks) and pulp industries (lines) in Finland (Source: Metinfo database 2008).

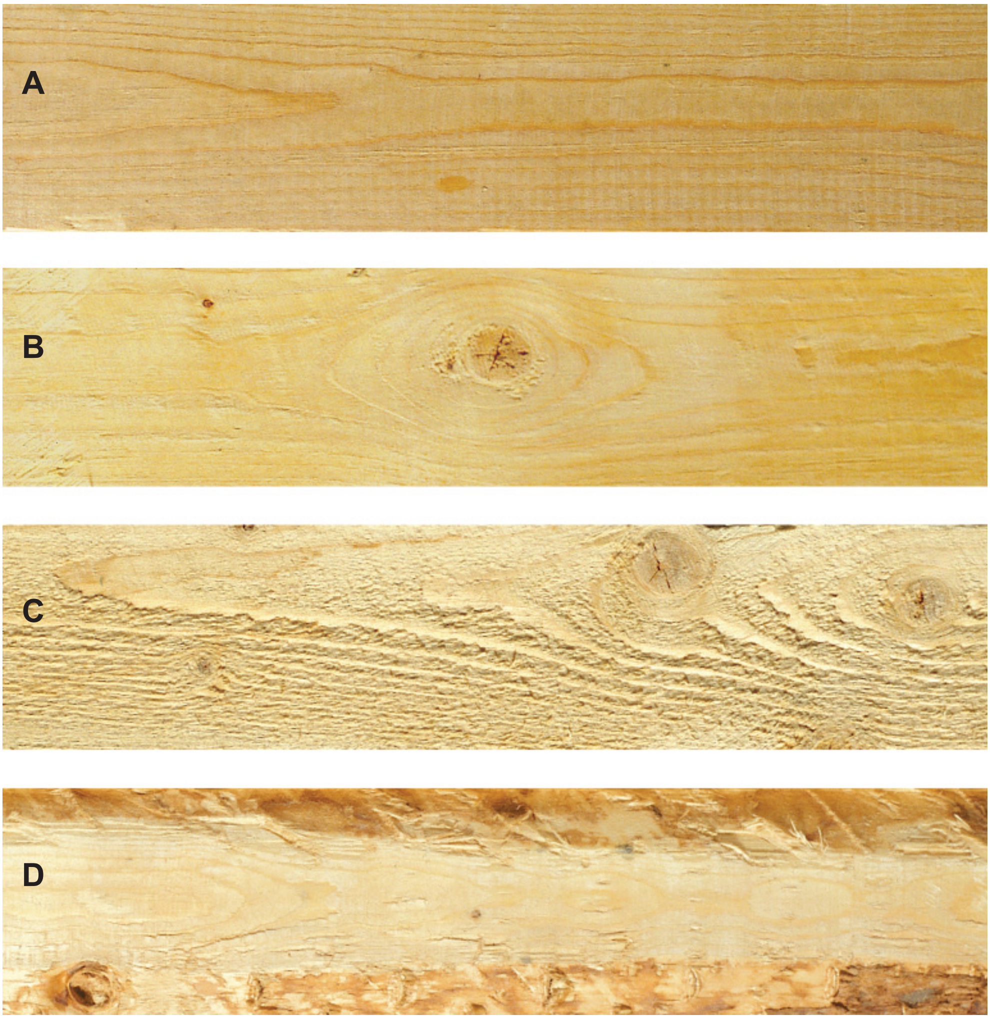

Figure 2. Graded timber from best A to poorest D grade of Norway spruce sawn goods according to Nordic timber grading rules (1997). The grading is mainly based on the number, size, quality and distribution of branches, as well as on wood colour, defects and wane. (Picture: Puuinfo Oy).

In Finland, Norway spruce stands are typically planted with 1600–1800 seedlings ha^{-1}, followed by a pre-commercial thinning and one to three thinnings before the final felling (Hyvän metsänhoidon suositukset 2006). The first commercial thinning is based on stand dominant height and the number of remaining stems per hectare. The later thinnings are based on basal area of the remaining stems and dominant height. The final felling is recommended when the stand average diameter at breast height has reached 26–32, 25–30, and 25–26 cm in southern, central and northern Finland, respectively. The timing can also be based on stand age (70–90, 70–100, and 100–130 yrs. in southern, central and northern Finland, respectively) (Hyvän metsänhoidon suositukset 2006).

1.2 Simulating stem structure and wood properties of sawn logs and boards

The most important challenge at the moment for improving the profitability of forest industry is to get the appropriate raw material out from the forests to the wood processing industry. New methods are needed for establishing links between structural wood properties and the growing conditions of trees and stands, allowing for efficient operational planning throughout the whole wood conversion chain. Modern growth and stem reconstruction simulators are therefore being increasingly developed for predicting the three-dimensional stem structure (stem/heartwood geometry, knots, growth rings) (e.g. Houllier and De Reffye 1996, Mäkelä et al. 2000ab, Johnsen et al. 2001) (Fig. 3). The integrated systems between three-dimensional stem simulators and industrial conversion simulators, such as sawing simulators, can be used for testing varying forest management and wood conversion scenarios in process analyses and in product development.

The growth simulators use either the static or dynamic approaches for predicting the three-dimensional stem and wood properties. The static growth simulators apply static equations, for properties such as stem taper and branch dimensions. The prediction of stem and log structure is then provided at the end of the simulation period, i.e., the stem and wood properties are independent of the growth processes. For example, the STANDPAK stand growth simulator was linked to a separate log quality/sawing simulator AUTOSAW (Todoroki and Carson 2003), and accordingly, TASS growth simulator was expanded by equations for the branch and stem properties (Goudie 2002).

The dynamic quality prediction allows more explicit prediction of the three-dimensional stem structure as the past growth of stem and branches affects their future increment. The simulators may include a dynamic description for branch growth only or separate dynamic models for stem growth as well. For example, SILVA simulator includes a semi-dynamic reconstruction for branch diameters, as the crown plasticity in relation to competition was taken into account in branch increment models (Seifert and Pretzsch 2002, Seifert 2003). Similarly, BWINPro has a dynamic description of crown development and branch growth (Schmidt 2001, 2004, Schmidt et al. 2006), and in the Sylview simulator the knot zones inside stems are determined on the basis of crown rise (Scott 2006). TreeBLOSSIM simulator by Grace et al. (2006) and the simulator of Kellomäki et al. (1999) and Ikonen et al. (2003) have also been developed to predict the whole stem three-dimensional structure dynamically.

The growth of the structural components can also be linked with each other, producing a dynamic description of the stem and wood properties where the increment of foliage increases growth allocation to branches and stem in certain proportions. Architectural tree simulators AMAPpara (Reffye et al. 1997) and LIGNUM (Perttunen et al. 1998) are assuming a proportional growth between tree compartments, and the model by Deleuze and Houllier

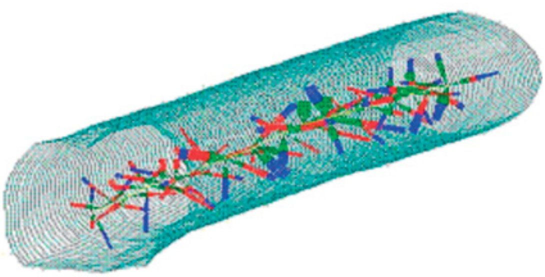

Figure 3. Three-dimensional illustration of a log (Picture: VTT).

(1995, 1997) predicts the stem form on the basis of the growth partitioning between foliage and stem. Similarly, the PipeQual simulator (Mäkelä et al. 2000b, Mäkelä 2002, Mäkelä and Mäkinen 2003), predicts dynamically the stand and tree increment and the three-dimensional structure of stems over time through relationships between foliage and woody pipes in whorls and stem.

As a complement to growth-quality simulators, stem reconstruction simulators can be used for simulating the stem three-dimensional structure from simple tree dimensions (height, stem diameter at breast height, crown ratio) at the time of harvest, such that no input data on the stand properties and past management operations are needed. In France, Leban et al. (1996) developed the Win-EPIFN simulation system by including models for stem and wood properties, as well as for the log and board grading. In Finland, Mäkelä et al. (2002) developed the RetroSTEM simulator for predicting three-dimensional stem structure and wood properties.

The virtual stems and logs can be converted to sawn timber by sawing simulators. In New Zealand, Todoroki (1990) developed a sawing simulation system, AUTOSAW, which provides visualisation of three-dimensional logs and timber products. It has been used e.g. for studying volume and value optimisation of timber (Todoroki and Rönnqvist 2002). In France, Leban and Duchanois (1990) developed the SIMQUA simulator to describe the quality of logs and boards, and e.g. Saint-André et al. (1996) used the system for simulating the quality distribution of sawn timber. In Sweden, various sawing simulators have been developed based on CT-scanned stem data: e.g. the Virtual Sawmill software or Saw2003 (Chiorescu and Grönlund 2000, Nordmark 2005). In Finland, Ikonen et al. (2003) introduced a sawing simulator for converting simulated logs into boards including their quality grading. At the Technical Research Centre of Finland (VTT), the WoodCIM and InnoSIM simulators were developed for research and industrial purposes in order to analyse virtually the wood conversion chain (Usenius 2002, Pinto 2004, Song and Usenius, 2007).

1.3 A theoretical framework for simulating Norway spruce stems

1.3.1 Background

Previous model systems in Finland have been developed for predictions of the three-dimensional stem structure in Scots pine (Kellomäki et al. 1999, Ikonen et al. 2003, Mäkelä 2002, Mäkelä and Mäkinen 2003, Mäkelä et al. 2002). Recently Ikonen (2008) has introduced empirical models for describing the distribution of wood density, early wood percentage and fibre length along Scots pine and Norway spruce stems, which can be integrated into a process-based growth and yield model. In this study, the PipeQual (Mäkelä and Mäkinen 2003) and RetroSTEM (Mäkelä et al. 2002) simulators were adapted to predict the three-dimensional stem structure of Norway spruce including stem tapers, branchiness and wood properties. Both simulators share a similar theoretical basis on tree structure, according to which the simulators have been formulated.

1.3.2 The regularity and plasticity in tree structure

The theoretical framework of this study is based on the idea that the vertical stem structure at any moment of time is a consequence of the growth process, following certain conservative structural regularities while allowing for plasticity in some other characteristics. The regular relationships constrain the development of tree structure through the growth allocation between foliage, branch and stem wood, while the plastic structures respond to the environment, such as stand density, yielding different stem properties under different thinning regimes and stocking densities. In order to describe these processes, it is important to identify the regular structures on one hand, and the plastic structures on the other hand.

1.3.3 The regular tree structure

The main theories utilised here for the regular tree structures are the pipe model theory (Shinozaki et al. 1964ab) and the theory of crown allometry (Zeide and Pfeifer 1991, Mäkelä and Sievänen 1992, West et al. 1999). According to the pipe model theory, the "active" (or sapwood) branch and stem wood cross-sectional areas at any height along the stem are proportional to the foliage mass above, showing a constant relationship throughout the crown (Eqns. 1 & 2), and that as the crown rises, the active pipes become disused, eventually accumulating as heartwood. The theory of crown allometry defines the photosynthetic capacity of a tree, postulating a functional relationship between foliage mass and crown dimensions, which can be expressed by crown surface area or length (Eqn. 3).

The hypotheses of regular crown and stem structure are formulated following Mäkelä (1986, 1997). Firstly, it is assumed that the trees follow the pipe model structure (Shinozaki et al. 1964ab). Foliage mass W_f (kg) is assumed to be proportional to stem cross-sectional area at the base of the live crown (crown base), A_c (m^2):

$$W_f = \eta_s A_c \tag{1}$$

where η_s is an empirical coefficient. Secondly, the cumulative cross-sectional area of live branches in the crown, A_b (m^2) is also proportional to stem cross-sectional area at crown base, A_c (m^2):

$$A_b = \eta_s / \eta_b \, A_c \tag{2}$$

where η_b is an empirical coefficient relating foliage mass to cumulative branch area. It is further hypothesized that there is an allometric relationship between foliage mass, W_f (kg) and crown length, H_c (m) (i.e. the distance from the tree top to the base of the live crown):

$$W_f = \xi H_c^{\,q} \tag{3}$$

where ξ and q are empirical parameters (Mäkelä and Sievänen 1992, Mäkelä 1997, Ilomäki et al. 2003).

In the previous studies, it was demonstrated that in some pioneer tree species, crown shape is stable across different environments, suggesting that the mean basal-area-weighted branch length in the crown, H_b (m) is proportional crown length, H_c (m) (Vanninen 2003, Ilomäki et al. 2003). However, the previous studies also suggested that crown shape of Norway spruce is not constant (Greis and Kellomäki 1981, Hakkila 1989, Deleuze et al. 1996). The crowns of Norway spruce are initially conical but branch lengths reach a maximum as crowns grow longer, decreasing the crown width to crown length ratio with increasing crown length. In addition, the mean length of branches in crowns of similar length may be regulated by growing space (Deleuze et al. 1996).

