Dissertationes Forestales 65

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

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Academic dissertation

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ABSTRACT

The objective of this study was to model the growth and development of the stem and wood properties of Scots pine (*Pinus sylvestris* L.) in order to investigate how silvicultural management affects the knots and other properties of wood. In the above context, an existing three-dimensional model for the structural growth, stem and wood properties (especially knots) of a Scots pine was further developed (Paper I) and used with a sawing simulator (Paper II) to study how management (initial spacing, thinning and artificial pruning of branches) affects the quantity and quality of the sawn timber (Paper III). In addition, empirical models were developed for the distribution of diameter growth along the stem (Paper IV) and prediction of early wood percentage, wood density and fibre length along the stem (Paper V). These empirical models were also integrated with a process-based growth and yield model simulations (Papers IV and V).

Based on simulations, it was found that in order to maximize the quality of sawn timber, trees should be grown at relatively narrow spacing (up to 5 000 stems ha^{-1}) at the beginning of the rotation to reduce the growth of branches, whereas towards the end of rotation they should be grown at relatively sparse spacing (e.g. 500 stems ha^{-1}) to accelerate the self-pruning of dead branches and occlusion of knots, and to increase the volume growth of the stem (Paper III). It was also found that the diameter growth and the properties of wood vary in individual trees significantly depending on the stand development phase, management and tree status in a stand and depending on which part of stem is considered (Papers IV and V). To conclude, the integrated models developed in this work provide possibilities to assess simultaneously the impacts of management on the growth and yield and the properties of wood.

Keywords: crown structure, knots, sawing simulator, tree status, diameter growth, wood quality.

ACKNOWLEDGEMENTS

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Joensuu, May 2008

Veli-Pekka Ikonen

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers, which are referred in the text by the Roman numerals I-V:

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

II Ikonen, V.-P., Kellomäki, S. and Peltola, H. 2003. Linking tree stem properties of Scots pine (*Pinus sylvestris* L.) to sawn timber properties through simulated sawing. Forest Ecology and Management 174:251-263.

III Ikonen, V.-P., Kellomäki, S. and Peltola, H. 2008. Sawn timber properties of Scots pine (*Pinus sylvestris* L.) as affected by silvicultural management: a model based approach. Submitted manuscript.

IV Ikonen, V.-P., Kellomäki, S., Väisänen, H. and Peltola, H. 2006. Modelling the distribution of diameter growth along the stem in Scots pine. Trees 20:391-402.

V Ikonen, V.-P., Peltola, H., Wilhelmsson, L., Kilpeläinen, A., Väisänen, H., Nuutinen, T. and Kellomäki, S. 2008. Modelling the distribution of wood properties along the stems of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) as affected by silvicultural management. Submitted manuscript.

Most of the work involved in Papers II, III, IV and V was carried out by Veli-Pekka Ikonen. He also had the main responsibility for the model development work and analyses of the datasets for the Paper I, the results of which were written up jointly with the co-authors.

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1 INTRODUCTION

1.1 Background

Management affects the growth and properties of the stem and wood of trees and thus the suitability of wood for pulp and paper production and mechanical wood processing. The effects of management (e.g. spacing, thinning, fertilising, artificial pruning of branches) and environment (soil, climate) on the growth and the consequent properties of the stem and wood are established through the interaction between biological processes (i.e. height growth, radial growth of stem, crown development) and the environmental conditions. Competition for light tends to modify the allocation of growth along the stem, whereas competition for water and/or nutrients affects the growth rate of trees (Cannell et al. 1984, Nilsson and Gemmel 1993, Nilsson 1994). Management such as thinning increases the living space of individual trees, resulting in faster growth and wider annual rings, with consequent effects on early wood percentage, wood density and fibre and knot properties. This is because the properties of the stem and wood are linked with the distribution of growth over the stem (Hakkila 1966, Uusvaara 1974, Saikku 1975). However, the effects of management, such as thinning, on the stem and wood properties of trees may vary depending on the type (from above or from below) and intensity of thinning, the length of interval between thinnings, the position of the tree in the stand (dominant, intermediate or suppressed) and the cambial age (i.e. the phase of forming juvenile or mature wood).

Dynamics of crown development is determined by the birth, growth and death of shoots and branches and the self-pruning off of dead branches. Consequently, the quality of sawn pieces is related to the concurrent growth and development of stem and crown, which determine the occurrence and quality of knots (living, dead) in the wood (Uusvaara 1974, 1985, 1993, Colin and Houllier 1991, 1992, Jäghagen and Lageson 1996, Björklund 1997, Björklund and Moberg 1999, Pape 1999). Especially, the role of knots representing the early phases in the lifespan of a tree is of primary importance. This is because they define the properties of wood in the butt log, with large impacts on the total yield and quality of sawn pieces provided by a single stem (Persson 1976, 1977). Because the occurrence, size and quality of knots in the wood substantially affect the quality of sawn pieces, they are also commonly used in the grading of sawn timber in the Nordic countries (Nordic Timber 1994).

However, the lifespan of a branch is short compared to that of a stem, which makes it difficult to relate the quality of sawn pieces experimentally to the crown dynamics. Moreover, the properties of saw logs and the sawing pattern used in sawing also affect the quality of sawn timber. Therefore, proper modelling tools are needed to understand how the growth history of the tree and sawing pattern interact and determine the quality of sawn pieces. In fact, several models have been developed in recent years in order to predict the mean or maximum dimensions of branches (Colin and Houllier 1992, Roeh and Maguire 1997, Mäkinen and Colin 1998, 1999, Grace et al. 1999, Mäkelä and Vanninen 2001) or knots in stem wood related to stem characteristics (Björklund and Petersson 1999, Moberg 1999, 2000, 2001, Mäkinen and Mäkelä 2003, Moberg 2006). Moreover, three-dimensional models for the structural development of stem and crown have been developed to link stem and wood properties with the growth of trees (Oker-Blom et al. 1988, Kellomäki et al. 1989, Houllier and De Reffye 1996). Such models also allow one to link the growth of trees directly to the quality of sawn pieces through simulated sawing (Väisänen et al. 1989, Houllier et al. 1995, Leban et al. 1996, Saint-André et al. 1996, Barbour et al. 1997, Mäkelä et al. 1997, Lönner and Björklund 1999). These kind of integrated models allow one also to study how the structural development of the stem and crown relate to a selected management (e.g. initial spacing, thinning and pruning of branches) and how management affects the quality and quantity of stem wood and sawn timber. However, until today these models have been used mainly for research purposes. The computing time also can be rather long in such models, because of their complex structure with a large number of parameters.

On the other hand, in recent years empirical models have also been developed which can be used to study other properties of wood than knots at any height of stem (e.g. late wood content, wood density and fibre properties) (Wilhelmsson et al. 2002, Ekenstedt et al. 2003). Since stem growth and the distribution of growth over the stem are dynamic processes, a combination of process-based growth and yield modelling (Kellomäki and Väisänen 1997, Matala et al. 2003) and empirical approaches for the distribution of growth and wood properties along the stem may offer successful tools, for example, for analyses on how management (e.g. spacing and thinning) and the status of the tree in the stand may affect the quality and quantity of raw material (e.g. early wood percentage, wood density and fibre properties, but also knots in wood). The use of process-based growth and yield models has several strengths. They start from processes such as photosynthesis, use weather and soil data and different tree cohorts in a stand as inputs for simulations and could, thus, predict the growth and dynamics of tree stands over a rotation under changing environmental conditions (climate, site) and management. However, similar to three-dimensional models, also process-based growth and yield models need a large number of parameters and detailed description of the properties of sites and trees for initiating the simulations. Despite of this, the need for this kind of integration of wood quality models with growth and yield models is emerging and will become increasingly important in the future, when more intensive forest management (e.g. heavy thinning and fertilization) and value-added wood utilization are aimed for in forestry. Very limited efforts have been made so far to develop wood quality models which could be integrated into growth and yield models.

1.2 Aims of the study

The objective of this study was to model the growth and development of stem and wood properties of Scots pine (*Pinus sylvestris* L.) in order to investigate how silvicultural management affects the knots and other properties of wood such as early wood percentage, wood density and fibre length. This research objective was addressed in two phases.

First, three-dimensional modelling for the structural growth, stem and wood properties (especially knots) of a Scots pine was developed (Paper I) and used along with a sawing simulator (Paper II) to study how management (such as initial spacing, thinning and artificial pruning of branches) may affect the quality and quantity of the sawn timber (Paper III).

Second, empirical models for the allocation of diameter growth along the stem (Paper IV) and the properties of wood such as early wood percentage, wood density and fibre length were developed and integrated with simulations using a process-based growth and yield model (Paper V) in order to study how the growth and properties of wood vary over the stem and how the management affects their variability in trees representing varying growing positions in the stand (Papers IV-V).

2 MATERIAL AND METHODS

2.1 Modelling three-dimensional structure of Scots pine with implications for simulated sawing (Papers I - III)

2.1.1 Modelling the effect of stand density on the growth of an individual tree

The three-dimensional model for the growth of individual Scots pine originally compiled by Kellomäki and Strandman (1995) has been further developed in this work (Papers I and III), focusing on the inclusion of the effects of between-tree shading on the growth and mortality of branches, with the consequent effects on the stem and wood properties. Modelling of the tree growth is based on the iteration of a shoot module, which is the basic computation unit. Shoots are either mother shoots or daughter shoots, which will later give birth to their daughter shoots. The structure of the tree is thus controlled by the generation, growth, death and pruning-off of the shoots and branches, with impacts on the stem and wood properties (Figure 1).

The number and dimensions of daughter shoots are related to the light intercepted by the mother shoot and interception supply from other shoots. The terminal shoots form the stem, while the shoots around the terminal shoots form the butt parts of the branches with the direct effect on the stem and wood properties. Also, when new shoots grow on each branch, the main branch grows in length and new lateral branches are formed. Whenever a new shoot occurs, its location (x,y,z co-ordinates for the point where it is attached to the parent shoot) and orientation (azimuth and inclination) are determined by the resulting spatial arrangement of shoots in the crown envelope (Kellomäki and Strandman 1995). The formation of new shoots within the branch gradually ceases and the branch dies and it is pruned off.

A tree (object tree) growing in a stand receives light throughout the hemisphere, but only that not intercepted by the neighbouring trees (shading trees), which are expected to be similar (the same size and crown structure). In the object tree, only a part of the light is intercepted by the shoots, the rest being transmitted through the crown onto the crowns of trees surrounding the object tree. The surrounding trees, and consequently the spacing, affect the amount of radiation reaching each shoot, and thus, reduce the available light for the development of branches and stem.

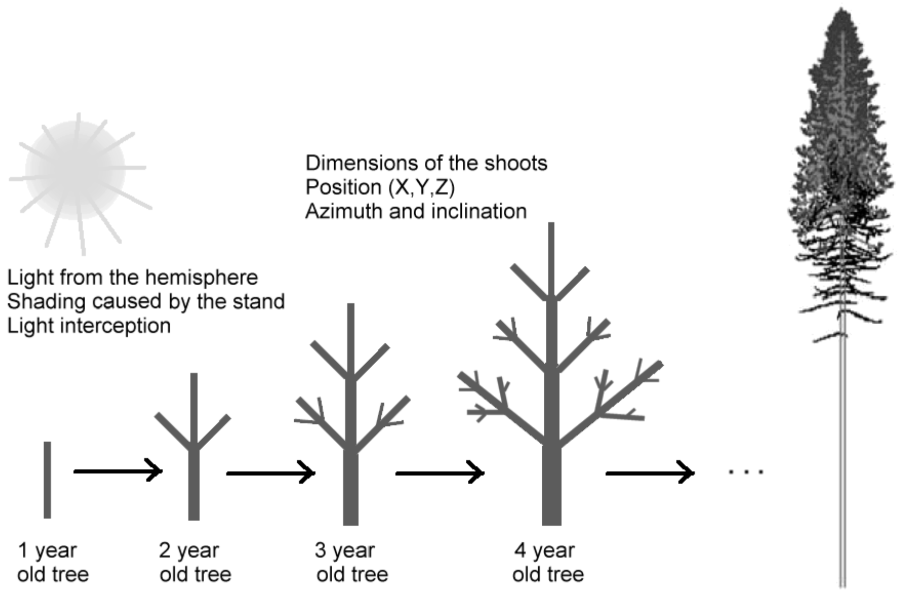

Figure 1. Outlines of the modelling task. Basic inputs and outputs of the model and an example of a simulated tree is presented.

The shading caused by the stand is calculated in a one year timeframe (Figure 2). In this context, the living crown of the object tree in a particular year is divided dynamically into up to 30 horizontal layers of equal depth and the sum of the intercepted light in each layer in the object tree is multiplied by the number of trees per hectare in order to provide the total amount of light intercepted in the stand. The relative shading of each layer equals the ratio between interception by the surrounding trees and the total radiation coming from the sun. The total shading is cumulative from the top of the canopy down to its bottom. In other words, the available light for the shoots of the object tree is equal to the sum of light above the canopy of the tree stand minus the light intercepted by the shoots in the crowns, assuming that the rest of the light is transmitted through the canopy downwards.

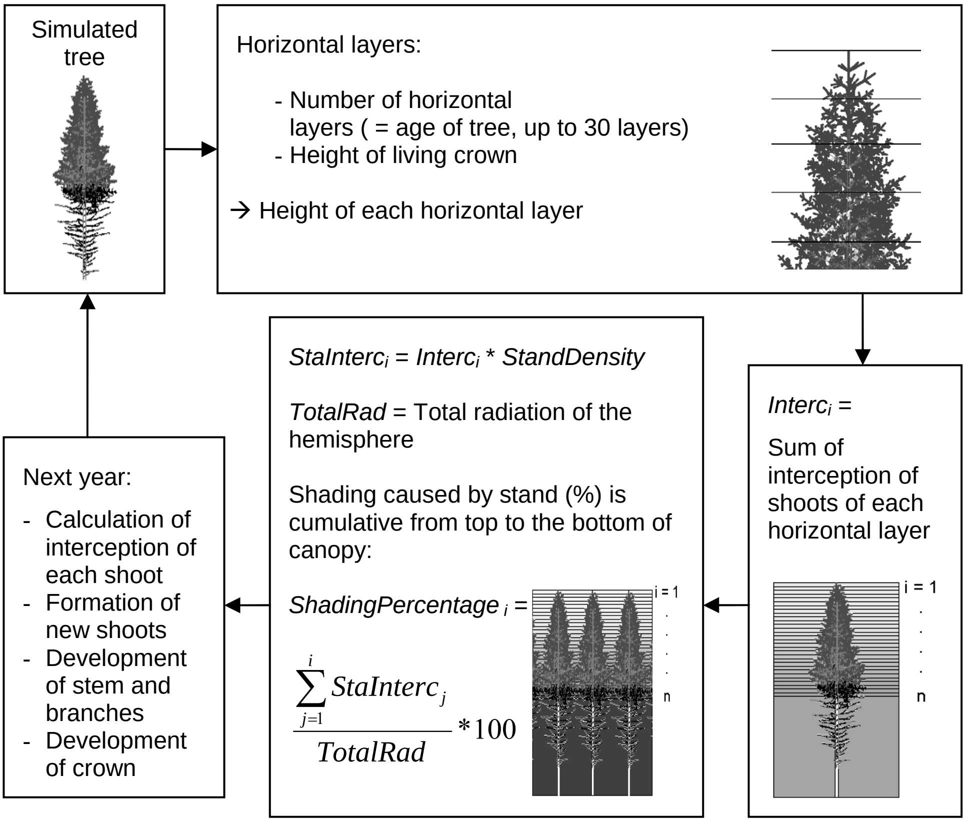

Figure 2. Outlines for calculating the shading caused by the stand. Shading percentages for each horizontal layer are calculated in a one year timeframe using information of intercepted light by the shoots of the simulated average tree in the previous year and the stand density in the current year.

2.1.2 Modelling the growth and mortality of branches and self-pruning of dead branches

The diameters of branches in the whorl and crown develop in interaction with (i) birth of a whorl, (ii) initial length of branches, (iii) growth of the branches, (iv) radiation coming from the sky, (v) interception of light by individual shoots and interception supply from other shoots, (vi) size and form of the crown and (vii) shading caused by the stand. In the final version of the model (Paper III), the branch growth was slightly modified in order to provide a more realistic distribution of branch diameters compared to the previous version (Papers I-II), in which the range of diameter distribution was found to be too narrow. For this purpose, the light intercepted by shoots below the particular whorl was shared amongst the branches of the whorl in relation to the percentage of cross-sectional area of each branch within the whorl, unlike in the previous version of the model, in which the supply for each branch in a whorl was equal.

Young branches have a high survival rate in the model as regards shoots attached to the branches, but the survival rate decreases rapidly when branches are deeper in the canopy. On the other hand, the branches of a young Scots pine will die earlier than those of an older one. Therefore, the survival of a branch is related, in the model, to the relationship between the number of needle-covered shoots and the total number of shoots on the branch (assuming the maximum needle age as four years). A branch will die when the percentage of the needle-covered shoots is less than that indicated by the theoretical rate of branch survival.

In the final version of the model shown in Paper III, the self-pruning of dead branches is modelled, in principle, in the same way as was described in Paper I, i.e. as a function of diameter of each dead branch. However, the procedure for the self-pruning of dead branches was improved by taking into account the sheltering effect of living branches against snow load, wind or other forces affecting the rate of self-pruning (e.g. Heikinheimo 1953). This was done by calculating the total cross-section area of living branches in a stand year by year (see Paper III for details). As a result of this model development, the time needed for self-pruning of dead branches is shorter in more sparse stands (or stands with Scots pines having smaller crowns). Furthermore, when branches are self-pruned, a short branch stub is left attached to the stem, whose length is depending on branch diameter (i.e. square root of the branch diameter). As a result of diameter growth of tree, the stubs are occluded during the following years and they become the knots affecting the sawn timber quality. In the model the knots have sound- and loose-knot segments, but not, for example, resin taps.

2.1.3 Modelling of the stem taper

The development of the length of stem in the model is driven mainly by the interception of light as described above. The diameter (D(i,t), cm) of the stem at any section (or shoot, height i) of the stem at any time (t) is related to the diameter of the same section in the previous year (t-1) plus the diameter growth in this section in the current year. In the final version of the model, it was assumed that the diameter growth of stem in any section is related to the formation of the new shoots, i.e. related to the sum of the volumes of the new shoots above the particular shoot in the stem (see Paper III for further detail).

2.1.4 Sawing simulator

The three-dimensional growth model was linked with a sawing simulator (Paper II), originally developed by Väisänen et al. (1989). The new version of the sawing simulator includes (i) the use of the new grading rules (Nordic Timber 1994) including wane in pieces of sawn timber, and (ii) the improvement of user interface with default values of cutting lengths of logs and default sawing pattern (as a function of upper diameter of the log) used to saw logs into pieces (Figure 3). Finally, the three-dimensional growth model linked with the sawing simulator was also applied in this work to study how varying initial spacing, number, intensity and timing of thinnings and artificial pruning of branches affect the quality and quantity of sawn timber (Paper III).