In order to incorporate these effects in a simple structural model, it is hypothesized that H_b (m) is a power function of crown length, H_c (m):

$$H_b = \gamma_b H_c^{\ b} \tag{4}$$

where γ_b and b are empirical parameters. Using (3) and (4), total branch biomass in the crown can be estimated from crown length and stem basal area at crown base.

In a tree, satisfying the above regularities, stem and branch mass are related to foliage mass through their cross-sectional areas. Then, branch biomass, W_b (kg) can be expressed as follows:

$$W_b = \rho_b \varphi_b H_b A_b = \rho_b \varphi_b \frac{\eta_s}{\eta_b} H_b A_c \tag{5}$$

where ρ_b is branch wood density and φ_b is an empirical coefficient. Because $A_b H_b$ denotes the volume of a cylinder with cross-sectional area A_b and height H_b, the parameter φ_b reflects the form of the branching system relative to that cylinder, and will hereafter be called "form coefficient".

Stem mass inside the live crown, W_{sc} (kg) can be similarly estimated from stem cross-sectional area at crown base, A_c (m^2), and crown length, H_c (m):

$$W_{sc} = \rho_s \varphi_{sc} H_c A_c \tag{6}$$

where ρ_s is stem wood density and φ_{sc} is an empirical form coefficient.

Stem mass below the crown, W_{sb} (kg) can be approximated by assuming that the bole, i.e. tree height, (m) minus crown height (m) (H-H_c), is a cut cone with top diameter A_c and base diameter A_c/r_c, where r_c is crown ratio (H_c/H) (Valentine et al. 1994). We may write

$$W_{sb} = \rho_s \varphi_{sb} (H - H_c) A_c \tag{7}$$

where the form coefficient φ_{sb} is calculated by

$$\varphi_{sb} = 1/2\,(r_c + 1)/r_c \tag{8}$$

1.3.4 The plastic crown profile and effect on stem structure

The crown profile theory (Chiba et al. 1988, Osawa et al. 1991) states that if the vertical density distribution of foliage and the rate of crown rise are specified, the development of the stem profile (taper, branch sizes) follows through the pipe model assumptions (see chapter 1.3.3) (Shinozaki et al. 1964ab). Chiba et al. (1988) and Osawa et al. (1991) further assumed, for simplicity, that the vertical foliage mass density distribution in a crown is constant throughout the life span of a tree, only moving upwards at the same rate as the tree grows taller, and that consequently, the active pipes turn over at the same specific rate as foliage. This allowed them to calculate the development of stem taper and branchiness from height growth.

If the simplifying assumptions of Chiba et al. (1988) and Osawa et al. (1991) are used, the crown profile theory can be applied by just predicting the height growth of the tree. If the crowns are described more realistically, i.e., allowing for plasticity in their lengthening and widening with increasing age and growing space, then a more complicated model of crown development is required. Mäkelä (2002) applied the crown profile theory for Scots pine trees that were allowed to increase their crowns if they grew taller or if their crown ratio increased. However, based on measurements in Scots pine by Mäkelä and Vanninen (2001), the relative vertical foliage mass distribution was assumed unchanged across tree ages, stand densities and dominance positions, the density distribution always peaking approximately at mid crown.

1.4 Simulation of stem structure using the PipeQual and RetroSTEM

1.4.1 Structure of simulators

The PipeQual (Mäkelä and Mäkinen 2003) and RetroSTEM (Mäkelä et al. 2002) simulators have been constructed to provide the growth rate that updates the vertical tree structure according to the ideas of the profile theory, allowing for crown plasticity. Both simulators share a similar modular structure; The 'Tree' module determines the growth of the tree and its crown development. The 'Whorl' module describes the vertical structure of the stem by

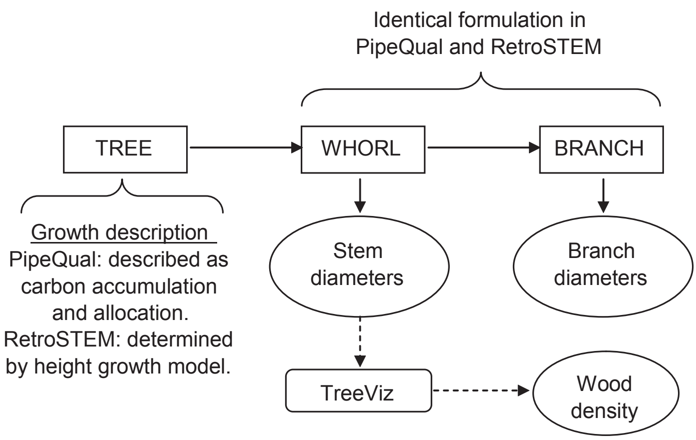

Figure 4. The modular structure of the PipeQual and RetroSTEM simulators and their outputs (in ovals), dashed arrow is used for the TreeViz tool.

whorls, while the 'Branch' module transfers the whorl level information to individual branches using empirical branch equations by Mäkinen et al. (2003) (Fig. 4). The structures of the PipeQual and RetroSTEM simulators only differ from each other for the growth formulation in the TREE module (Fig. 4).

1.4.2 Tree growth

In PipeQual, growth is calculated on the basis of the difference between photosynthesis (affected by shading of neighbouring trees) and respiration. The growth allocation maintains the assumed balanced structure (Eqns. 1–8), as described above. The relative distribution of the total foliage follows a given shape between tree top and crown base, and crown rise is determined by the available growing space. Height growth follows from crown rise and foliage increment, so as to maintain the assumed allometry of the crown (Eqn. 3).

In RetroSTEM, growth is driven by height growth and crown rise which provide the amount of foliage mass through Eqn. (3). The estimation of past height from current height at felling is based on a family of empirical site index curves (Vuokila and Väliaho 1980). It is also assumed that the crown base begins to rise at age 20, reaching finally the current height of the crown base at felling.

1.4.3 Vertical stem structure and branches

The growth updates each year the vertical structure of the stem formulated by whorls (Fig. 4). Each whorl is described by the active and disused pipe area of the stem and branches, internode length, mean branch length, and foliage attached to the whorl. The foliage density in each whorl determines the growth rate of branches and stem diameter at that whorl because the area of active pipes is assumed proportional to foliage mass (Shinozaki et al. 1964ab). The area of disused pipes in the stem and branches is added each year to wood that is no longer connected to live foliage. In RetroSTEM, the stem diameter simulation is further repeated iteratively until the simulated stem diameter at breast height (DBH) matches the measured one within a pre-determined accuracy.

The branch module is based on empirical, stochastic models by Mäkinen et al. (2003), which calculate the annual dynamics of individual branches and their properties (initial number, relative sizes, compass and insertion angles) in each whorl using branch cumulative basal area as input from each whorl (Fig. 4). As the whorl ages, the module updates these variables using sub-models for branch death within the crown, insertion angle, size distribution, and self-pruning of branches below the live crown. Each branch initiates from a stem internode and the internal knot remains embedded in the stem after self-pruning.

1.4.4 Wood properties

The wood basic density is calculated by the visualising tool TreeViz, using the three-dimensional stem prediction. In addition to wood density, TreeViz calculates and visualises latewood proportion, tracheid length and width in stems (Mäkinen et al. 2007a). For the wood property simulations, a complete description of ring structure is needed (available in Whorl module of PipeQual and RetroSTEM) (Fig. 5). If the ring structure is only partially available, TreeViz utilises statistical models and interpolation methods to provide estimates of the missing inputs, e.g. by interpolating ring widths over the whole stem from measured stem disks.

1.4.5 Summary

PipeQual and RetroSTEM were initially developed for Scots pine. In spite of their partly similar model structure, the PipeQual and RetroSTEM simulators have been developed for different purposes. This is reflected in the inputs and outputs of the simulators. PipeQual predicts the development of the three-dimensional stem structure for ten mean stems at any given age representing different size classes in a stand. The simulator uses the initial density of a young seedling stand as an input variable, taking tree interactions, thinnings and mortality within a stand into account. Instead, RetroSTEM reconstructs three-dimensional stem structure and wood properties from measured input (tree age, diameter at breast height, height and crown ratio) at felling. PipeQual is therefore focused on analysing the impacts of growth conditions or forest management operations on tree and stand growth and stem properties, whereas RetroSTEM can be strictly used for predicting the stem properties. However, both simulators can be used for several purposes, from silvicultural to industrial aspects. PipeQual and RetroSTEM are developed and parameterised by A. Mäkelä; PipeQual is described in detail by Mäkelä (1986, 1997, 2002) and Mäkelä and Mäkinen (2003), and RetroSTEM by Mäkelä et al. (2002).

1.5 Objectives and hypotheses

This study tests the structural description of Norway spruce stems and crowns in stands of varying ages and densities and simulates the raw material properties in stems (taper, branchiness, wood basic density) and sawn timber (quality grades) (Fig. 5).

The first objective was to evaluate the postulated structural regularities in crowns and stems using empirical data, and to test to what extent they could be regarded independent of stand age or the dominance position of the tree (Study I, II). The results were further utilised for parameterising the PipeQual and RetroSTEM simulators for Norway spruce.

The second objective was to evaluate the performance of both simulators against measured trees, regarding stem form, branchiness and wood density (Study III, IV). The accuracy of the predictions can be traced back to the theoretical assumptions, and the adequacy of the assumptions is discussed. If needed, alternatives to structural description of Norway spruce are proposed. After model evaluation, when understanding the potentials and limitations of both simulators, they can be used in describing the quality distribution of sawn timber.

The third objective was to integrate the RetroSTEM simulator with the InnoSIM sawing simulator and to examine the behaviour of the combined tool by analysing the timber quality distribution of trees at stand scale in different thinning regimes (Study V).

More specifically, the following **hypotheses** (Fig. 5) were posed:

(1) Structural regularities exist between foliage, branches and stem in Norway spruce (Study I and II):

- Relative vertical density distribution of foliage mass in a crown is constant over time.
- Branch and stem sapwood cross-sectional area at any height in the crown is proportional to foliage mass above (Eqn. 1, 2).
- An allometric relationship exists between foliage mass and the length of the live crown (Eqn. 3).
- Basal-area-weighted mean branch length is a power function of crown length (Eqn. 4).
- Branch or stem form coefficients inside the live crown (Eqn. 5–6) are independent of stand age or the competitive status of the tree.
- The stem form coefficient below the live crown varies with crown ratio (Eqn. 8)

(2) Stem structure (taper, branchiness, ring width and wood density) can be predicted based on the structural regularities in trees (Study III, IV).

(3) The yield and quality distribution of sawn timber can be predicted on the basis of the structural regularities in trees (Study V).

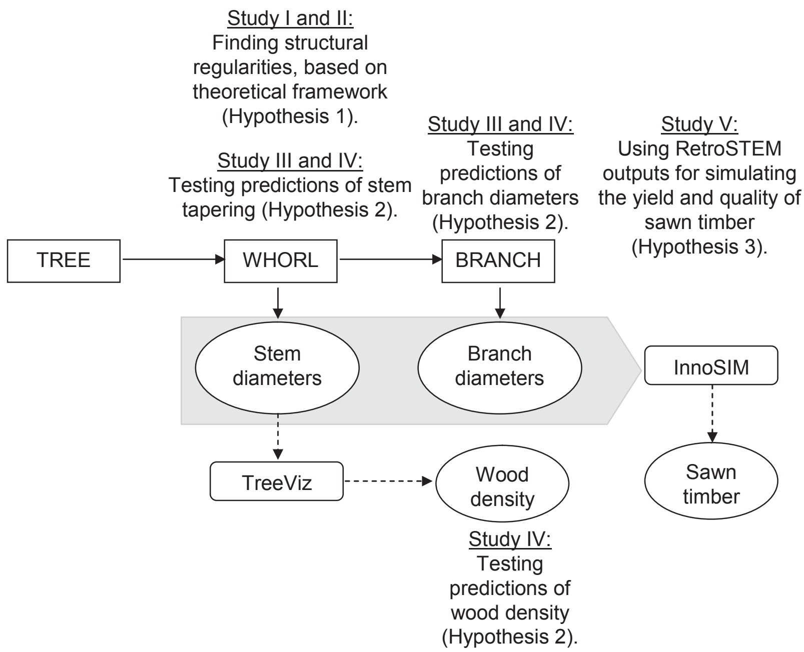

Figure 5. Schematic presentation of the studies in relation with the simulators. The grey block arrow defines the input data to the InnoSIM sawing simulator.

2 MATERIAL AND METHODS

2.1 The main principles

In order to test the hypotheses, tree and crown structure were measured in stands with different ages and thinning treatments (Study I, II). The structural interpretations were used when parameterising structural modules (‘Tree’ and ‘Whorl’) in the PipeQual and RetroSTEM simulators (Fig. 5). The simulator outputs were then tested for stem taper, branch diameters, ring widths and wood density, and the outputs of ‘Whorl’ and ‘Branch’ modules were used when applied the RetroSTEM in analysing the yield and quality distribution of sawn timber on a stand scale.