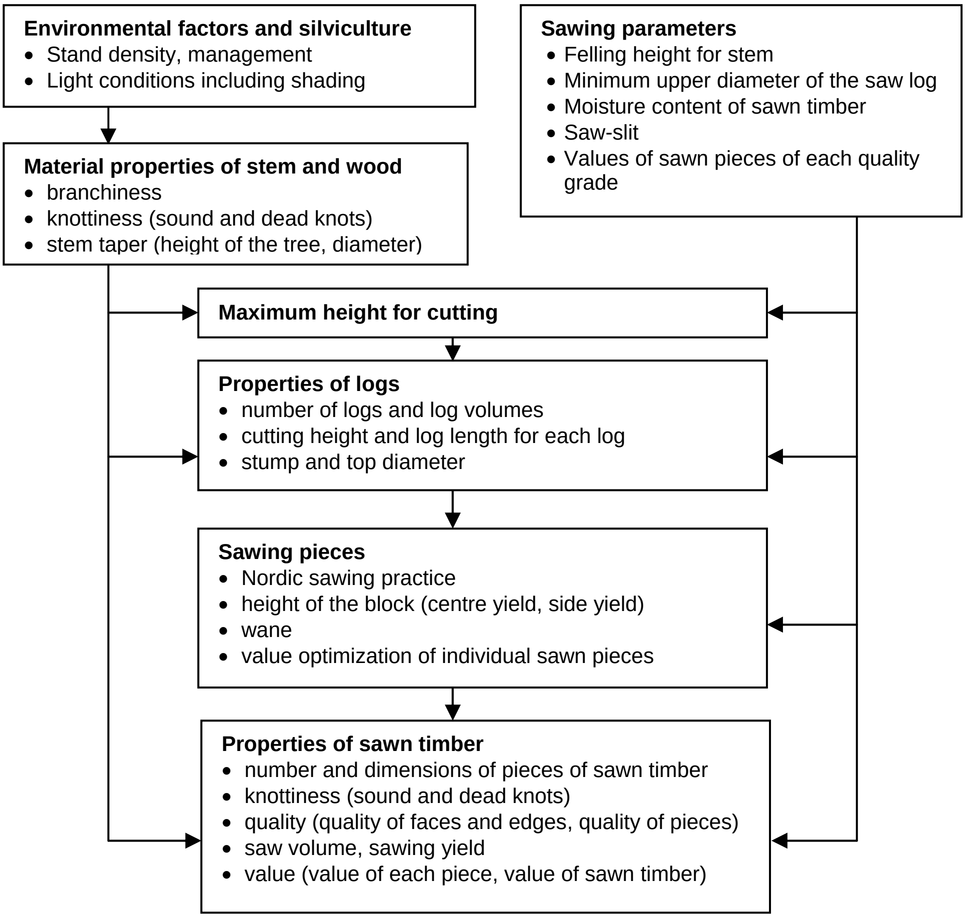

Figure 3. Outlines of the sawing simulator with links to the three-dimensional growth model.

2.2 Empirical modelling for the allocation of diameter growth along the stem (Paper IV)

2.2.1 Outlines for the modelling

The three-dimensional growth model of an individual Scots pine tree (shown in Papers I-III) does not allow the studying of how the management affects the diameter growth and consequent wood properties of trees grown at different growing positions in the stand. For this purpose, a new model for diameter growth was developed and integrated with a process-based growth and yield model, which is capable of simulating such effects (see more details in Papers IV and V, and Kellomäki and Väisänen 1997, Matala et al. 2003). In model building, it was assumed that the diameter (D (k,t), cm) of any section of the stem (distance k from the stem apex) at any time (t) is related to the diameter of the same section in the previous year (t-1) and the diameter growth in this section in the current year (ΔD(k,t), cm) (Figure 4).

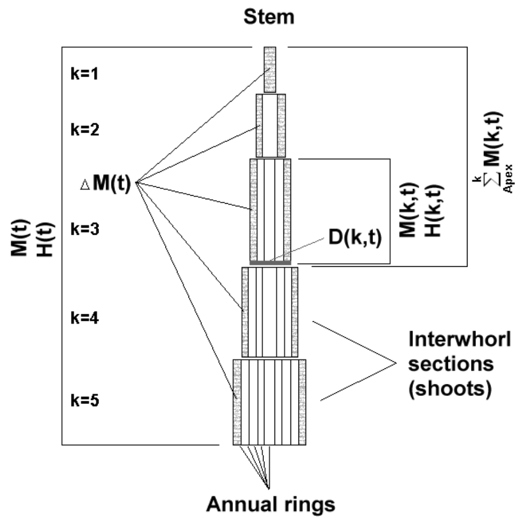

Figure 4. Outlines for calculation of diameter growth along the stem. Legends: M = mass, H = height, D = diameter, k = height of any section of the stem, t = time (year). Reprinted from Trees, Vol. 20, 2006, pages 391–402, Modelling the distribution of diameter growth along the stem in Scots pine, Ikonen, V.-P., Kellomäki, S., Väisänen, H. and Peltola, H., Figure 1, © Springer-Verlag 2006, with kind permission of Springer Science and Business Media.

2.2.2 Empirical datasets

The data used for estimation of the parameters and validation of the model include two datasets for Scots pines in a forest close to the Mekrijärvi Research Station, University of Joensuu, in Eastern Finland (62°47'N, 30°58'E, 145 m a.s.l.). The first (dataset A, for further detail see Paper IV) originates from a long-term early thinning experiment established in summer 1986 in a naturally regenerated stand of Scots pines growing on a site with a rather low nitrogen supply (*Vaccinium* type). The experiment employed ten plots (of size 40 m by 30 m), in which the thinning treatments were randomized; i.e. one plot was not thinned and nine were thinned from below to densities of 575 to 3400 stems ha^{-1} in winter 1986-1987 (Peltola et al. 2002, 2007). A total of 30 sample trees (approximately 40 years old) in this thinning experiment were felled in autumn 1998 (3 from each plot) and their height was measured together with annual height growth (distances between interwhorls) whenever a whorl was recognisable. In addition, 5 cm thick cross-sectional discs were taken from each interwhorl for detailed stem analyses. These sample trees showed a large between-tree variation in growth rates (3 trees of the same age per plot representing different sizes (diameters) and different positions (suppressed, co-dominant and dominant). The mean height of the sample trees was 13.4 m (range 10.2-15.9 m), diameter at breast height 11 cm (range 6.1-16.1 cm) and age at breast height 33.5 years (range 31-37 years).

The second set of Scots pine data (dataset B, for further detail see Paper IV) originated from a mature (90- year-old) Scots pine stand with a 20% mixture of Norway spruce (*Picea abies* (L.) Karst.), growing on a site with a medium fertility (*Myrtillus* type) representing a soil of sandy moraine. The stand density was ca. 900 stem ha^{-1}. Measurements were made in summer 2002 on seven Scots pine trees with a mean diameter at breast height of 21.6 cm (range 16.6-27.5 cm), mean height of 20.4 m (range 15.4-24.3 m) and age at breast height 72.6 years (range 59-81 years).

Regardless of the dataset, ring widths were determined from each disc (with an air-dry moisture content of 12%) in a north-south direction using the image analysis technique WinDendro™ with an Agfa scanner (Regent Instruments Inc.). The ring widths were measured separately towards the south and north to the nearest 0.01 mm, working from the pith outwards, and the two sets of data were summed for the analysis of diameter growth. Moreover, the mass growth (dry mass) of each stem section, and that of the whole stem was calculated annually based on the ring width measurements, assuming that the basic density of the wood was 420 kg m^{-3}.

2.2.3 Analysis of the datasets and estimation of the model parameters

When estimating the parameters for the model, non-linear regression was applied using SPSS for Windows. The first dataset (A: young trees) was divided into two equal subsets (A1, A2) representing similar growth data, i.e. 50% of the sample trees were used for estimating the parameters (A1) and 50% for independent validation of the model (A2). The whole second dataset (B: mature trees) was used to test whether the model based on the parameters obtained from dataset A1 (younger trees) was also valid for mature trees. It was also divided into two subsets (B1: 3 trees, B2: 4 trees) in order to obtain new parameters for a combined dataset including young (A1) and mature trees (B1), to find out whether this combined dataset increased the validity of the model for mature trees (dataset B2) relative to that based only on dataset A1 (see in details Paper IV)**.**

2.3 Empirical modelling of the wood properties (Paper V)

2.3.1 Empirical datasets

For the development of ring-based models for early wood percentage, wood density (air dry) and fibre length in Scots pine, sample trees originating the same sites as for Paper IV were used. Moreover, the first Scots pine dataset included some of the sample trees used in dataset A (sample trees cut in 1998-1999) and the second included 7 of 8 same sample trees used in dataset B (sample trees cut in summer 2002) used in Paper IV. But, the number of sample trees and discs was in this work significantly larger, i.e. altogether 136 trees and total of 337 discs (Paper V).

For wood density analyses, small rectangular wood specimens, of size 5 mm x 5 mm (a radial segment from pith to bark), were cut out of stem discs using a twin-bladed circular saw. Thereafter, air dry wood specimens were scanned in batches using a direct scanning ITRAX X-ray microdensitometer (Cox Analytical Systems, Göteborg, Sweden). The X-ray radiographic images were further analysed with the Density software program (Bergsten et al. 2001) to determine intra-ring density profiles for each sample from pith to bark. Based on these radiographic images and intra-ring density profiles and with the help of Excel macros, the following ring width and ring density parameters for each ring were determined: ring width (mm), early and late wood widths (mm) and their proportions (%), mean wood density (g cm^{-3}), minimum and maximum wood densities (g cm^{-3}) and early wood and late wood densities (g cm^{-3}). Similar to previous corresponding analyses, the mean of the maximum and minimum intra-ring densities were used as the threshold for early- and late wood in each ring, i.e. the values above and below this threshold representing the late- and early wood (Kilpeläinen et al. 2005, Peltola et al. 2007).

Intra-ring average fibre lengths were determined with a light microscope and Image Pro Plus 4.0 for Windows (Media Cybernetics, Silver Spring, MD) for each annual ring pair (a radial segment from pith to bark) by averaging lengths of at least 25 undamaged fibres. Altogether, significantly smaller number of sample trees could be analyzed on average for fibre length compared to other relevant variables due to the very time-consuming methodology used for this purpose (see in details Paper V). Corresponding ring widths needed for fibre length modelling were measured by ITRAX (Scots pine dataset 2) or image analyses technique WinDendro™ with an Agfa scanner (Regent Instruments Inc.) depending on the dataset measured (Scot pine dataset 1).

2.3.2 Development of ring-based properties models

Empirical ring-based models for early wood percentage, wood density (air dry) and fibre length were formulated based on various datasets, which consisted of 337 sample discs taken from breast height to canopy top at various tree heights from 136 Scots pines (for further information see Paper V). Different kinds of relevant variable combinations were tested for each wood property model based on all the ring-based measurements. Model simplicity and accuracy were the most significant criteria for the acceptance of the final model in addition to their general applicability together with the process-based growth and yield model. Instead of mixed modelling approach, it was preferred to build the models based on pooled observations, without considering variation between the stands, plots, individual trees or individual discs taken from the same tree.

Thus, ring width was simply used to explain early wood percentage, whereas early wood percentage and cambial age were used to explain air dry wood density, and radial growth percentage and cambial age to explain fibre length. The parameters of the empirical models were estimated in SPSS based on linear regression methods. The models were evaluated in terms of coefficient of determination (R^2), RMSE (Root Mean Squared Error) and residuals of the models. In this context, the performance of the ring-based models was also compared against corresponding disc-based models, which predict the cross-sectional properties based on the number of annual rings and diameter at breast height and/or the cross-section being considered and temperature sum (for further detail see Wilhelmsson et al. 2002, Ekenstedt et al. 2003, and Paper V).

2.4 Integration of models for empirical diameter growth and wood properties with a process-based growth and yield model simulations (Papers IV and V)

In Paper IV, the empirical model for the diameter growth of Scots pine trees was integrated into a process-based growth and yield model (FinnFor), which was developed by Kellomäki and Väisänen (1997) (Figure 5). In the FinnFor model, the dynamics of the forest ecosystem and stem growth are linked to climate directly through photosynthesis, respiration and transpiration and indirectly through the hydrological and nitrogen cycles (Kellomäki and Väisänen 1997). The model works on an hourly basis, with computations covering an entire year, and the stem growth is determined in terms of the amount of annual photosynthesis allocated annually to the maintenance and growth of the tree stem.

Model inputs
- Tree and stand characteristics (e.g. number, age, height and diameter of trees in various cohorts)
- Environmental factors (climate and site)
- Forest management (e.g. initial spacing, thinning and rotation length)

↓

Physiological model and calculation of radial growth of trees
- Tree and stand level processes (e.g. photosynthesis, respiration and transpiration)
- Soil processes (e.g. temperature, water, nitrogen, carbon)
- Mass growth
- Calculation of radial growth (based on empirical diameter growth model, Paper IV) and stem dimensions of various tree cohorts

↓

Wood properties models
- Distribution of early wood percentage, air dry wood density and fibre length along the stem (Paper V)

Figure 5. Outlines for the integrated modelling of growth and yield and wood properties of tree stands.

Based on the integration of the empirical model for the diameter growth of Scots pine trees into FinnFor model (see Paper IV for further information), the annual growth of stem mass can be allocated to the stem as a function of current stem mass and its distribution along the stem and as a consequence, the growth of stem mass at each height can be converted into the ring width. As different tree cohorts can be simulated simultaneously, the FinnFor model can be used to study how the diameter growth and properties of wood such as early wood percentage, wood density (air dry) and fibre length (Paper V) are distributed over the stem as controlled by spacing, thinning and the status of the tree in the stand (dominant, co-dominant or suppressed) over a rotation (Figure 5). The input data needed for the simulations consist of the number of trees in each cohort, their diameter, height and age, the site characteristics of the stand and the relevant management schedules. For further information regarding the FinnFor model and its performance see Kellomäki and Väisänen (1997) and Matala et al. (2003) and Papers IV and V.

3 DEMONSTRATION OF MODEL PERFORMANCE

3.1 Three-dimensional growth modelling of tree with integration to sawing simulator (Paper III)

The performance of the integrated model was demonstrated through calculating how different management schedules, including varying initial spacing, thinning and artificial pruning of branches, may affect the quality and quantity of the sawn timber. The growth of trees was modelled in an even-aged pure Scots pine stand representing quite a poor site in southern Finland (latitude 62°N) over a simulated rotation period of 100 years. The simulated trees, with simulated growth to 100 years, were compared at the end of rotation in terms of height and diameter development, properties of knots (location, size and quality) and quality and quantity of sawn timber yield. Altogether, 12 different management scenarios were applied (Table 1).

Table 1. Management scenarios applied (in all scenarios clearcut at the end of rotation at the age of 100 years was applied).

Scenario: initial stand density	Timing and post-thinning stand density (stems ha^{-1}) of pre-commercial and commercial thinnings					
	Year 15	Year 30	Year 45	Year 65	Year 70	Year 85
1: 2 500			1 100	800		500
2: 2 500			1 100		500	
3: 5 000	2 500		1 100	800		500
4: 5 000	2 500		1 100		500	
5: 5 000		2 500	1 100	800		500
6: 5 000		2 500	1 100		500	
7: 2 500			1 100, Pruning	800		500
8: 2 500			1 100, Pruning		500	
9: 5 000	2 500		1 100, Pruning	800		500
10: 5 000	2 500		1 100, Pruning		500	
11: 5 000		2 500	1 100, Pruning	800		500
12: 5 000		2 500	1 100, Pruning		500	

Moreover, outputs of 10 repeated simulations from each scenario were averaged (because of random effects were included in the model) when comparing how different management schedules differ from each other. All simulated trees were sawn by applying the grading, which optimised the value of individual sawn pieces. For the butt logs, the same sawing pattern was applied (i.e. the height of the centre block is 150 mm and the thickness of the thickest sawn piece in the centre of the stem is 50 mm) in order to facilitate the better comparison between different schedules. For the second and third logs of each stem, the default pattern selected by the sawing simulator were used (sawing pattern is selected as a function of the top diameter of the log). Dimensions of sawn pieces were, thus depending on the log dimensions, the sawing pattern, and the value optimization of individual sawn pieces.

3.2 Integrated use of empirical models for the diameter growth and wood properties with the process-based growth and yield model (Papers IV and V)

3.2.1 Empirical model for the diameter growth

The study on the performance of the empirical model for the distribution of diameter growth in the context of the FinnFor model simulations was carried out for unthinned and thinned Scots pine stands growing on a site of medium fertility representing the *Myrtillus* type with three-year-old seedlings (of an average height of 0.30 m and diameter 0.30 cm at stem base) and stand density 3300 stems ha^{-1} (of which 1100 seedlings in each of the three cohorts) (see Paper IV for further detail). Thinning was applied based on stem volume development over a hundred-year simulation, assuming that it took place in simulation years 35 and 75 by harvesting 40% of the stem volume on each occasion. Trees were, however, assumed to be removed across the whole diameter distribution, with preference for suppressed and intermediate trees, as is typical for thinning from below. The performance of the empirical model for the distribution of diameter growth in the context of the FinnFor model was analysed by comparing the simulated growth of the trees between the thinned and unthinned stands, i.e. in trees of different status in the stand (dominant, suppressed).

3.2.2 Empirical models for the wood properties

In Paper V, the performance of the wood properties models for early wood percentage, air dry wood density and fibre length was also demonstrated by the simulation of the development of growth and wood properties over the stem (from the stem butt to the apex and from the pith to the stem surface at any height in the stem) and over the lifespan of the tree as affected by tree status in the stand and silvicultural management. This was done by simulating the growth and dynamics of unthinned and thinned Scots pine stands grown on a site representing the *Myrtillus* type in eastern Finland. These stands were planted with 2500 seedlings ha^{-1} (also three-year-old seedlings with average height and diameter of 0.30 m and 0.30 cm, but divided into five cohorts with 500 seedlings in each). In the thinned stand, two thinnings from below were done during the 90 year rotation (first at the age of 40 years into 1000 stems ha^{-1} and second at the age of 70 years into 500 stems ha^{1}). Based on these simulations, it was compared the differences in growth and wood properties of dominant and suppressed trees (i.e. lowest and highest tree cohort) grown in unthinned (stand density at the time of final cut about 800 stems ha^{-1}) and thinned stands as an average of tree stems. Furthermore, differences in wood properties of various parts of the stems were also studied (i.e. whole stem, inner part, outer part or top part of the stem) (see Paper V for further detail).

4 RESULTS

4.1 Development and performance of the three-dimensional growth model with integration to sawing simulator (Paper III)

4.1.1 Development of the three-dimensional growth model

In this study, it was further developed three-dimensional modelling (Papers I and III), in which growth of individual shoots in Scots pine are driven mainly by interception of light, and as a result an average tree in a stand is simulated over a rotation in a one year timeframe. The model describes (i) crown structure (as a population of shoots and branches), (ii) branches (birth, growth, death and self-pruning of branches), (iii) knottiness (position and angle, number and diameter, and length of sound- and loose-knot segments), (iv) stem form (height growth and diameter growth), and (v) other properties of wood (as annual ring basis, e.g. wood density). In the further model development, it was concentrated especially on modelling of shading caused by other trees in a stand, and impact of stand density and crown structure of the trees on self-pruning of branches. This model development finally made it possible to analyze effects of management options (initial spacing, thinnings and artificial pruning of branches) on the quality and quantity of sawn timber.

In this study, the three-dimensional model was linked with the sawing simulator (Paper II), originally developed by Väisänen et al. (1989). In this new version of sawing simulator a procedure was presented in which the sawing of logs into pieces and the quality grading of these pieces are simulated more accurately than in the earlier version. In the above context, it was concentrated especially on (i) the use of the new grading rules (Nordic Timber 1994) including wane in pieces of sawn timber, and (ii) improving of user interface with default values of cutting lengths of logs and default sawing pattern (as a function of upper diameter of the log) used to saw logs into pieces. Although the improvement of the sawing simulator was mainly engineering, it was essential in order to analyze the relationship between silvicultural treatments and timber quality.