2.2 Study sites and measurements

2.2.1 Data bases

Studies I, II, III and V were based on five permanent thinning experiments in southern Finland, established and maintained by the Finnish Forest Research Institute (Metla) (Table 1, Fig. 6). Study IV was based on the temporary sample plots of Vapu (Valtakunnallinen Puututkimus; “National Tree Study”) data base collected by Metla (Korhonen and Maltamo 1990).

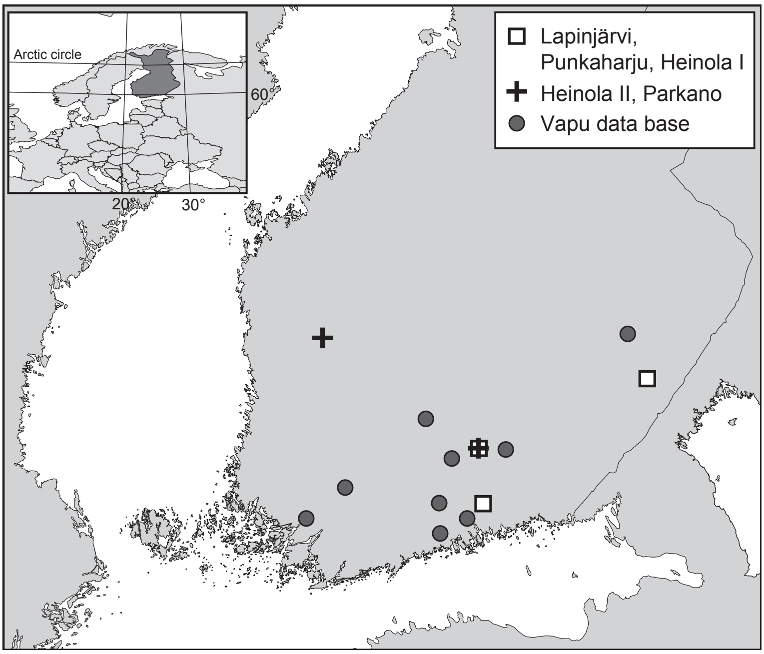

Figure 6. Location of the stands. The different symbols represent the data sets measured in different years and for different purposes.

Table 1. Stand characteristics.

Study Sites	I, II Lapinjärvi	I, II, III, V Punkaharju	I, II, III Heinola I	III Heinola II	III Parkano	IV Vapu data set
Measured (year, month)	2001 Nov	2001 Nov	2001 Nov	2004 Oct	2004 Oct	1988-90
Location	60°39´N, 26°07´E	61°49´N, 29°19´E	61°11´N, 26°01´E	61°11´N, 26°01´E	62°09´N, 22°52´E	61°05´N-62°14´N, 22°46´E-28°58´E
Temperature sum (*d.d*)	1360	1236	1250	1254	1085	1140-1340
Altitude (m)	50	85	120	115	190	30-150
Stand age (years)	25	67	86	73	79	47-104
Site type [a)]	OMT	OMT	OMT	OMT	MT	VT-OMT
Site index [b)] (H_{100}, m)	27	32	33	33	28	18-34
Experiment type	seeding	thinning	thinning	thinning	thinning	temporary plots
Plots [c)]	1*a*	3*a,b,c*	3*a,b,c*	1*c*	1*c*	9
Sample trees [d)] (*n*)	5	12	12	6	6	31

[a)] *Vaccinium* (VT), *Myrtillus* (MT) and *Oxalis-Myrtillus* (OMT) (Cajander 1949), [b)] dominant height at 100 years: Gustavsen (1980), Vuokila and Väliaho (1980), [c)] number of plots and their thinning intensities: (*a*) unthinned, (*b*) normal thinning, (*c*) intensive thinning, [d)] number of felled sample trees.

2.2.2 Studies I and II

For tree structure analysis, a total of 29 trees were sampled from three stands with different ages and thinning regimes (Table 1, Fig. 6). The stands represented the *Oxalis-Myrtillus* (OMT) site type (Cajander 1949). In the youngest stand (25 yrs), after regeneration no silvicultural treatments were carried out, whereas both of the older stands (67 and 86 yrs) had one unthinned, one normally thinned and one intensively thinned plot each. The removal was 20–30% of stand basal area when normally thinned, and 30–40% when intensively thinned. In the older stands, five trees were sampled from the unthinned, four from the normally thinned, and three from the intensively thinned plot. The trees were sampled according to the stem cumulative basal area distribution in each plot (the sampling procedure is described in detail in Study I, II and III).

The felled sample trees were measured for their stem and branches. Measured variables were: stem diameter at breast height (1.3 m), tree height, height to crown base, distance of each whorl from the tree top, and stem diameter between the whorls. The crown base forms the bottom of the live crown and was defined by the lowest whorl, which had at least one living branch, being separated from the other living whorls above it by no more than one dead whorl. For each branch in the whorl, the horizontal diameter was measured, as well as the branch status (live, dead). From each sample tree, a total of 10 living branches were sampled and measured for their length and dry masses of foliage and branch wood separately (the branch sampling is described in Study I). Seven sample disks were cut from the stem at stump height, crown base, 1.3 m, 6 m, 30%, 70% and 90% heights in all sample trees. The disks were measured for heartwood, sapwood and bark width. Omitting stump and 6 m heights, five disks were measured for wood basic density as well.

2.2.3 Study III

The PipeQual simulator was evaluated for predicting stem taper and the diameter distribution of branches over the stem. The test material consisted of two data sets. Data set 1 (Punkaharju and Heinola I) is introduced in studies I and II. It was also used in the PipeQual simulator when determining the structural parameters at whorl level (Table 1, Fig. 6).

Data set 2 was an independent test data set. It consisted of two stands (Heinola II and Parkano), each with one intensively thinned plot. Heinola II represented the *Oxalis-Myrtillus* (OMT) site type, while Parkano was of the *Myrtillus* (MT) site type (Cajander 1949). In both of these stands (age 73 and 79 yrs) six trees were sampled according to the stem cumulative basal area distribution (see the sampling procedure in Study III). The sample trees were felled and measured for stem and crown dimensions similarly to studies I and II. However, the diameter and branch status measurements were only taken in every fifth whorl, and no sample branches were taken for biomass measurements.

2.2.4 Study IV

The RetroSTEM simulator was evaluated for predicting stem taper, branch diameter, ring width and wood density distribution over the stem. The test material consisted of an independent data set (VAPU) (see the sampling procedure in Study IV). It was collected in southern Finland in years 1988–90, as a sub-sample of the temporary plots of the 8th National Forest Inventory (NFI8) (Korhonen and Maltamo 1990, Tomppo et al. 2001, Tomppo 2006).

For this study, all defect-free (no broken or forked tops, no decay) Norway spruce sample trees (DBH > 10 cm) were selected from spruce dominated (85–100% of total tree volume in dominant tree storey), middle-aged and mature stands (>45 yrs) of the VAPU data base. Approximately 20% of the spruce sample trees were discarded from the 9 plots because of the defects. The material consisted of 31 Norway spruce trees from nine stands (Table 1, Fig. 6). The sites ranged from relatively infertile to relatively fertile: *Vaccinium* (VT), *Myrtillus* (MT) and *Oxalis-Myrtillus* (OMT) (Cajander 1949) with H_{100} (dominant height at 100 years) between 18 and 34 m (Gustavsen 1980, Vuokila and Väliaho 1980).

The sample trees were measured for height, height to crown base and stem diameter at 19 heights. The crown base was defined by the lowest whorl, which had at least one living branch, being separated from the other living whorls above it by no more than one dead whorl. All branches, including internodal branches, were measured over every second one-meter interval along the stem (starting between 0–1 m) for their distance to ground level and diameter (after basal swell). Because the whorls were not identified in the data, branch maximum diameters determined per measured even meter over stem, and were compared to corresponding simulated values. Disks for measuring ring widths were taken at 10 heights and those for measuring wood basic density at 5 heights (see the precise measuring heights in Study IV). The sampling and measurements were described in detail in Korhonen and Maltamo (1990).

2.2.5 Study V

The RetroSTEM simulator was used for predicting the three-dimensional structure of stems in Punkaharju, in the same stand as in study I (Table 1). Since the number of trees on the differently thinned plots was too low to represent an adequate number of trees on a stand scale, additional trees were generated on the basis of stem frequency distributions between DBH classes for each thinning treatment resulting in 100 trees per plot (the procedure is described in detail in Study V). The RetroSTEM simulated stems were then virtually cut to logs and sawn using the InnoSIM sawing simulator. It computes the yield, quality distribution and value of sawn timber.

2.3 Methods

2.3.1 Analysing tree structure (Study I, II)

In studies I and II, it was investigated under what conditions the hypothesized structural regularities and constants could be applicable to predicting three-dimensional stem structure. In study I, the stem vertical structure was tested in terms of pipe model and crown profile theories (Shinozaki et al. 1964ab, Chiba et al. 1988, Osawa et al. 1991). In study II, the tree structure was analysed concerning pipe ratios, crown allometry and form coefficients (Eqn. 1–8).

In Study I, the foliage and branch wood biomasses as well as the branch length were estimated for each branch in the crown (the equations and parameters are given in Study I). In study I, the relationship between foliage mass or cumulative branch cross-sectional area to stem cross-sectional area was analysed from the stem apex downwards. In Study II, the foliage mass (W_f, kg) was hypothesized to be proportional to stem cross-sectional area at crown base (A_c, m^2) by pipe ratio η_s, and branch cross-sectional area (A_b, kg) was hypothesized to be proportional to stem cross-sectional area at crown base (A_c, m^2) by η_s/η_b (Eqns. 1 and 2). The linearity of all pipe relationships was tested by non-linear regression analysis (see the formulation in Study I). The structural regularities in crown were calculated by Eqns. 3 and 4.

For estimating the form coefficients for branches and stem, wood basic density and mass needed to be calculated (described in detail in Study II). The wood basic density was adjusted over the stem at 1 cm intervals by interpolating wood density measurements from 5 heights of a tree for sapwood, heartwood and bark separately. The stem volume, calculated by spline-curves, was fitted through measured diameters of stem (under and above bark) and heartwood. The sapwood, heartwood and bark mass in each section were calculated as a product of wood density and stem volume. The wood basic density in a whole stem was calculated by summing up the sapwood and heartwood masses and dividing this by stem volume. The branch wood basic density was calculated using an empirical relationship between branch diameter and branch wood basic density (Hakkila 1972). The form coefficients for branches and stem inside the live crown were calculated as the ratio of the mass of a component to its cylinder volume multiplied by wood density (Eqn. 5, 6, 7). The form coefficient below the live crown was calculated by Eqn. 8 as well.

The pipe ratios at tree level, the structural regularities in a crown and form coefficients were tested to see if they vary between stands or correlate with slenderness (H/D), defined as tree height (m) divided by stem diameter (cm) at breast height. Slenderness describes the competitive status of a tree.

In the regressions (Tables 2, 3, 4) and correlations (Table 5), weights were introduced that gave measurements in each subgroup equal relative weights. The subgroups were defined differently in Study I (stands and thinning regimes) and II (stands). The definition of Study II was adopted in this summary.

2.3.2 Simulator testing (Study III, IV)

The structural regularities (Studies I and II) were then used in the parameterisation of the Tree and Whorl modules in the PipeQual and RetroSTEM simulators. Thereafter, their predictions of stem form, diameter distribution of branches (Studies III and IV), and ring width and wood basic density distribution over stem (Study IV) were tested.

In Study III, the stem properties were simulated by PipeQual for the mean trees of 10 size classes forming the whole stand. For the test, the most similar simulated tree was selected for each sample tree, based on tree height and DBH. The stem diameters were compared over the relative distance from the apex, because the sample and simulated trees could slightly differ from each other in height. In Study IV, the stem structure and wood properties were simulated by RetroSTEM for each sample trees. The simulated trees were identical to sample trees for their height, so the stem diameters were compared both in absolute and relative scales. Both simulators, the PipeQual and RetroSTEM ignore the butt swell, and therefore the butt swell area is not included in the residual analysis of stem taper (<10% height of a tree).

Residuals were calculated between measured (y_i) and simulated values ($\hat{y}_i$). Average residuals (bias=$\sum(y_i - \hat{y}_i)/n$) and the root mean square errors (RMSE) were calculated for each tree, plot and dataset (RMSE =$\sqrt{\sum(y_i - \hat{y}_i)^2/n}$) (n is the number of observations).

2.3.3 Simulator application (Study V)

The RetroSTEM simulator was applied to produce stem three-dimensional structure for 100 individual stems per plot in the same way as in Study IV. The three plots represented varying thinning regimes. The simulated stems were bucked and cross-cut virtually and then converted into sawn timber by the InnoSIM simulator system, which uses measured or modelled three-dimensional input data of the stem and heartwood geometry and knots. InnoSim simulates the operations of the entire sawing process chain from stem bucking to end products: timber, wood components, chips and sawdust.