4.1.2 Performance of the three-dimensional growth model

At the beginning of the rotation, the number of shoots with living needles increases rapidly. Consequently, the shading caused by the stand is increasing rapidly, especially in dense stands (Figure 6). When the canopy is closed the formation of new shoots decreases and shading caused by the stand levels off. The levelling-off is faster in stands with narrow spacing than in the stands with wide spacing. Thinning reduces shading, which accelerates the formation of new shoots.

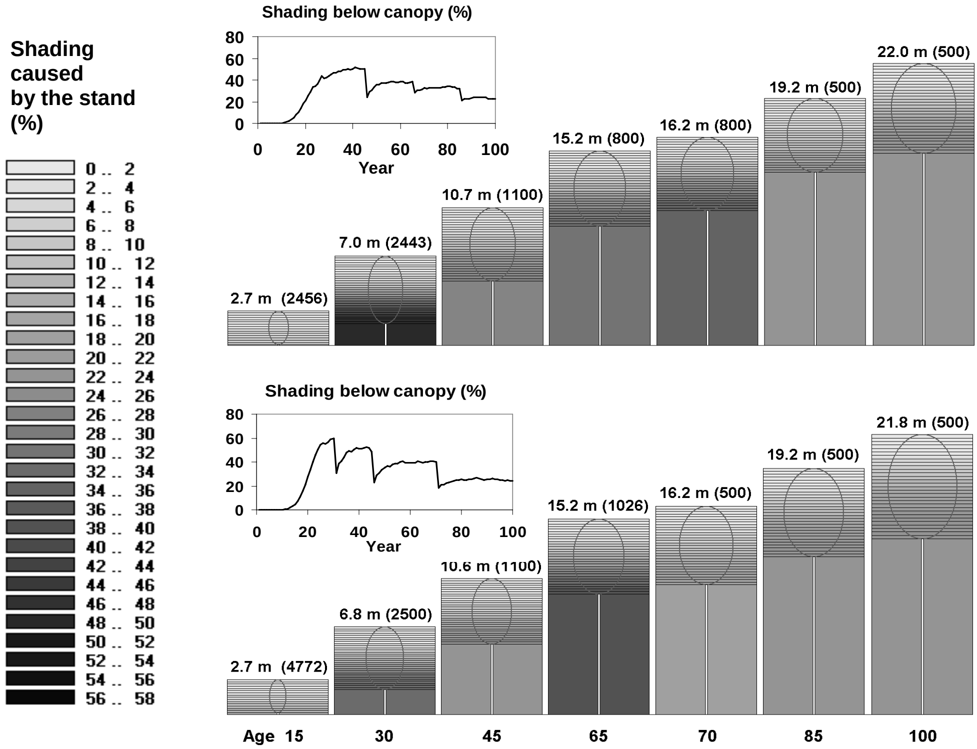

Figure 6. Example of shading caused by the stand. Examples of iterations have been taken from management scenario 1 (top) and 12 (bottom). The presented shading percentages (in the grey scale images) are post-thinning values for each horizontal layer. The presented years are those in which at least one management scenario includes thinning in that particular year. Also height of the tree (m) and post-thinning stand density (stems ha^{-1}, in parenthesis) have been presented. Shading percentages below canopy are presented in the charts.

In the example shown for management scenario 12 (with initial stand density of 5 000 stems ha^{-1}) the shading percentage shows the maximum value of 60% just before tending of the seedling stand (into stand density of 2 500 stems ha^{-1}) in year 30. However, as a result of the 45% decrease in stand density, the shading percentage decreases immediately to 31% (Figure 6). In the corresponding example for management scenario 1, with a smaller initial stand density (2 500 stems ha^{-1}), the shading percentage in the same year was 44% (the scenario includes no thinning in that year, having 2 443 stems ha^{-1}). This implies that for scenario 1 the shading percentage (with smaller stand density) becomes larger as a result of higher growth rate of the tree (and larger crown) compared to scenario 12 in the post-thinning situation.

Usually the shading percentage is larger in the scenarios with higher stand density. For example in year 65 in scenario 1 the post-thinning stand density was 800 stems ha^{-1} and the shading percentage below canopy was 29%, whereas in scenario 12 the corresponding values were 1 026 stems ha^{-1} and 39%. In year 70 the situation between the scenarios is opposite, i.e. scenario 1 had both larger stand density (800 stems ha^{-1}) and shading percentage (33%) than scenario 12, where the corresponding values were 500 stems ha^{-1} and 18% (Figure 6). At the end of the rotation from years 85 to 100 the shading percentages in both examples were similar implying that growing conditions were alike in both cases (both quite sparse stands).

4.1.3 Effect of management on quality of sawn timber

Scenarios 1, 2, 7 and 8 represent planted stands (2500 stems ha^{-1}), whereas other scenarios represent natural regeneration (5000 stems ha^{-1}). In scenarios 5, 6, 11 and 12 the stands were rather dense in the first 30 years, supposing that branches will remain rather small and self-pruning of branches will be faster. In scenarios 2, 4, 6, 8, 10 and 12 stand density of 500 stems ha^{-1} was achieved earlier than in other scenarios with the supposition that the stems will grow larger and branches will be self-pruned slightly earlier than in more dense stands. In scenarios 7-12, the management differs from counterparts 1-6 only in terms of artificial pruning of branches (Table 1).

In these scenarios the stem volume was not very sensitive to the management indicating that trees grown under thinning had enough space to grow, especially later in the rotation. However, using higher stand density in the first years of the rotation with delayed tending of the seedling stand, the quality of sawn timber was higher. This was especially demonstrated by the stands subjected to pruning (management scenarios 11 and 12). This was also clear for the un-pruned stands, 5 and 6, with the high stand density at the beginning of the rotation. In the dense stands, the sawing yield percentage (volume of sawn pieces / volume of the log * 100 %) became, however, smaller due to a slower growth rate, e.g. in the scenarios 5 and 6. Scenario 8 had a high sawn value (€ ha^{-1}) even if the stand was rather sparse over the rotation compared to other scenarios. In this case, the sawing yield percentage was also rather high (Table 2).

Table 2. Average tree and stand level results of simulated sawing of each management scenario. The results are average values of 10 iterations of each management scenarios from final cutting (at the age of 100 years).

Scenario	Stem properties			Sawing yield and value of the stem							Sawing value of the stand	
	Height	Dbh	Volume	Value (€ m^{-3})		Total value (€)		Sawing yield [a] (%)		Quality frequencies [b]	Total value [c] (€ ha^{-1})	
	(m)	(cm)	(m^3)	Butt log	All logs	Butt log	All logs	Butt log	All logs	of butt log (A / B / C)	Butt log	All logs
1	22.1	22.7	0.490	157	143	20	38	62	61	1.9 / 2.6 / 3.5	9 791	18 990
2	22.1	23.0	0.501	166	147	21	40	61	60	2.4 / 2.0 / 3.6	10 282	19 792
3	22.1	22.7	0.488	167	147	21	39	62	61	2.1 / 3.2 / 2.7	10 399	19 530
4	22.2	23.0	0.507	174	150	22	41	60	60	2.9 / 1.6 / 3.5	10 819	20 495
5	22.1	22.7	0.491	188	157	22	41	59	60	3.7 / 1.4 / 2.9	11 209	20 526
6	22.2	22.9	0.504	185	155	22	41	58	59	3.6 / 1.3 / 3.1	11 000	20 607
7	22.2	22.8	0.492	261	191	32	51	61	60	6.1 / 1.9 / 0.0	16 060	25 334
8	22.1	23.0	0.506	272	197	35	55	63	61	6.3 / 1.7 / 0.0	17 563	27 297
9	22.2	22.8	0.495	267	194	33	52	61	60	6.3 / 1.7 / 0.0	16 493	25 824
10	22.2	23.0	0.506	268	194	34	54	62	61	6.0 / 2.0 / 0.0	17 065	26 794
11	22.1	22.5	0.487	296	207	36	54	61	60	6.5 / 1.5 / 0.0	17 881	27 062
12	22.0	22.9	0.503	308	213	39	58	62	61	6.4 / 1.6 / 0.0	19 560	29 179

[a] Sawing yield (%) is volume of sawn pieces divided by volume of the log multiplied by 100.
[b] Quality frequencies shows the number of sawn pieces in each main grade.
[c] Total value of the stand (€ ha^{-1}) is calculated assuming that all the trees in a stand are like the average tree (number of stems in all cases is 500).

4.1.4 *Effects of the value optimization of individual sawn pieces on dimensions and quality grading of sawn pieces*

In the sawing, value optimization of individual pieces is used. Depending on the log dimensions, a given sawing pattern can be used, whilst the thicknesses of the sawn pieces is determined by the sawing pattern used. Using the optimal thickness for each piece, the sawing simulator searches (based on the knots of the log) an optimal width and length so that this particular sawn piece gets its maximum value. Based on the dimensions and grade of each piece, the value of each piece, and thus also the value of the sawn log and timber, can be calculated.

The dimensions of sawn pieces depend, thus, on the log dimensions, the sawing pattern, and the value optimization of individual pieces. In this work, two simulations were selected to demonstrate in more detail the effect of value optimization (Figure 7 and Table 3). The example simulation of management scenario 4 is named "4E" and the example simulation of the management scenario 11 is named "11A". The volume of the stem in simulation 11A is smaller than the volume in simulation 4E. This is because in 11A the tending of the seedling stand is done as late as in year 30, compared to that of 4E, in which it was done already at the age of 15 into a stand density of 2 500 stems ha^{-1}. Moreover, in 11A the stand was thinned to a density of 500 stems ha^{-1} at the age of 85 years, whereas in 4E it was done earlier at the age of 70 (Table 1). Also artificial pruning of branches in simulation 11A slows down the diameter growth of the tree for a few years. On the other hand, quality and sawing yield is higher in 11A, mainly because the artificial pruning makes the section of knot free wood substantially larger than in simulation 4E without pruning. It is mainly the knottiness of the butt logs, that makes the sawing yield (€ m^{-3}, €, sawing yield percentage and quality frequencies) of simulation 11A clearly higher than in simulation 4E.

In the sawing of the butt logs, the same sawing pattern was used regardless of simulation, i.e. height of the centre block was 150 mm both in 4E and 11A. From both butt logs the thicknesses of sawn pieces are the same when comparing counterpart pieces from both logs (piece number 1 from both logs, pieces number 2 from both logs, etc.). The width of the sawn pieces is larger in pieces 1, 2, 5 and 6 in the tree grown without pruning, but the lengths of pieces are larger in pieces 1, 2, 6 and 8 from pruned stem (only piece number 7 is shorter) (Figure 7). The knottiness of sawn pieces from the log of the pruned stem is much less than the knottiness of the un-pruned case, as could be expected. This allows the sawing simulator to saw longer pieces without any knots and without any wane leading to only slightly higher sawing yield percentage, but much better quality and significantly higher value of sawn pieces.

The butt log of the un-pruned stem has several knots, except sawn pieces 1, 2, 7 and 8 which are knot free. This implies that these pieces from the outer part of the log have been shortened from the maximum length in order to get knotless pieces with higher quality and to maximize their value. The same effect of value optimization (shortened length) is demonstrated by piece 6 of un-pruned log, i.e. the length of piece 6 is less than the length of piece 5. It is most probable, that if piece 6 had been longer, its quality class would have been C instead of B, and the value would have been less than that obtained now. For further detail see Figure 7.

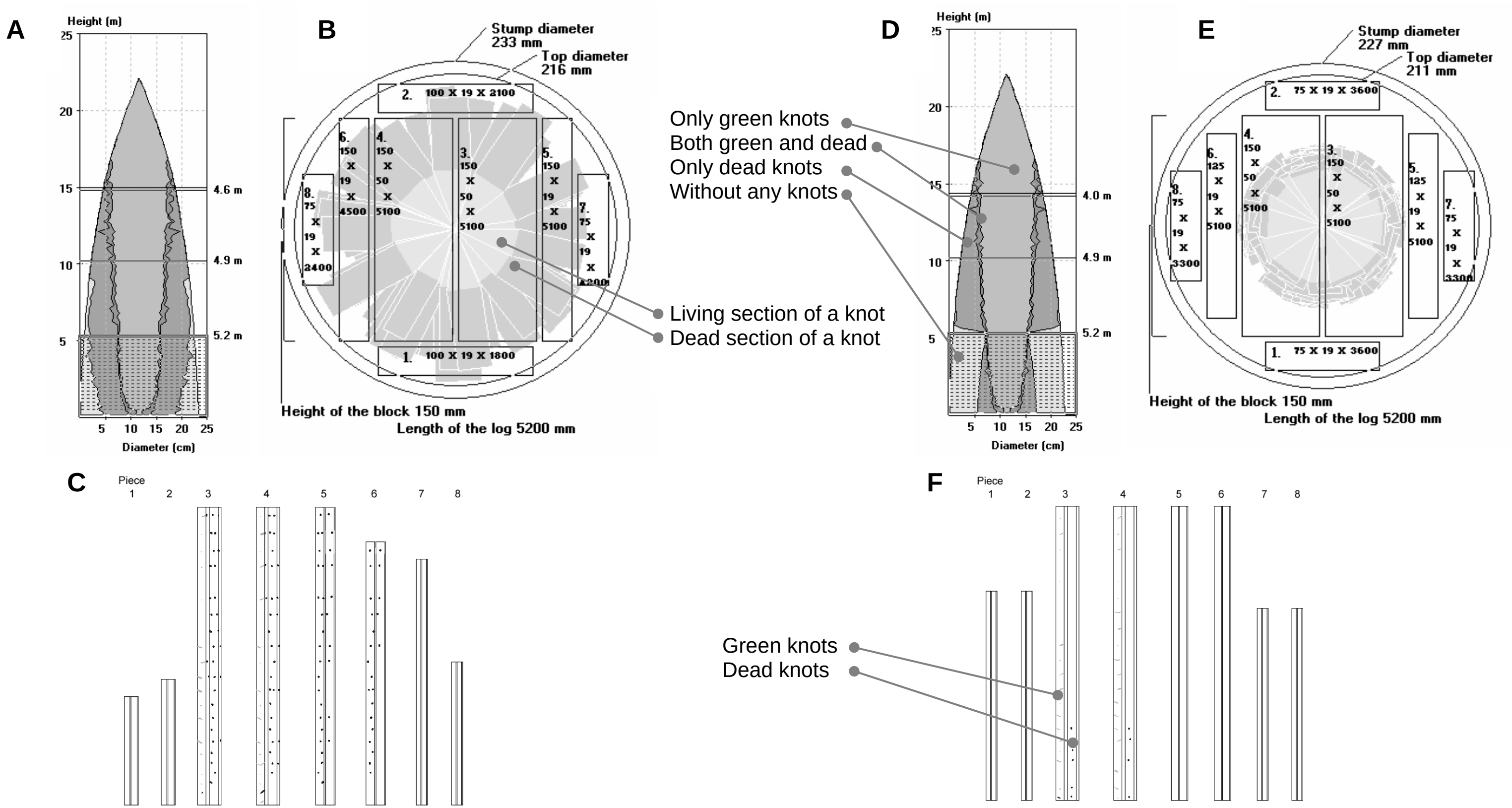

Figure 7. Example of results of sawing of two simulated trees from scenarios 4 (left: without pruning) and 11 (right: with pruning), trees being from final cutting. Figures **A** and **D** present form and knottiness of the stem, and cutting of logs. Figures **B** and **E** present used sawing pattern of the butt logs and knottiness. Figures **C** and **F** present knots on the surfaces of faces and edges of the pieces of butt logs.

Table 3. An example of two simulated trees and their simulated sawing yield and value from final cutting (at age of 100 years).

Scenario and simulation	Sawing yield and value from the stem Value (€ m^{-3})		Total value (€)		Sawing yield [c] (%)		Quality frequencies [d] (A/B/C)	
	Butt log	All logs	Butt log	All logs	Butt log	All logs	Butt log	All logs
4 E [a]	219	169	26	46	58	59	4 / 4 / 0	4 / 4 / 12
11 A [b]	338	227	41	59	61	60	8 / 0 / 0	8 / 0 / 12

[a] Simulation 4E is the fifth simulation of the fourth management scenario (height 22.1 m, dbh 23.1 cm, volume of the stem 0.515 m^3).
[b] Simulation 11A is the first simulation of the eleventh scenario (height 22.1 m, dbh 22.5 cm, volume of the stem 0.484 m^3).
[c] Sawing yield (%) is volume of sawn pieces divided by volume of the log multiplied by 100.
[d] Quality frequencies shows the number of sawn pieces in each main grade.

The value optimization of the individual sawn pieces, especially in scenarios without pruning, affects the interaction between sawing yield percentage and quality of the sawn timber. While the sawing algorithm tries to optimize the value of the individual sawn piece (which in practice often means pieces without any knots or wane), the pieces are sawn into smaller lengths and sometimes even into smaller widths. This leads to higher quality (€ m^{-3}), but also to a lower utilization of the log volume, which in turn leads to smaller sawing yield percentage. This effect was well demonstrated by the trees originating from management scenarios 5 and 6 (Figure 8). Thus, higher quality was achieved at the expense of the amount of sawn timber, i.e. increased sawing waste. Under a suitable combination of quality and sawing yield percentage, the total value (€ ha^{-1}) of sawn timber became higher (see e.g. scenarios 4, 5 and 6 compared to the other management scenarios with no artificial pruning). However, in the pruned trees (scenarios 7-12) the amount of the wood without any knots inside the stems became larger and sawing utilized more efficiently the volume of the logs. As a result, the quality of sawn pieces became higher (more pieces with grade A and higher value per m^3) in contrast to trees without pruning. Also sawn value (€ ha^{-1}) became higher for the pruned trees.

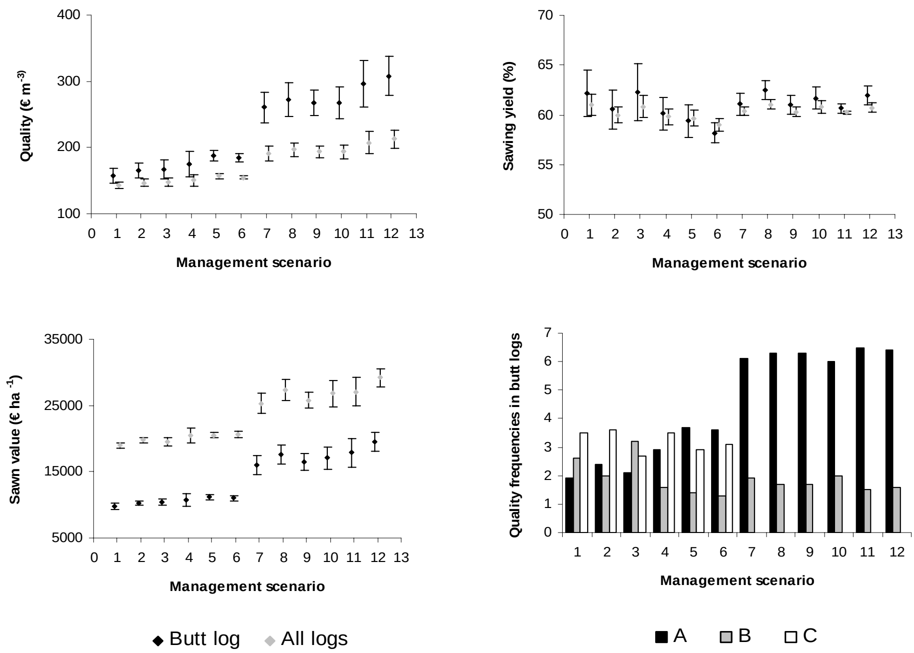

Figure 8. Mean values and standard deviations for the quality, sawing yield percentage, sawn value and quality frequencies (of quality classes) of sawn timber in each management scenario.