The output of sawn products imitates real-life breakdown and can be simulated as standard dimension timber or according to specific customer needs. Dimension timber can be graded by various grading rules. In this study, bucking rules for cross-cutting, and the sawing method were based on industrial practices in Finland. The resulted sawn timber thickness varied from 19 mm to 75 mm and the widths from 100 mm to 225 mm, such that larger dimensions were cut from sawlogs of larger diameter classes. The thickness of centre goods was 32, 38, 50, 63 and 75 mm, and that of side boards was 19 and 25 mm. Sawn timber was graded into quality classes ranging from highest to lowest A (sub-grades A1, A2, A3 and A4), B, C and D (Nordic timber grading... 1997). Pricing of sawn timber, chips and sawdust was based on actual prices received from the industry (spring 2006).

3 RESULTS

3.1 The tree structure (Studies I and II)

3.1.1 The vertical crown profile and stem structure

The crown profile theory (Chiba et al. 1988, Osawa et al. 1991) postulated that the relative vertical foliage density distribution from the stem apex to the crown base is constant over time. However, branch length (m) and foliage density distribution (kg m^{-1}) over the crown were clearly different between the stands of different age and density (Fig. 7, Study I). The mature trees (86 yrs.) had the longest branches throughout the live crown compared to the middle-aged (67 yrs.) or young stand (25 yrs.), and the thinnings increased the crown length, widening similarly the crowns, particularly at their base. Before canopy closure (young stand), the crowns were the densest and widest at the crown base. After canopy closure (mature and middle-aged stands), the aging and poor dominance position of a tree accelerated the foliage density accumulation to the upper crown. Approximately the top 5 m of the living crown was above the maximum foliage density, which therefore seemed to be free from canopy competition.

The ratio between foliage and branch cross-sectional area was further analysed from the apex to the crown base (Study I). The ratio increased from the stem apex downwards having a peaking point at 2–4 m, after which (below 40% from the apex) the foliage shedding and heartwood formation started (Fig. 8).

In order to test the pipe model theory (Shinozaki et al. 1964ab) along the stem, the foliage mass as well as the cumulative branch cross-sectional area were analysed as a function of the stem cross-sectional area (Study I). The relationship between cumulative foliage mass (kg)

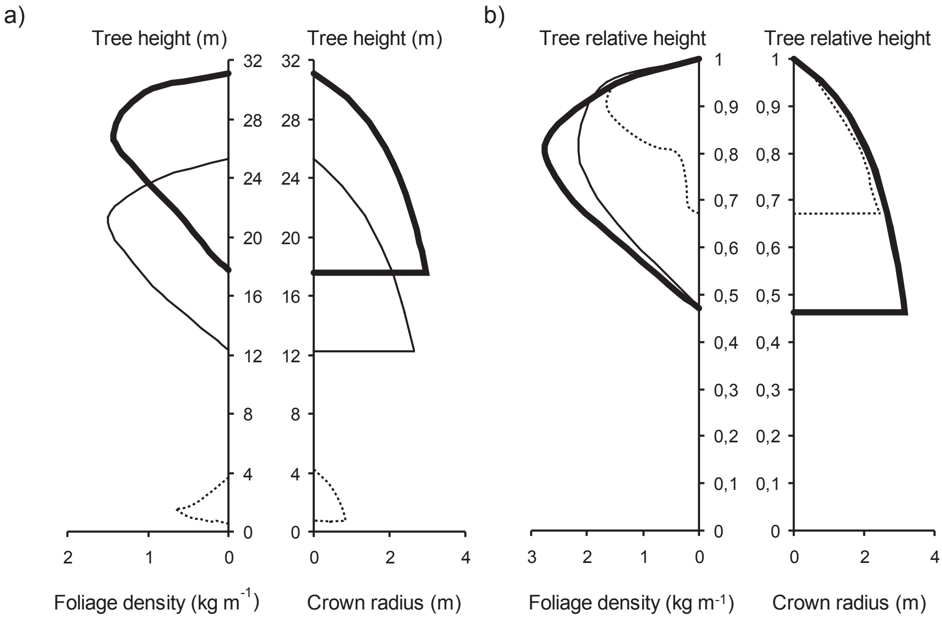

Figure 7. The vertical profile of crowns in three randomly selected sample trees by a) tree age (thick solid line: 86 yrs, solid line: 67 yrs, dotted line 25 yrs.; trees are from unthinned plots) and b) thinning option (thick solid line: intensive thinning, solid line: normal thinning, dotted line: unthinned; note that the line for crown radius in the normal thinning is hidden under the line for the intensive thinning; trees are from Heinola I) (Study I).

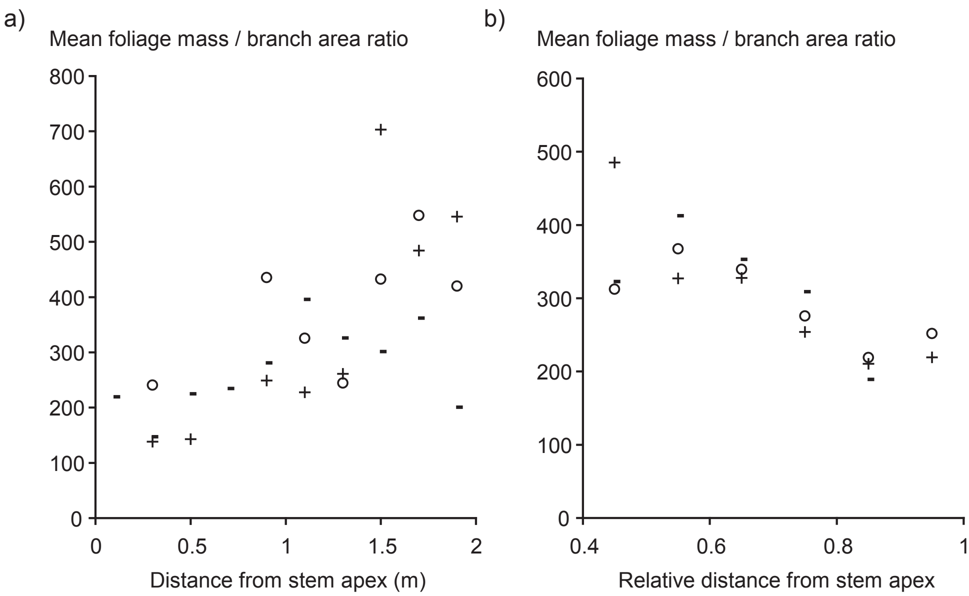

Figure 8. Mean ratio of foliage mass to branch cross-sectional area in sample branches a) as 0.2 m intervals from the stem apex to 2 m downwards, and b) as 5% intervals from 40% to crown base. Circles represent the mature, pluses the middle-aged and stripes the young stand (Study I).

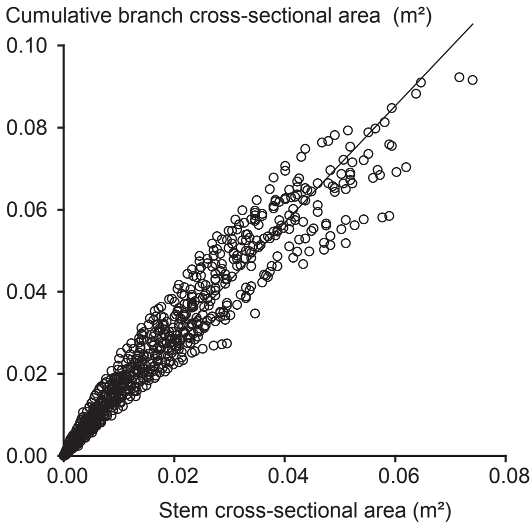

Figure 9. Cumulative branch cross-sectional area as a function of stem cross-sectional area in the whole data set (Study I).

and stem cross-sectional area (m^2) from the apex to the crown base was clearly non-linear. The relationship first increased rapidly from the stem apex and then levelled off, starting to decrease below 5 m, because of foliage shedding and branch mortality. The relationship between cumulative branch and stem cross-sectional area (m^2) throughout the crown was linear in the whole data set (Fig. 9). The result corroborated the pipe model theory, particularly in the part of the crown where no significant branch mortality has taken place.

The upper 5 m of the crowns, which was assumed to be above the maximum foliage density and free of branch mortality, was analysed separately. In this part of the crown, the relationship between the cumulative cross-sectional area of branches and the cross-sectional area of the stem was linear with zero intercept, the slope varying between 1 and 2, depending on the stand and thinning regimes. The slope was largest in the mature stand and smallest in the young stand, and smaller in the normally thinned stand than in the intensively thinned or unthinned stands (see Table 5 in Study I).

3.1.2 The pipe ratios at the tree level

According to the pipe model theory (Shinozaki et al. 1964ab), branch and stem sapwood cross-sectional area at any height in the crown is proportional to the foliage mass above. Promoting this theory, the pipe ratios at tree level were stable (Study II) even though the crown profiles varied considerably between trees and the pipe ratios between foliage mass and branch or stem cross-sectional area were not constant from the stem apex to the crown base.

The total foliage mass in the crown (kg) was strongly related to the cumulative branch cross-sectional area (m^2) at crown base (Table 2), and the relationship was almost linear. The crown total foliage mass (kg) had a strong linear relationship with the stem cross-sectional area (m^2) at crown base, and the pipe ratio η_s, determined as the slope of the corresponding regression line with zero intercept, was constant across stands of varying ages (Eqn. 1, Table 2, 5). Stem sapwood area at crown base (m^2) was a slightly better predictor of foliage mass than stem cross-sectional area (Table 2, 5), but the relationship was found slightly nonlinear.

Table 2. The pipe ratios at crown base, derived from the following equation form: y=*a*x, in which *a* is the pipe ratio (*s* is standard error for the value of *a*, and R^2 is coefficient of determination), *n*=29 sample trees (Study II).

Eqn.	y	x	a				R^2
			Pipe ratio	Unit	Value	*s*	
2	Foliage mass (W_f)	Branch cumulative cross-sectional area (A_b)	η_b	kg m^{-2}	399	24	0.91
1	Foliage mass (W_f)	Stem cross-sectional area at crown base (A_c)	η_s	kg m^{-2}	549	37	0.88
1 [a)]	Foliage mass (W_f)	Sapwood cross-sectional area at crown base (A_{sap})	η_{sap}	kg m^{-2}	938	55	0.91
2	Branch cumulative cross-sectional area (A_b)	Stem cross-sectional area at crown base (A_c)	η_s/η_b		1.37	0.06	0.94

[a)] Converted by replacing A_c by A_{sap}.

The relationship between branch cumulative cross-sectional area and stem cross-sectional area at crown base (slope η_s/η_b) was linear, but was found to vary between stands (Eqn. 2, Table 2, 5). The pipe ratios (η_s, η_s/η_b) correlated with slenderness (H/D) in the whole data set (Table 5), but no correlation was detected if the dependence was analysed separately in individual stands, as Study II indicated.

3.1.3 The structural regularities in a crown

An allometric relationship was found between foliage mass (kg) and crown length (m) in the whole data set (Eqn. 3, Table 3) (Study II). The residuals between measured and predicted values for foliage mass (kg) did not vary between stands, nor did they correlate with slenderness (H/D) (Table 5), indicating some regularity in the relationship across stands of varying ages and in trees representing different dominance positions.

The relationship between the basal-area-weighted mean branch length (m) and crown length (m) followed a power function (Eqn. 4, Table 3) (Study II). The coefficient (γ_b) was estimated for each stand separately, because the residuals between measured and predicted values for basal-area-weighted mean branch length varied clearly between stands if the same parameter value was used for all stands (Table 5). γ_b was largest in the mature stand and smallest in the young stand (Table 3). The relationship between basal-area-weighted mean branch length and crown length did not depend on slenderness (H/D) (Table 5).

3.1.4 Branch and stem form

A strong dependence with zero intercept was found between a woody mass component (branch wood, stem wood inside the live crown) and its cylinder volume (length (m) * cross-sectional area (m^2)) multiplied by the basic density of wood (kg m^{-3}) (Eqn. 5, 6, Table 4, Study II). The form coefficients for branches (φ_b) and stem inside the live crown (φ_{sc}) did not vary between stands, however, a clear correlation with slenderness (H/D) was detected (Table 5). When the correlation was analysed separately in individual stands, only φ_{sc} in the middle-aged stand correlated with slenderness (Study II). The stem form coefficient below the live crown did vary with the crown ratio, as suggested by Eqn. 8 (Fig. 10). In the young stand φ_{sb} was 1, because the crown rise was recently started and the stems consisted mainly of active sapwood pipes, and as the crown ratio decreased, φ_{sb} started to increase (Fig. 10).