4.1.5 Effect of artificial pruning of branches on the quality of sawn timber

Pruning increased the quality (both in terms of € m^{-3} and number of A quality pieces) and the total sawn value (€ ha^{-1}) compared to management without pruning. In some cases, the stem volume and sawing yield percentages became higher with pruning compared to their un-pruned counterparts (scenario 8 compared to scenario 2), but in some cases the situation was the opposite (especially in terms of sawing yield percentages, see scenario 1 compared to 7 and scenario 3 compared to 9). Even if the dimensions (height, diameter and volume) of the simulated trees representing various management scenarios differed from each other only on a small scale, the inner quality of the stems and the quality of the sawn timber differed from each other remarkably. These differences were mainly due to the differences in the butt logs, i.e. due to changes in the log quality, stem volume and value yield. The second and the third logs had, in general, quite similar yields in all scenarios. This was because of the high frequency of sound and dead knots of these logs. For further detail see Table 2 and Figure 8.

4.2 Development and performance of the models for empirical diameter growth and wood properties (Papers IV and V)

4.2.1 Empirical diameter growth model

In the empirical model for the distribution of diameter growth along the stem in Scots pine (Paper IV), the distribution of annual mass growth in the stem is determined as a function of the total annual growth in stem mass, current stem mass and the distribution of the latter along the stem. Moreover, the distribution of radial growth is obtained by converting the fraction of annual growth in the stem mass at a given height of the stem into the thickness of the annual ring at the same height.

Application of the model to Scots pine datasets, including both young and mature trees not used in parameter estimation, showed that the model was quite capable of reconstructing the distribution of diameter growth from the stem butt to the apex and from the pith to the stem surface at any height in the stem in both young and mature trees. The performance of this empirical model is demonstrated in Figure 9, which shows the distribution of the measured and predicted radial growth in two mature dominant and suppressed sample trees. Both in the suppressed and dominant tree, the calculations seem to reproduce quite well the measured distribution of radial growth over the stem.

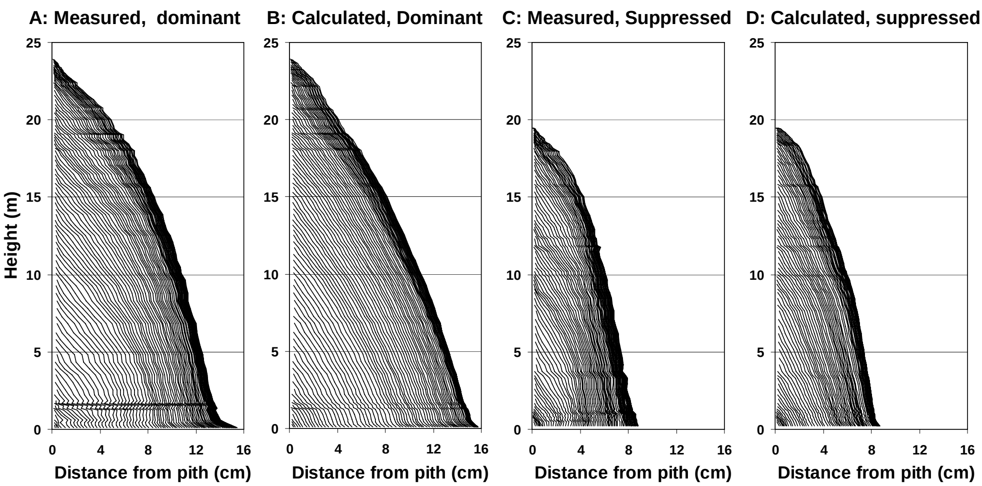

Figure 9. Example of the distribution of measured and predicted (Paper IV) radial growth along the stem in two mature trees (validation trees). The values for the parameters were estimated on the basis of the combined data subsets for young and mature trees. From left to right: **A**: measured dominant tree, **B**: predicted dominant tree, **C**: measured suppressed tree and **D**: predicted suppressed tree. Reprinted from Trees, Vol. 20, 2006, pages 391–402, Modelling the distribution of diameter growth along the stem in Scots pine, Ikonen, V.-P., Kellomäki, S., Väisänen, H. and Peltola, H., Figure 7, © Springer-Verlag 2006, with kind permission of Springer Science and Business Media.

Simulations carried out with the FinnFor model together with the model for empirical diameter growth, and representing trees grown in unthinned and thinned Scots pine stands with trees of different status (from dominant to suppressed), showed that also the response in tree growth to thinning in terms of the distribution of diameter growth along the stem was quite realistic relative to measured data (Paper IV). As expected, the amount of diameter growth decreased with age most in the lower stem, especially in suppressed trees. Growth remained higher in the upper stem, even in suppressed trees, but the region of higher growth moved gradually further up the stem. Thinning enhanced the diameter growth of trees, especially at base of the stem, but also higher up the stem. In the dominant trees, the relative response to thinning was clearly smaller than in the suppressed ones. In absolute terms, however, the dominant trees showed a larger response to thinning than the suppressed ones.

4.2.2 Wood properties models

In this work (Paper V), the early wood percentage was best explained in Scots pine by ring width (R^2 was 0.48) (Table 4). The air dry wood density was explained best by combined use of early wood percentage and cambial age (R^2 0.40). Moreover, the fibre length was best explained by combined use of radial growth percentage and cambial age (R^2 0.80). These models predicted, in general, reasonably well the wood properties at an intra-ring level, but also as an average at a cross-sectional level. The fibre length model predicted best the range from small to large values. The models for early wood percentage and wood density overestimated, to some degree, the lowest measured values and underestimated the highest ones. Large variation occurred also around the mean trend regardless of property considered, which could be seen in the relatively large RMSE (Root Mean Squared Error) values (early wood percentage 7.9 %, wood density 49 kg m^{-3}, and fibre length 0.28 mm). However, predictions of these ring-based models (averaged at cross-sectional level) were, in general, quite well in line with corresponding cross-sectional predictions by the disc-based models (see in details Paper V).

The example simulations carried out with the FinnFor model together with wood properties models predicted slightly lower wood density for dominant trees compared to suppressed ones, this was the case both in thinned and unthinned Scots pine stands. Wood property models predicted, on average, slightly higher early wood percentage in dominant trees, but fibre length was not affected when averages of the whole stem was studied. The average growth and properties of the dominant trees grown in thinned and unthinned stands differed from each other significantly less than those of suppressed trees (Figure 10). However, the properties differed significantly depending on which development phase of stand was considered (e.g. from first thinning to final cutting) and which part of the stem was examined (i.e. inner, outer and top part) (Figure 11).

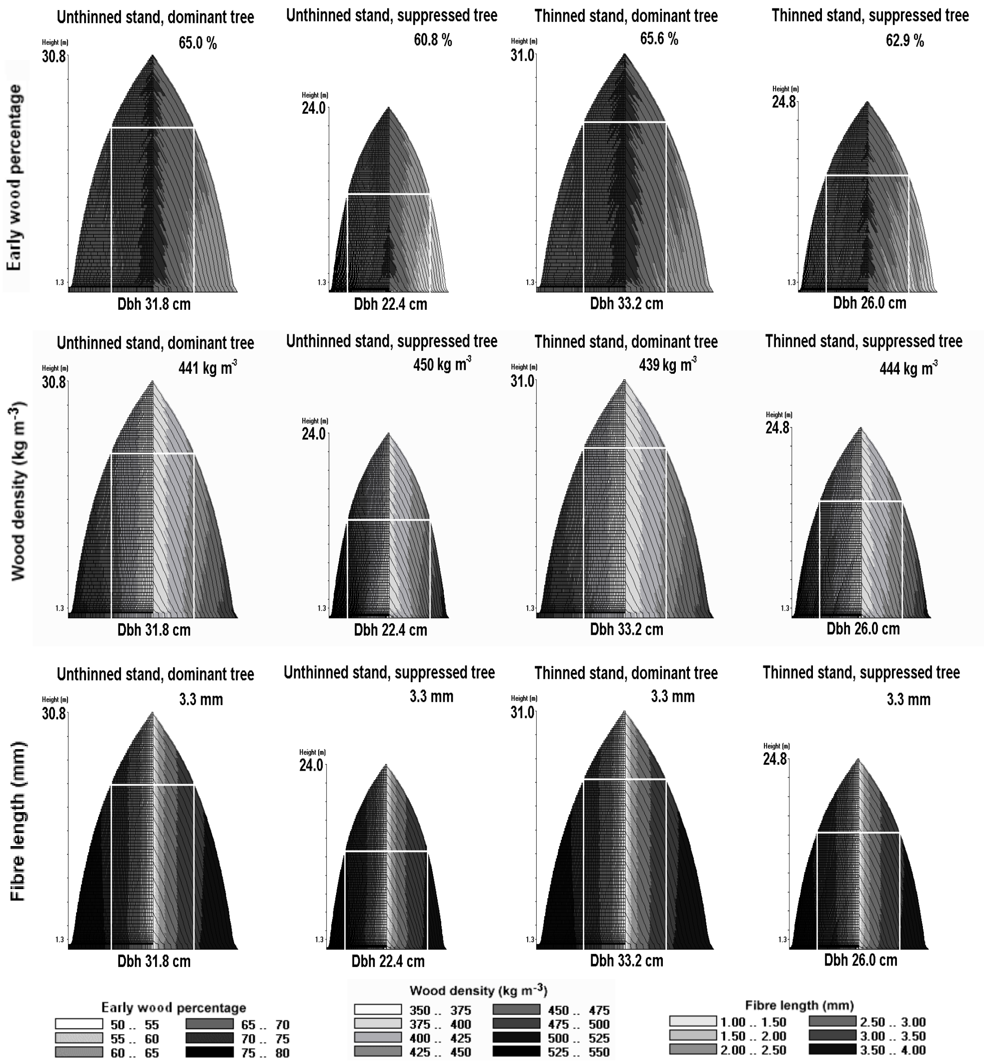

Figure 10. Examples of the performance of the integrated model (FinnFor simulations with the wood properties models): early wood percentage (above), air dry wood density (middle) and fibre length (below) in dominant and suppressed Scots pine trees grown in unthinned and thinned stands over a 90 year rotation. The figure also shows the borders (white squares) for the inner, outer (>16 cm) and top part of tree stem.