Table 3. The allometric coefficients and exponents in a crown on the basis of 29 sample trees (Study II).

Eqn.	Parameter	Definition	Value
3	ξ	Coefficient of allometric equation for foliage mass	0.1655
3	q	Allometric exponent for foliage mass	1.78
4	γ_b	Coefficient of equation for mean branch length	
		Young stand	0.3502
		Middle-aged stand	0.4614
		Mature stand	0.5243
4	b	Exponent in the power function for mean branch length	0.5198

Table 4. Form coefficients inside live crown, derived from the following equation form: y=*a*x, in which *a* is the form coefficient (*s* is standard error for the value of *a*, and R^2 is coefficient of determination), *n*=29 sample trees (Study II).

Eqn.	y	x	*a*			R^2
			Coefficient	Value	*s*	
5	Branch mass (W_b)	$H_b{*}A_b{*}\rho_b$	φ_b	0.6306	0.02	0.98
6	Stem mass inside live crown (W_{sc})	$H_c{*}A_c{*}\rho_s$	φ_{sc}	0.4186	0.01	0.98

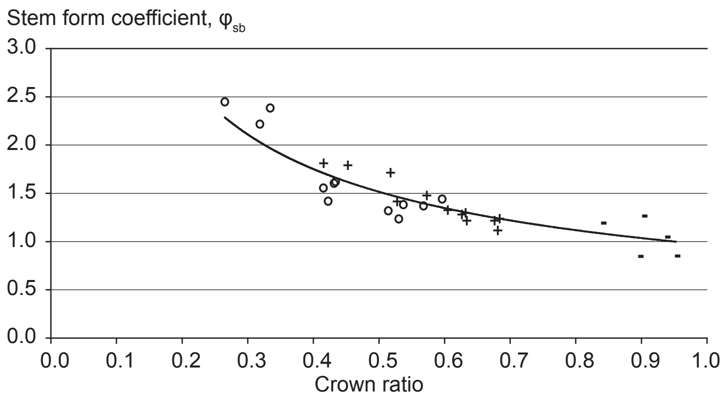

Figure 10. Stem form coefficient below the live crown as a function of crown ratio. Circles represent the mature, pluses the middle-aged and stripes the young stand (Eqn. 7). The trend line represents data points calculated by Eqn. 8.

Table 5. Structural relationships at tree level and their variation (*F* and its *p*-value) between stands and correlation (*r* and its *p* value) with slenderness (H/D), *n*=29.

Eqn.	Factor	Stand		H/D	
		F	*p*	*r*	*p*
1	η_s	0.12	0.88	0.48	0.01
2	η_s/η_b	11.85	0.00	0.52	0.00
3	W_f [a)]	1.21	0.31	-0.19	0.32
4	H_b [a)]	25.55	0.00	0.08	0.68
5	φ_b	3.10	0.06	0.57	0.00
6	φ_{sc}	2.39	0.11	0.54	0.00

[a)] Analyses are made from the residuals between measured and predicted value for foliage mass (W_f) (Eqn. 3) and basal-area-weighed mean branch length (H_b) (Eqn. 4).

3.2 Testing the PipeQual and RetroSTEM simulators (Studies III and IV)

The prediction accuracy of PipeQual (Study III) and RetroSTEM (Study IV) was approximately similar when assessed on the basis of the bias and RMSE values of stem relative diameter and maximum branch diameters (Table 6). However, it should be noted that the evaluation data set was different between the simulators. The biases and RMSE values were firstly calculated on the basis of the average residuals of individual sample trees, and secondly, on the basis of individual observations, but no clear differences were detected between the methods (Table 6).

The stem diameters were slightly but systematically overestimated, showing the largest bias in the intensively thinned plot of data set 1 when the PipeQual simulator was used (Table 6). The mean branch diameters were underestimated or overestimated depending on the data set and thinning option (only PipeQual simulations were available) (Table 6). However, the average bias was small, -0.02 cm for all sample trees (n=36). The maximum values of branch diameters were underestimated by up to 0.3 cm in both simulators. The mean ring width (cm) was slightly underestimated, whereas wood basic density (kg m^{-3}) was overestimated by 4% (only RetroSTEM simulations were available) (Table 6).

PipeQual overestimated the stem diameters from the mid stem upwards, and so did RetroSTEM in the middle part of the stem (Fig. 11). RetroSTEM underestimated the maximum branch diameters (cm) near the crown base in trees with long live crowns (56% of the sample trees had crown ratio over 80%) (Fig. 12). In PipeQual, the maximum branch diameters near the crown base were similarly underestimated, but in the PipeQual simulations the crown base was in upper stem, because no trees with long living crowns were available in the data set. The dead branch diameters varied around zero in PipeQual and RetroSTEM, however, showing some overestimation at the very bottom of the stem in both of the simulators (Fig. 12).

Table 6. Comparison between measured and simulated trees (Study III, IV).

Simulator	Data set (plot)[a]	Variable	Sample trees			Observations		
			number	Bias	RMSE	number	Bias	RMSE
PipeQual	1(a)	Stem diameter (relative units)	10	-0.01	0.03	591	-0.01	0.03
	1(b)		8	-0.02	0.03	470	-0.01	0.04
	1(c)		6	-0.03	0.04	369	-0.03	0.04
	2(c)		12	-0.01	0.02	714	-0.01	0.02
PipeQual	1(a)	Mean branch diameter (cm)	10	0.13	0.48	631	0.13	0.51
	1(b)		8	-0.13	0.60	496	-0.12	0.62
	1(c)		6	0.06	0.49	385	0.07	0.51
	2(c)		12	-0.12	0.47	158	-0.12	0.48
PipeQual	1(a)	Max branch diameter (cm)	10	0.33	0.59	631	0.34	0.62
	1(b)		8	0.15	0.57	496	0.16	0.58
	1(c)		6	0.32	0.56	385	0.32	0.61
	2(c)		12	0.14	0.57	158	0.14	0.59
RetroSTEM	Vapu	Stem diameter (cm)	31	-0.28	0.79	408	-0.27	0.90
RetroSTEM	Vapu	Stem diameter (relative units)	31	-0.01	0.04	408	-0.01	0.04
RetroSTEM	Vapu	Max branch diameter (cm)	31	0.23	0.60	309	0.25	0.71
RetroSTEM	Vapu	Mean ring width[b] (cm)	31	0.04	0.06	304	0.04	0.07
RetroSTEM	Vapu	Wood density[b] (kg m^{-3})	31	-13.96	30.74	172	-14.13	35.14

[a] Data set 1: Punkaharju and Heinola I, 2: Heinola II and Parkano. Thinning intensity in the plots is: (a) unthinned, (b) normal thinning, (c) intensive thinning. [b] Average values from sample disks. The branch diameters (cm) include live and dead branches.

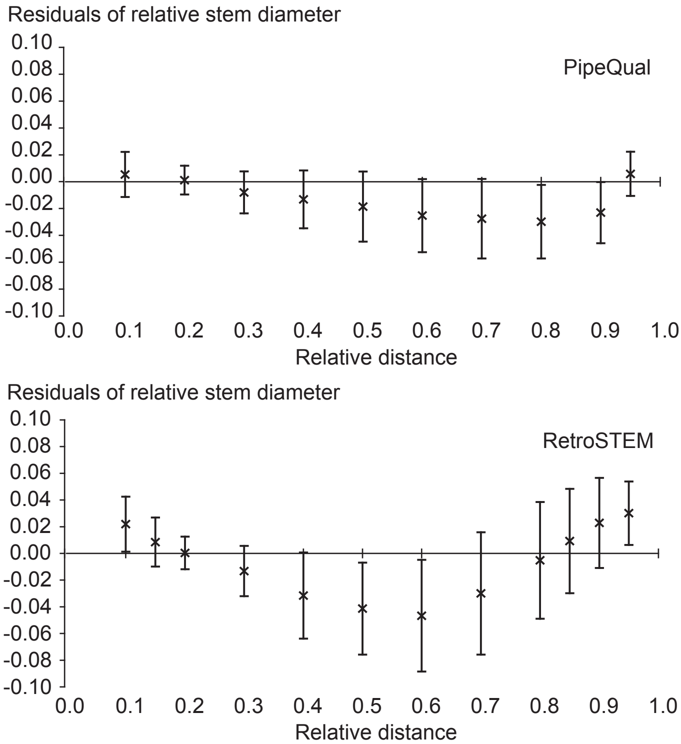

Figure 11. Average residuals between measured and simulated stem diameters and their standard deviations as a function of relative distance above ground in the PipeQual and RetroSTEM (Study III, IV).

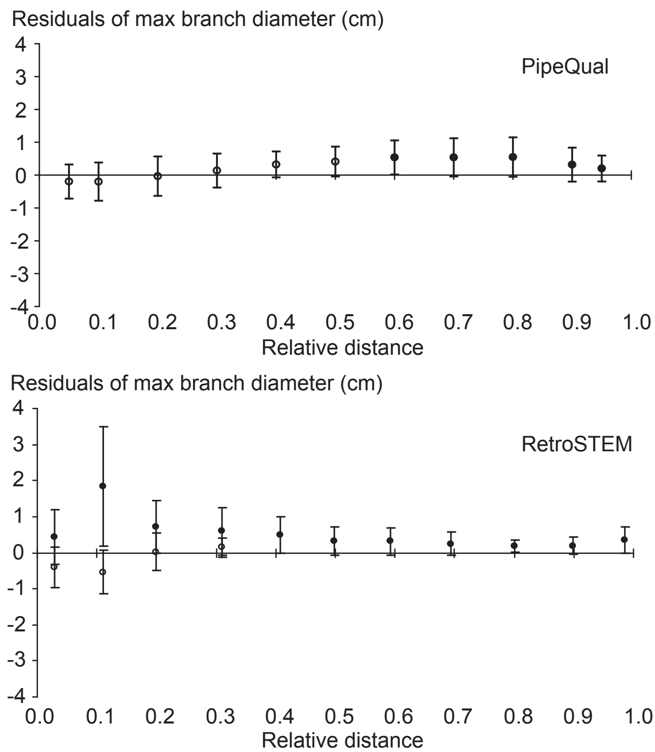

Figure 12. Average residuals between measured and simulated maximum branch diameters and their standard deviations as a function of relative distance above ground within the live crown (●) and below it (○) in the PipeQual and RetroSTEM (the crown base in the PipeQual testing is determined by the average crown base of the sample trees) (Study III, IV).

3.3 Case study: the yield and timber quality distribution of sawn timber (Study V)

The case study demonstrated an integration of the RetroSTEM and InnoSIM simulators and predicted the timber yield and quality distribution of sawn timber from final felling in one measured stand in Punkaharju with unthinned, normally and intensively thinned plots. Because data was only available from one stand, the results are here reported with reference to other studies for Norway spruce. However, as demonstrated in Study IV, the virtual stems predicted by RetroSTEM were only expected to have a small tree-level bias in variables describing their three-dimensional structure.

The stem sizes varied between thinning options (Table 7). The intensive thinning strategy resulted in large-sized logs (m^3), yielding the highest proportion of large dimensional sawn timber. The normal thinning alternative yielded the greatest log volume (m^3 ha^{-1}) and the greatest volumes (m^3 ha^{-1}) of sawn timber, however, with small differences between the other thinning alternatives (<8% of sawn timber) (Table 7). Mäkinen and Isomäki (2004a) and Pape (1999a) showed similar effects of thinning intensities (m^3 ha^{-1}), as the less intensive thinnings resulted in the highest log yields.

Dense stands are expected to yield high quality timber with small knots, because knot sizes correlate closely with stem diameters (Pape 1999a). The normal thinning and unthinned options resulted in the best sawn timber grade distribution, yielding more A-grade centre goods, whereas the intensive thinning strategy yielded relatively more B-grade (Fig. 13). The proportion of A-graded side boards was approximately 50% in all thinning alternatives. The yield of C or D timber grades was marginal (<5% of the total yield) regardless the thinning strategy. Verkasalo et al. (2002) showed a similar quality distribution of sawn-timber centre goods and side boards in Norway spruce logs, sawn with a similar sawing pattern and quality-graded by the same rules as in this study.

The highest gross value of the product volumes (sawn timber, sawmill chips and sawdust) per log volume (€ log m^3) and total value per hectare (€ ha^{-1}) was achieved by using the normal

Table 7. Mean tree dimensions (standard deviations) and the volume yield and value of sawn timber in the different thinning regimes at final felling (Study V).

Characteristics	Unthinned	Normal	Intensive
Stem number (*n* ha^{-1})	805	682	456
Mean DBH [a] (cm)	26 (*5.1*)	28 (*4.7*)	33 (*3.5*)
Mean tree height (m)	25 (*1.8*)	26 (*2.9*)	27 (*0.9*)
Mean crown ratio	0.5 (*0.1*)	0.6 (*0*)	0.7 (*0*)
Mean log volume [b] (m^3)	0.7 (*0.4*)	0.9 (*0.4*)	1.2 (*0.3*)
Log volume [b] (m^3 ha^{-1})	545	584	556
Sawn timber (m^3 ha^{-1})	289	314	299
Large boards [c] (%)	44	46	51
Small boards [d] (%)	56	54	49
Sawmill chips (m^3 ha^{-1})	152	159	154
Sawdust (m^3 ha^{-1})	83	89	81
Gross value [e] (€ log m^{-3})	131	135	134
Total value [f] (€ ha^{-1})	71351	79055	74338

[a] Stem diameter at breast height, [b] sawn logs, [c] thickness 50, 63, 75 mm, [d] thickness 19, 25, 32, 38 mm, [e] the value of sawn timber, sawmill chips and sawdust per log volume, [f] the value of sawn timber, sawmill chips and sawdust.

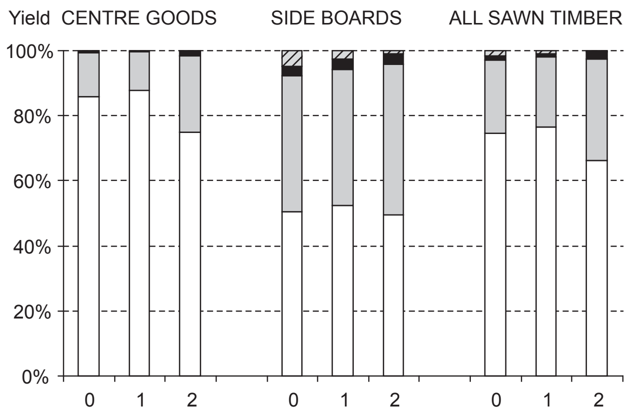

Figure 13. The simulated sawn timber yield (centre goods, side boards and total volume) by quality grades for different thinning treatments (0 unthinned, 1 normal and 2 intensive thinning). Stack colours for quality grades: A (white), B (grey), C (black) and D (striped) (Study V).

thinning alternative, and the smallest value obtained when no thinnings were used (Table 7). The differences were small in the gross value (€ per log m^3), but higher in the total value (€ ha^{-1}). However, the value is highly dependent on the current pricing mechanism of timber.

4 DISCUSSION

4.1 Applicability of the theoretical framework to wood quality studies

The structural regularities of Norway spruce stems were analysed for simulating stem properties, in order to profile the raw material in standing or felled trees to be converted to sawn timber. The simulation of three-dimensional stem structure was carried out by the PipeQual and RetroSTEM simulators, which were evaluated by analysing their prediction accuracy and specifying further needs for simulator development. The simulated logs (using RetroSTEM) were virtually sawn by the InnoSIM sawing simulator.

In order to predict three-dimensional stem properties dynamically from static rules of tree structure (Shinozaki et al. 1964ab, Osawa et al. 1991), an accurate description of growth at the tree level is needed. In the PipeQual simulator, growth is driven by photosynthesis in a carbon balance model, while in RetroSTEM, growth is driven by empirical height growth equations. The growth engine of both systems produces the annual growth (kg), then to be divided to the stem and branches at the appropriate stem heights, determined by the pipe ratios and the foliage density distribution in the crown. Other dynamic simulators based on similar structural relationships are, for example, LIGNUM (Perttunen et al. 1998) and AMAPpara (Reffye et al. 1997). In all these systems, as the tree grows, the stem structure is updated dynamically, and as a result, the development of stem structure is recorded for every growth period.

These theory-based approaches rely on a description of tree structure quantified by empirical data. The generality of the structural regularities should be evaluated, such that the reliability of the predictions can be approximated when the simulators are used in various environments and situations. In this study, the tree structure was tested by 29 sample trees from southern Finland, which is a limited data set for far-reaching generalisations. However, similar structural regularities as found in this study have been shown in previous studies regarding

Scots pine, Norway spruce and silver birch from stands representing different site fertilities and geographic locations (Mäkelä and Vanninen 1998, Ilomäki et al. 2003, Berninger et al. 2005, Lehtonen 2005). For example, Lehtonen (2005) found for Norway spruce that the pipe ratio (η_s) determined at the stand level, varied between measured stands, but no clear trend between geographical location in southern Finland could be found. Similarly, the structural regularities have been used successfully in model calculations, as the predictions have been in good agreement with measured trees (Mäkelä 2002, Mäkelä and Mäkinen 2003).

In this study, it was examined to what extent the theoretical structural relationships (Section 1.3) could be observed in Norway spruce, and whether they (Eqns. 1–6) were independent of the slenderness of trees and invariable between stands. In Scots pine or silver birch, the pipe ratios (η_s, η_s/η_b) at crown base were found to be close to constant, regardless of stand age or density (Mäkelä and Vanninen 2001, Ilomäki et al. 2003, Vanninen 2003), and similarly this study showed that in Norway spruce the pipe ratio (η_s) did not vary between stands of different ages. However, the results of Longuetaud et al. (2006) indicate that in Norway spruce η_s/η_b may vary with stand age and slenderness, which observation can be promoted by this study as η_s/η_b varied between stands, and all pipe ratios (η_s, η_s/η_b) varied somewhat with slenderness in the whole data set. In line with earlier studies on Scots pine and silver birch (Mäkelä and Vanninen 2001, Ilomäki et al. 2003), crown length in Norway spruce was found to be allometrically related to foliage mass, and basal-area-weighed mean branch length was a power function of crown length. Branch and stem form coefficients inside the live crown (φ_b, φ_{sc}) were relatively invariable between stands, however, slenderness may have an effect on the form coefficients, as also shown for silver birch (Ilomäki et al. 2003). Further, the form coefficient of the stem below the live crown was dependent on crown ratio.

The crown of Norway spruce expressed both regularity and plasticity in its development. The maximum value of foliage density peaked at about 5 m from the stem apex downwards regardless of tree age or growing space. At the same time, the maximum value of foliage density, crown length and width were related to tree age and growing space. Branch and stem wood cross-sectional area at any height in the crown was proportional to foliage mass above, however, the pipe ratio between foliage mass and branch or stem cross-sectional area increased in the upper crown (above 5 m from the stem apex) and below it, started to decrease because of foliage shedding. This indicates that when predicting the stem taper on the basis of the allometric relationship between foliage mass and the stem sapwood cross-sectional area in each whorl, the coefficient of proportionality should be allowed to vary with distance to the stem apex. The relationship between branch and stem cross-sectional area along the stem was linear. Mäkelä and Vanninen (2001) reported a similar pattern in the pipe ratios along the stem in Scots pine.

The present evaluation process on the structural relationships between the stem dimensions indicates that the young stand differed from the two stands after canopy closure, as the most significant differences between stands were detected in η_s/η_b (Table 5, Study II) and γ_b (Table 3). This suggests that before canopy closure, the branches may be larger for their diameter relative to stem cross-sectional area at the crown base, and similarly shorter relative to crown length. This may lead to an inaccurate prediction of branch diameters and unreasonable prediction of the crown shape in the young trees. If the crown shape parameters for older trees are used in the young stand, the crown diameter may be overestimated. Too wide crown shape in simulated trees may further overestimate crown rise, which is accelerated by crown overlap in the PipeQual simulator. Based on this, more data should be collected on η_s/η_b and γ_b from stands before canopy closure and their effect on the prediction efficiency of the simulators should be further analysed. One hypothesis could be that the heartwood formation change the relationship of η_s/η_b. Additionally it would be reasonable that the stem structural relationships would be further analysed in different site types and stand densities throughout the country, which would give more perspective on the prediction accuracy in order to apply the simulators in different forest sites in various locations.

4.2 Simulators and their prediction efficiency

4.2.1 Different approaches

The evaluation of the simulators is essential for understanding the potential and limitations of the simulator. A comparison between prediction and measured data or a comparison with other models gives perspective for developing and using the simulator. However, few studies have been carried out previously with the objective of evaluating wood quality simulators.

The prediction accuracy may differ on the basis of whether the simulator uses a static or dynamic approach to the predictions of stem and wood properties. As the static prediction is based on the final state of the growth prediction, the simulators may be better suited for describing the stem external taper and branch properties rather than the three-dimensional stem structure including growth rings and knots embedded in the stem. A static model may change the tree structure in one tree over the simulation, because the predicted values of the wood properties do not depend on the values in the earlier growth periods. This may lead to illogical predictions, e.g. negative increment in the stem and branches. The problem of the negative predictions may be pronounced if the simulator uses a small sample of stems to implicate the whole stand wood quality distribution, but the inaccuracy may diminish if the simulator (e.g. TASS by Goudie (2002)) predicts the wood properties for every solitary stem in the stand. Similarly, the bias may diminish if the prediction of the stem structure is produced dynamically from its past growth, such that the properties of the stem and branches influence their future increment (e.g. TreeBLOSSIM by Grace et al. (2006)).

In order to evaluate the biological causality between the predicted characteristics, the dynamic growth prediction should include the description of the interactive physiological processes and carbon allocation between the stem and branches. For example, in PipeQual, LIGNUM or AMAPpara (Reffye et al. 1997, Perttunen et al. 1998, Mäkelä and Mäkinen 2003), the branch and stem growth are dependent on each other and their past development. A simple model is easier to evaluate than a complex one, but the model structure is strongly dependent on the objectives of the systems. PipeQual relies on simple model structure, in order to focus on the critical physiological relationships in the tree growth. LIGNUM and AMAPpara have an elaborate model structure, which follows the physiological processes in order to describe the detailed architecture of the shoot and branching system. On the other hand, various simulators, such as SILVA or BWINPro (Pretzsch et al. 2002, Seifert 2003, Schmidt 2004) use complex statistical equations for maximising their prediction efficiency and minimising the bias. Using any of the simulator applications, their outputs should, however, be tested for evaluating their applicability.

In the previous studies, Schmidt (2001) evaluated the BWINPro simulator for stem taper and crown base development predictions, whereas Seifert (2003) tested vertical crown development and branchiness using the SILVA simulator. Kellomäki et al. (1999) demonstrated the prediction accuracy of their simulator regarding crown development, stem taper and wood density in individual trees. Todoroki et al. (2001) evaluated the timber grades predicted by the AUTOSAW simulator, and Leban et al. (1996) tested the stem reconstructions of the

Win-EPIFN simulator for simulating the quality of boards. The PipeQual and RetroSTEM simulators have been evaluated with respect to stand growth and the three-dimensional structure of Scots pine (Mäkelä 2002, Mäkelä and Mäkinen 2003, Mäkelä et al. 2002). In addition, the branch models of Scots pine and Norway spruce included in the simulators have been tested separately (Mäkinen and Song 2002, Mäkinen et al. 2007b). In this study, both simulators were tested by comparing the simulated stem properties (stem and branch diameters, wood density) of Norway spruce to measured trees. In the following, the properties of both simulators are compared to the above-mentioned simulators and their prediction efficiency.

4.2.2 Stem diameter predictions and wood density

The tests of PipeQual and RetroSTEM revealed a small tree-level bias in stem diameters in Norway spruce, showing similar accuracy as the simulations by Kellomäki et al. (1999) for Scots pine. In a comparison of simulated stem taper with the empirical taper curve model of Laasasenaho (1982) Kellomäki et al. (1999) found that the simulated stem diameters were overestimated with respect to the predictions with the Laasasenaho (1982) model in the upper part of the stem and underestimated at the middle part of the stem. In this study, RetroSTEM overestimated stem diameter in the middle part of the stem, while PipeQual produced overestimation higher up along the stem. The overestimation may slightly increase the yield of sawn boards from individual simulated stems.

The overestimation of stem diameter inside the upper crown was traced back to the parameterisation of the relationship between the vertical foliage mass distribution and active pipe area in the stem, which was particularly apparent in the PipeQual simulations. As the hypothesis of constant vertical foliage mass density over time (stated in the crown profile theory by Chiba et al. (1988) and Osawa et al. (1991)) was disproved, and the pipe ratios between foliage and branch/stem cross-sectional areas varied with the distance from the stem apex (Study I), the whorl position in the crown was taken into account in model parameterisation (Study III). This was done by making the ratio of foliage to active pipes increase with distance from the stem apex downwards and reach a maximum at 5 m. This may have resulted in too large stem diameters in the upper crown. A similar phenomenon was detected in the simulations for Scots pine with PipeQual (Mäkelä 2002).

In RetroSTEM, the overestimation was related to the empirical height growth model (Vuokila and Väliaho 1980) which predicted too rapid early height growth. Because the simulated trees were forced to equal the total height, DBH and age of the measured trees, the rapid early height growth resulted in overestimating the number of outer growth rings and underestimating the corresponding average ring widths up to the middle part of the stem (Fig. 14). At the same time, stem diameter was overestimated in the middle part of the stem (Fig. 14). In RetroSTEM, wood densities were predicted on the basis of the simulated ring widths using the empirical equation of Mäkinen et al. (2007a). Although there was some bias in predicted ring width, the wood density predictions were in good agreement with the measured values at the tree level. The RetroSTEM predictions showed similar or better accuracy in wood density predictions than the predictions by Win-EPIFN which was also used for retrospective stem simulation in Norway spruce (Leban et al. 1996). Kellomäki et al. (1999) achieved roughly similar accuracy in Scots pine for the simulated wood density.

The butt swell area reaches up to 1.3 m in Norway spruce stems (Study IV), making the accurate prediction of stem diameter in the lower stem more difficult than in, e.g., Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) or Scots pine (Schmidt 2001, Mäkelä et al. 2002). To

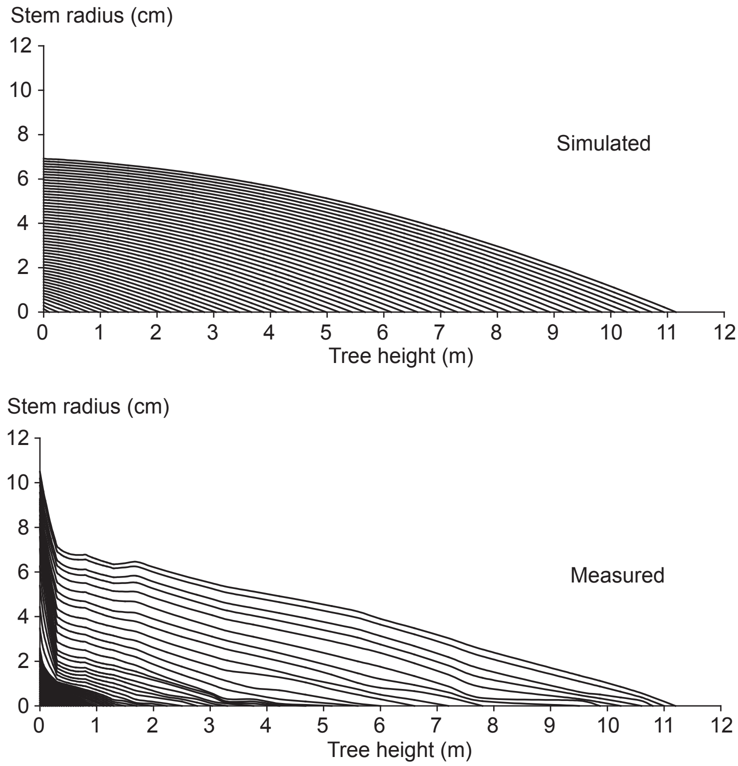

Figure 14. Stem tapers in one simulated and measured sample tree from Vapu data set. The ring widths were reconstructed by TreeViz.

resolve this problem, Schmidt (2001) therefore fitted taper functions separately for the upper and lower stem for the BWINPro simulator, resulting in more accurate predictions particularly for the butt swell area. Neither RetroSTEM nor PipeQual predict the butt swell (Fig. 14), and similar difficulties were detected regarding the long butt swell area in Norway spruce. In RetroSTEM simulations, it is recommended that stem diameter at 20% height is used as input instead of the regular breast height diameter, in order to avoid the effect of the butt swell in the taper predictions.

4.2.3 Branches

Branch diameter predictions for Norway spruce have been relatively successful using either SILVA, Win-EPIFN, RetroSTEM or PipeQual simulators, showing only a small bias at the tree level (Study III, IV, Leban et al. 1996, Seifert 2003). RetroSTEM and PipeQual showed similar biases in branch maximum diameters along the stem, slightly (<5 mm) overestimating the size of the dead branches in the butt log. This could grade down the quality classes of the sawn product. In addition, both simulators underestimated the maximum branch diameters near the bottom of the live crown. In the evaluation data set for PipeQual, this was approximately at 50% of tree height, while in the data set for RetroSTEM it was clearly lower, approximately at 30% of tree height from the ground level. This underestimation may lead to overrating the quality of sawn boards with sound knots. However, when the quality distribution of sawn timber simulated using RetroSTEM and InnoSIM (Study V) was compared with sawn timber properties from other studies, the resulting quality grades were found realistic. As Verkasalo et al. (2002) and Todoroki et al. (2001) showed, the timber quality decreased with increasing stem/log diameters, and the resulted quality distribution of sawn timber according to Verkasalo et al. (2002) was close to the results in this study.

The origin of the bias in branch diameter near the crown base can be either in the branch equations or in the crown rise, which is modelled differently in the two simulators. In PipeQual, crown rise is accelerated by contact with neighbouring trees, and there seems to be a tendency of overestimating the height of the crown base, which in the data set of this study was in the order of 80 cm. In RetroSTEM, crown rise begins at age 20, then follows stem height growth and finally reaches the measured height of the crown base.

4.3 The applicability of PipeQual and RetroSTEM and future developments

At the moment, simulators describing stand growth and stem structure expressing the wood properties for industrial purposes already offer an attractive approach to control the quality development of trees in order to rationalise the raw material supply. BWINPro is in use e.g. in a forest planning agency in Germany (Schmidt et al. 2006). PipeQual has been used as a tool in case studies of forest management (Mäkelä et al. 2000b) and in applications of economic optimisation to forest management (Hyytiäinen et al. 2004, 2006). The model has also been embedded in educational software as an internet version (Vanninen et al. 2006).

This study showed that the PipeQual and RetroSTEM simulators offer adequate tools for predicting the three-dimensional structure of Norway spruce stems, providing valuable information of the available raw material. In addition, the simulators can be integrated with a sawing simulator and as this study demonstrated, the yield and quality distribution of sawn timber can be predicted on the basis of the structural regularities in a tree. According to the present preliminary evaluation of the PipeQual and RetroSTEM simulators for Norway spruce, this study has drawn light on some issues that need improvement and further development regarding both simulators:

(1) **More extensive data for tree structure testing:** The assumptions tested in this study concerning regular tree structure were generally consistent with the present data sets, but more extensive data including wider variation in geographical location, stand age and density, as well as site fertility could provide useful information for further specification of the relationships. The branch diameter and crown shape development should be further analysed in stands before canopy closure.

(2) **Parameter refitting (stem taper):** The prediction of stem taper was reasonable in stands with varying ages and thinning intensities in southern Finland. However, some further improvement is needed, especially in the PipeQual simulator. The formulation of the dependence of the pipe ratios between foliage and stem pipe area on the distance from the stem apex in the upper crown should be further analysed and refitting the parameters should be considered.

(3) **Developing the model formulation (stem taper and lower crown development):** In the RetroSTEM, the height growth models should be further developed to account for the slow early height growth pattern typical of juvenile spruces in suppressed crown

layers (Surminski 2007). Further, the reasons for the bias in branch diameters near the base of the crown should be identified in both simulators. In RetroSTEM, the crown rise follows the height growth, and after revising the height growth model it should be further analysed if the current rise pattern is adequate for describing the crown base development. In PipeQual, the crown shape has been formulated to be independent of tree age or dominance position leading to too inflexible crown development in simulated trees. In further studies the crown shape should be reformulated and similarly branch growth and mortality in the lower crown as a consequence of overlap of neighbouring trees should be analysed in a larger data set.

(4) **Butt swell:** An empirical or a mechanistic equation correcting the prediction of the butt swell area should be included in PipeQual and RetroSTEM. Compared to Scots pine, Norway spruce has a larger butt swell area probably due to a lower resistance to wind damages, which can be partly explained by differences in wood strength, rooting system and crown coverage between the species (Gardiner et al. 2000, Peltola et al. 2000).

(5) **Additional evaluation:** After the above development tasks (1–4), both simulators, PipeQual and RetroSTEM need additional testing against extensive independent data sets from different parts of Finland.

(6) **Analysing the wood conversion chain:** For analysing the whole wood conversion chain, both simulators should be integrated with a sawing simulator and the yield and quality distribution of simulated sawn timber should be evaluated against measured data.

In the future, integrated tools including a model for the generation of virtual stems, such as PipeQual or RetroSTEM, and a sawing simulator, such as InnoSIM, will offer new possibilities for forest operators to plan silvicultural management operations and analyse different scenarios for producing the raw material. For forest industry, such tools will provide opportunities to sort logs on the basis of their inner properties or to plan optimal sawing operations. PipeQual has already been implemented in a user friendly form, available as the PuMe simulator via the internet (Vanninen et al. 2006). Similarly, RetroSTEM and an integrated sawing simulator should be developed as an easy-to-use tool to be available for different users, such as forestry students, forest owners, officers in forestry or forest industry.

REFERENCES

Berninger, F., Coll, L., Vanninen, P., Mäkelä, A., Palmroth, S. & Nikinmaa, E. 2005. Effects of tree size and position on pipe model ratios in Scots pine. Can. J. For. Res. 35: 1294–1304.

Brüchert, F., Becker, G. & Speck, T. 2000. The mechanics of Norway spruce [*Picea abies* (L.) Karst: mechanical properties of standing trees from different thinning regimes. For. Ecol. Manage. 135: 45–62.

Cajander, A.K. 1949. Forest types and their significance. Acta For Fenn 56.

Chiba, Y., Fujimori, T. & Kiyono, Y. 1988. Another interpretation of the profile diagram and its availability with consideration of the growth process of forest trees. J Jpn For Soc 70: 245–254.

Chiorescu, S. & Grönlund, A. 2000. Validation of a CT–based simulator against a sawmill yield. Forest Prod. J. 50(6):69–76.

Deleuze, C. & Houllier, F. 1995. Prediction of stem profile of Picea abies using a process–based tree growth model. Tree Physiol. 15: 113– 120.

— & Houllier, F. 1997. A transport model for tree ring width. Silva Fenn. 31(3): 239–250.

— , Herve, J.–C., Colin, F. & Ribeyrolles, L. 1996. Modelling crown shape of Picea abies: Spacing effects. Can. J. For. Res. 26: 1957–1966.

Finnish Statistical Yearbook of Forestry. 2006. Metla. 438 p.

Gardiner, B. A., Peltola, H. & Kellomäki, S. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. Ecol. Model. 129: 1–23.

Grace, J.C., Pont, D., Sherman, L., Woo, G. & Aitchison, D. 2006. Variability in stem wood properties dye to branches. New Zeal. J. For. Sci. 36(2/3): 313–324

Greis, I. & Kellomäki, S. 1981. Crown structure and stem growth of Norway spruce undergrowth under varying shading. Silva Fenn. 3: 306–322.

Gustavsen, H. 1980. Site index curves for conifer stands in Finland. Folia For. 454: 1–31.

Goudie, J.W. 2002. Modelling the impact of silvicultural activities on the wood characteristics of Coastal western hemlock in British Columbia. In: Nepveu, G. (ed.). IUFRO WP S5.01.04 Fourth workshop, Connection Between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software. Harrison Hot Springs, British Columbia, Canada, September 8–15, 2002. p. 528–536.

Hakkila, P. 1969. Weight and composition of the branches of large Scots pine and Norway spruce trees. Commun. Inst. For. Fenn. 67.6: 1– 37.

— 1972. Coniferous branches as a raw material source. Commun. Inst. For. Fenn. 75.1: 1–60.

— 1989. Utilization of residual forest biomass. Springer-Verlag, Berlin Heidelberg New York. p. 11–99.

Hanhijärvi, A., Ranta-Maunus, A. & Turk, G. 2005. Potential of strength grading of timber with combined measurement techniques, Report of the Combigrade-project – phase 1. VTT publications 568. 81 p.

Houllier, F. & De Reffye, P. 1996. Linking tree architecture, stem growth and timber quality: a review of some modelling approaches. In: Nepveu, G. (ed.). Iufro WP S5.01–04 Second workshop “Connection between silviculture and wood quality through modelling approaches and simulation softwares”. INRA–Nancy, France. p. 294–303.

Hyvän metsänhoidon suositukset. 2006. Metsätalouden kehittämiskeskus Tapio. Helsinki, Finland. [Recommendations for good silviculture]. 100 p. (In Finnish)

Hyytiäinen, K., Hari, P., Kokkila, T., Mäkelä, A., Tahvonen, O. & Taipale, J. 2004. Connecting a process-based forest growth model to stand-level economic optimization. Can. J. For. Res. 34: 2060–2073.

— , Ilomäki, S., Mäkelä, A. & Kinnunen, K., 2006. Economic analysis of stand establishment for Sots pine. Can. J. For. Res. 36: 1179–1189.

Ikonen, V.-P. 2008. Modelling the growth and properties of stem and wood of Scots pine (*Pinus sylvestris* L.) as related to silvicultural management with implications for sawing yield and properties of sawn pieces. Dissertationes Forestales 65. 41 p.

— , Kellomäki, S. & Peltola, H. 2003. Linking tree stem properties of Scots pine (Pinus sylvestris L.) to sawn timber properties through simulated sawing. For. Ecol. Manage. 174: 251–263.

Ilomäki, S., Nikinmaa, E. & Mäkelä, A. 2003. Crown rise due to competition drives biomass allocation in silver birch. Can. J. For. Res. 33: 2395–2404.

Jäppinen, A. & Beauregard, R. 2000. Comparing grade classification criteria for automatic sorting of Norway spruce saw logs. Scand. J. For. Res. 15: 464–471.

Johansson, G., Kliger, R. & Perstorper, M. 1994. Quality of structural timber-product specification system required by end–users. Holz. Roh. Werkst. 52: 42–48.

Johnsen, K., Samuelson, L., Teskey, R., NcNulty, S. & Fox, T. 2001. Process models and tools in forestry research and management. Forest Science 47: 2–8.

Kellomäki, S., Ikonen, V.-P., Peltola, H. & Kolström, T. 1999. Modelling the structural growth of Scots pine with implications for wood quality. Ecol. Model. 122: 117–134.

Korhonen, K.T. & Maltamo, M. 1990. Männyn maanpäällisten osien kuivamassat Etelä-Suomessa. Metsäntutkimuslaitoksen tiedonantoja 371: 1–29. (In Finnish)

Kärkkäinen, M. 1986. Value relations of pine and spruce stems. (In Finnish with English abstract. Silva Fenn. 20: 117–127.

Laasasenaho, J. 1982. Taper curve and volume functions for pine, spruce and birch. Commun. Inst. For. Fenn. 108: 1–74.

Leban, J.M. & Duchanois, G. 1990. SIMQUA : un logiciel de simulation de la qualité du bois. Ann. For. Sci. 47: 483–493.

— , Daquitaine, R., Houllier, F. & Saint-Andre, L. 1996. Linking models for tree growth and wood quality in Norway spruce. Part I: Validation of predictions for sawn boards properties, ring width, wood density and knottiness. In: Nepveu, G. (ed.). IUFRO WP S5.01.04 Second workshop, Connection between silviculture and wood quality through modelling approaches and simulation softwares. Berg-en-Dal, Kruger National Park, South Africa, August 26–31, 1996. p. 220–228.

Lehtonen, A. 2005. Estimating foliage biomass for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) plots. Tree Physiol 25:803–811.

Longuetaud, F., Mothe, F., Leban, J.-M. & Mäkelä, A. 2006. *Picea abies* sapwood width: Variations within and between trees. Scand. J. For. Res. 21: 41–53.

Lycken A. 2006. Appearance Grading of Sawn Timber. Doctoral Thesis, Luleå University of Technology LTU, Division of Wood Science and Technology, Skellefteå Sweden.

Mäkelä, A. 1986. Implications of the Pipe Model Theory on Dry Matter Partitioning and Height Growth in Trees. J. theor. Biol. 123: 103–120.

— 1997. A carbon balance model of growth and selfpruning in tree based on structural relationships. For. Sci. 43: 7–24.

— 2002. Derivation of stem taper from the pipe theory in a carbon balance framework. Tree Physiol. 22: 891–905.

— & Mäkinen, H. 2003. Generating 3D sawlogs with a process–based growth model. For. Ecol. Manage. 184: 337–354.

— & Sievänen R. 1992. Height growth in open–grown trees. J. theor. Biol. 159, 443–467.

— & Vanninen, P. 1998. Impacts of size and competition on tree form and distribution of aboveground biomass in Scots pine. Can. J. For. Res. 28(2): 216–227.

— & Vanninen, P. 2001. Vertical structure of Scots pine crowns in different age and size classes. Trees 15: 385–392.

— , Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågren, G.I., Oliver, C.D. & Puttonen, P. 2000a. Process–based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiol. 20: 289–298.

— , Mäkinen, H., Vanninen, P., Hynynen, J., Kantola, A. & Mielikäinen K., 2000b. Männiköiden tuotoksen ja laadun ennustaminen. Finnish Forest Research Institute Research papers 794. [Predicting yield and quality of Scots pine stands]. (In Finnish, with English summary). 89 p.

— , Mäkinen, H. & Usenius, A. 2002. Predicting 3D stem structure from simple sample tree measurements. In: Nepveu, G. (ed.). IUFRO WP S5.01.04 Fourth workshop, Connection Between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software. Harrison Hot Springs, British Columbia, Canada, September 8–15, 2002. p. 298–307.

Mäkinen, H. & Song, T. 2002. Evaluation of models for branch characteristics of Scots pine in Finland. For. Ecol. Manage. 158: 25–39.

— & Isomäki, A. 2004a. Thinning intensity and growth of Norway spruce stands in Finland. Forestry 77(4): 349–364.

— & Isomäki, A. 2004b. Thinning intensity and long–term changes in increment and stem form of Norway spruce trees. For. Ecol. Manage 201: 296–309.

— , Ojansuu, R., Sairanen, P. & Yli-Kojola, H. 2003. Predicting branch characteristics of Norway spruce (*Picea abies* (L.) Karst.) from simple stand and tree measurements. Forestry 76: 525–546.

— , Jaakkola, T., Piispanen, R. & Saranpää, P., 2007a. Predicting wood and tracheid properties of Norway spruce. For. Ecol. Manage. 241: 175–188.

— , Mäkelä, A. & Hynynen, J. 2007b. Predicting wood and branch properties of Norway spruce as a part of a stand growth simulation system. In: Acker, J.V. & Usenius, A. (eds.). Modeling the wood chain: Forestry – Wood industry – Wood product markets. Cost Action E44, September 17–19, 2007, Helsinki, Finland. p. 11–20.

Metinfo database. 2007. [Internet statistics]. Metinfo – forest information services. The database of Metla – Finnish Forest Research institute. Available from: http://www.metla.fi/metinfo/ . [Cited 10 Apr 2008].

Nordic timber grading rules for pine and spruce sawn timber. 1997. The Assosiation of Finnish Sawmillmen, Finland, 2nd edition. 64 p. ISBN: 9173222275.

Nordmark, U. 2005. Value recovery and production control in the forestry-wood chain using simulation technique. Doctoral thesis, Luleå University of Technology. 51 p.

Osawa, A., Ishizuka, M. & Kanazawa, Y. 1991. A profile theory of tree growth. For. Ecol. Manage. 41:33–63.

Pape, R. 1999a. Effects of Thinning Regime on the Wood Properties and Stem Quality of Picea abies. Scand. J. For. Res. 14: 38–50.

— 1999b. Influence of thinning and tree diameter class on the development of basic denstiy and annual ring width in Picea abies. Scand. J. For. Res. 14: 27–37.

Peltola, H., Kellomäki, S., Hassinen, A. & Granander, M. 2000. Mechanical stability of Scots pine, Norway spruce and birch: analysis of tree pulling experiments in Finland. Special Issue Wind and other abiotic risks to forests. For. Ecol. Manage. 135(1–3): 143–153.

Perttunen, J., Sievänen, R. & Nikinmaa, E., 1998. LIGNUM: A model combining the structure and the functioning of trees. Ecol. Modelling 108(1–3), 189–198.

Pinto, I. 2004. Raw material characteristics to maritime pine (Pinus pinaster Ait.) and their influence on simulated yields. VTT Publications 533. 51 p.

Pretzsch, H., Biber, P. & Dursky, J. 2002. The single tree–based stand simulator SILVA: construction, application and evaluation. For. Ecol. Mange. 162: 3–21.

Reffye (De), P., Fourcaud, T., Blaise, F., Barthelemy, D. & Houllier, F. 1997. A functional model of tree growth and tree architecture. Silva Fenn 31: 297–311.

Saint-André, L., Leban, J.-M., Daquitaine, R. & Houllier, F. 1996. Linking models for the tree growth and wood quality in Norway spruce. Part II: Assessment of a regional resource for wood industry supply. In: Nepveu, G. (ed.). Iufro WP S5.01–04 Second workshop «Connection between silviculture and wood quality through modelling approaches and simulation softwares». INRA–Nancy, France. p. 229–236.

Schmidt, M. 2001. Prognosemodelle für ausgewählte Holzqualitätsmerkmale wichtiger Baumarten. Dissertation, Forstwissenschaftliche Fakultät Georg–August–Universität, Göttingen. 296 p.

— 2004. Simulative Astigkeits- und Qualitätsprognose für Douglasien-Rundholz. Allg. Forst- u. J-Ztg. 175: 49–60. (In German with English summary).

— , Böckmann, T. & Nagel, J. 2006. The use of tree models for silvicultural decision making. In: Hasenauer, H. (ed.). Sustainable forest management. Springer-Verlag, Berlin-Heidelberg-New York. p. 237–261.

Scott, I.R. 2006. Sylview: a visualization system for forest management. A Thesis – the faculty of the Graduate School University of Missouri–Columbia. 63 p.

Seifert, T. 2003. Integration von Holzqualität und Holzsortierung in behandlungssensitive Waldwachstums–modelle. Ph.D. thesis at the Science Center Weihenstephan, Technische Universität München, 314 p. (in German with English summary and captions).

— & Pretzsch, H. 2002. Modeling growth and quality of Norway spruce (Picea abies Karst.) with the growth simulator SILVA. In: Nepveu, G. (ed.). IUFRO WP S5.01.04 Fourth workshop, Connection Between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software. Harrison Hot Springs, British Columbia, Canada, September 8–15, 2002. p. 562–574.

Shinozaki, K., Yoda, K., Hozumi, K. & Kira, T. 1964a. A quantitative analysis of plant form: the pipe model theory. I. Basic analyses. Jpn J Ecol 14: 97–105.

—, Yoda, K., Hozumi, K. & Kira, T. 1964b. A quantitative analysis of plant form: the pipe model theory. II. Further evidence of the theory and its application in forest ecology. Jpn J Ecol 14: 133–139.

Song, T. & Usenius, A. 2007. InnoSim – a simulation model of wood conversion chain, Conference proceedings, COST Action E44 Conference on Wood Processing Strategy Helsinki, September, 2007. p. 95–108.

Surminski, J. 2007. Wood properties and uses. In: Tjoelker, M.G., Boratynski, A., Bugala, W. (Eds.), Biology and ecology of Norway spruce. Forestry Sciences, Vol. 78, pp. 333–342.

Todoroki, C. 1990. Autosaw system for sawing simulation. New Zeal. J. For. Sci. 20(3): 332–348.

— & Rönnqvist, M. 2002. Dynamic control of timber production at a sawmill with log sawing optimization. Scand. J. For. Res. 17: 79–89.

— & Carson, S.D. 2003. Managing the future forest resource through designer trees. International Transactions In Operational Research, 10, 449–460.
— , West, G.G. & Knowles, R.L. 2001. Sensitivity analysis of log and branch characteristics influencing sawn timber grade. New Zeal. J. For. Sci. 31(1): 101–119.
Tomppo, E. 2006. The Finnish National Forest Inventory. In: Kangas, A. & Maltamo, M. (ed.). Forest Inventory, Methodology and Applications Springer. Netherlands. p. 179–194.
— , Henttonen, H. & Tuomainen, T. 2001. VMI8. Metsätieteen aikakauskirja 1B. [in Finnish]
Usenius, A. 2002. Experiments from industrial implementations of forest – wood chain models. In: Nepveu, G. (ed.). IUFRO WP S5.01.04 Fourth workshop, Connection Between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software. Harrison Hot Springs, British Columbia, Canada, September 8–15, 2002. p. 600–610.
Valentine, H.T., Baldwin, V.C., Gregoire & T.G., Burkhart, H.E. 1994. Surrogates of foliar dry matter in Loblolly pine. Forest Science 40: 576–585.
Vanninen, P. 2003. Development of the production and biomass structure of Scots pine: effects of competition, tree age and site fertility. University of Helsinki Department of Forest Ecology, Publications 28. 29 p.
— , Härkönen, S., Enkenberg, J. & Mäkelä, A. 2006. PuMe — Interactive learning environment employing the PipeQual model for forest growth and wood quality. New Zeal. J. For. Sci. 36 (2–3): 280–292.
Verkasalo, E. & Leban, J.-M. 1996. External quality of the saw timber stock of Scots pine and Norway spruce in Finland and France. Paper and Timber 5: 313–322.
— , Sairanen, P. & Melén, P. 2002. Kuusirunkojen ja –tukkien arvon riippuvuus metsikön, rungon ja tukin ominaisuuksista sekä runkojen ja niistä saatavan sahatavaran laatu ja arvo perinteisessä ja erikoistuvassa sahauksessa. In: Saranpää, P. & Verkasalo, E. (ed.). Kuusen laatu ja arvo. Finnish Forest Research Institute, research Papers 841. [The quality and value of Norway spruce] (In Finnish). p. 91–113.
Vuokila, Y. & Väliaho, H. 1980. Growth and yield models for conifer cultures in Finland. Commun. Inst. For. Fenn. 99.2: 1–271.
West, GB., Brown, JH. & Enquist, BJ. 1999. A general model for the structure and allometry of plant vascular systems. Nature 400: 664–667.
Zeide, B. & Pfeifer, P.1991. A method for estimation of fractal dimension of tree crowns. For. Sci. 37(5), 1253–1265.