Table 4. Wood properties models developed for Scots pine.

Dependent	Independent	Parameter	Df	R^2
Early wood percentage (%)	Constant	56.193	5 724	0.48
	Ln(Ring width)	13.564		
Wood density (air dry) (g cm^{-3})	Constant	0.596	5 724	0.40
	Early wood percentage	-0.00298		
	Cambial age	0.000953		
Fibre length (mm)	Constant	1.837	2 830	0.80
	Ln(Radial growth percentage)	-0.0414		
	(Ln(Radial growth percentage))^2	-0.0362		
	Ln(Cambial age)	0.449		

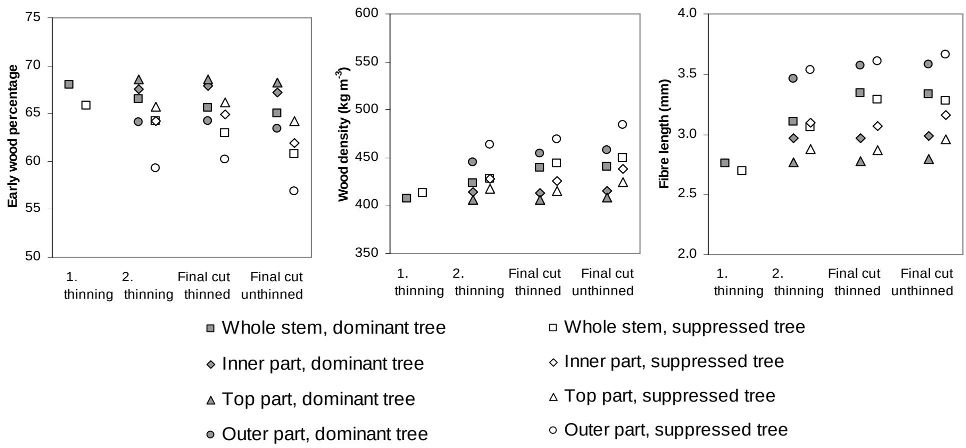

Figure 11. Example of wood properties at different parts of the tree stem (inner, outer and top part and as average for whole stem) in dominant and suppressed Scots pine trees grown in unthinned and thinned stands in first and second thinning and final cutting based on predictions of the integrated model. The simulated trees are the same as in Figure 10.

5 DISCUSSION AND CONCLUSIONS

5.1 Three-dimensional growth modelling and simulated sawing (Papers I-III)

In this study, a model for the structural growth of Scots pine (Paper I) was further developed and integrated with a sawing simulator (Paper II) in order to relate the quality of sawn pieces to the properties of the stem and wood as affected by the management of tree stands with varying initial spacing, thinning and pruning (Paper III). Based on this work, it could be concluded that in order to optimise the production of high-quality timber it should be carefully considered how the timing and intensity of silvicultural management will affect the development of branches, and knots concurrently, over the whole life span of the tree.

Altogether, the properties of wood are clearly linked to the structural growth of the tree, and thus, also to the distribution of radial growth over the stem (Hakkila 1966, Uusvaara 1974, Saikku 1975). Therefore, there also exists a clear correlation, for example, between the thickness of the annual growth ring in Scots pine and the growth of branches and knots (Hakkila 1966, Uusvaara 1974). Furthermore, the quality of sawn pieces is inversely related to the growth rate of the stem (Uusvaara 1974, 1985, Jäghagen and Lageson 1996). Minimizing the loose knot period in branch development is, however, difficult because a substantial period of time is needed before dead branches self-prune, and, according to some studies, the process seems to be relatively independent of stand density (Mäkinen 1999).

From the qualitative point of view, the three-dimensional growth model (Paper III) produces quite a realistic crown and stem structure for simulated Scots pines over the life span of the tree. Differences in management should lead to differences in stem volume, taper, knottiness, and sawn timber value. However, the differences in diameters and volumes of the stems (of the average tree) in the used scenarios were rather small (Paper III). This may partly be due to the fact that the data used for the parameterisation of the model represented mainly relatively young trees (about 25 years old) and relatively low site fertility (*Vaccinium* site type) (Kurttio and Kellomäki 1990). As a result, in the model the formation and growth of shoots were not sensitive to the shading conditions. Some of the model parameters needed also to be based on theoretical consideration, because proper data was not available. Nevertheless, the inner quality of stems and the quality of sawn timber differ from each other quite substantially due to the occurrence, size and quality of knots in wood.

The effect of stand density (and effect of size and structure of the crown) on self-pruning of branches was modelled in the final version of the three-dimensional growth model (Paper III) through calculating the cross-section area of living branches to indicate how the surrounding trees protect, in dense stands, dead branches from self-pruning (i.e. in dense stand exists less snow and wind loading, for example). Consequently, in the simulations the self-pruning was faster in thinned stands, as were, to some degree, the diameter growth and occlusion rate of dead branches.

The results of sawing represent the timber obtained in final cuttings (Paper III). The differences between results of various management scenarios were mainly due to the differences in the pieces representing the butt logs. The value optimisation of individual sawn pieces led to smaller lengths and sometimes even to smaller widths of sawn pieces, which led to better quality (€ m^{-3}) but also to worse utilization of the log volume, which in turn led to smaller sawing yield percentage.

In the simulations with the integrated model system (Paper III), scenario number 12 seemed to give the best results in sawing, i.e. quality of sawn timber (€ m^{-3} and quantity of quality A pieces), volume of logs (m^3), total value of sawn timber (€ ha^{-1}) and sawing yield percentage were highest or almost the highest. In this scenario, the stand at the beginning of the rotation was very dense (5000 stems ha^{-1}), but sparse towards the end of the rotation, and it also included pruning. One of the worst scenarios was scenario number 1, having quite sparse initial stand density (2500 stems ha^{-1}) at the beginning, but towards the end of rotation higher density than in some other scenarios, and no pruning was applied. However, it should also be noted that artificial pruning is not normally economically profitable in stands growing on sites of mostly poor fertility. Thus, the pruning costs and the fertility of site have to be considered when decision regarding pruning is made.

5.2 Empirical models for diameter growth and wood properties (Papers IV and V)

An empirical model for diameter growth was integrated with a process-based growth and yield model (Paper IV) in order to simulate the distribution of growth, but also wood properties such as early wood percentage, wood density and fibre length over the stem in Scots pine (Paper V). The integrated model was also used to analyse how management and position of the tree in the stand (dominant or suppressed) affected the growth and wood properties distributed along tree stems (Papers IV and V).

The empirical model for diameter growth was found to be capable of reproducing well the distribution of diameter growth from the stem butt to the apex and from the pith to the stem surface at any height in the stem. This held true both in dominant and suppressed Scots pines, as well as both in young and mature trees. The fit of the model was rather good also in butt swell representing less regular growth than other parts of the stem. This kind of enhanced growth observed in trees in the butt region probably indicates growth modification associated with the links between the stem and root systems and the effects of mechanical stress on these links (Valinger 1992). However, little is still known about the mechanisms involved in butt swell development.

The simulations with the FinnFor model also showed that the empirical model for diameter growth responded properly to the thinning, with a realist change in the distribution of growth over the stem regardless of the tree position in the stand. For example, in an unthinned stand, the diameter growth decreased with time most quickly in the lower part of the stem, this being most pronounced in suppressed trees. Dominant trees showed a smaller relative growth response to thinning than suppressed ones, but the release of dominant trees from competition in thinning helped them to maintain a higher growth rate than corresponding trees in an unthinned stand (see Papers IV and V for further information). On the other hand, dominant trees showed a larger growth response to thinning in absolute terms than suppressed trees. These results were also in line with several earlier experimental studies, e.g. by Hynynen (1995), Tasissa and Burkhart (1997), Pukkala et al. (1998) and Peltola et al. (2002, 2007).

The empirical wood properties models developed for early wood percentage, air dry wood density and fibre length predicted, reasonably well, these wood properties in Scots pine (for further detail see Paper V). However, the wood properties model overestimated the lowest measured values of early wood percentage and wood density to some degree and underestimated the highest ones. On the other hand, the same kind of model behaviour has also been observed earlier, for example, in the intra-ring wood density model developed for

Norway spruce by Mäkinen et al. (2007). It should be kept in mind, when these kinds of models are constructed, that relatively large variation is desirable in datasets used for model construction (i.e. variation in tree size, age and wood properties, as well as variation in geographical origin of trees and in site conditions) and independent datasets are needed for model validation, in order to make the models more applicable. For this purpose, additional datasets should be measured for further development and validation of the models developed in this work.

The model simulations for unthinned and thinned Scots pine stands (Paper V) showed, however, that the response in tree growth to thinning in terms of the distribution of diameter growth, early wood percentage and air dry wood density along the stem seem quite realistic for both dominant and suppressed trees. In principle, it could also have been expected that lower growth rate of suppressed trees may result, to some degree, in different length of fibres compared to dominant trees of the same age, but this was not the case when averages of the whole stem was studied. On the other hand, all wood properties differed clearly from each other depending on which part of the stem was examined (inner part, outer part or top part of the stem). Wood density and fibre length were predicted by the wood properties models to be, on average, highest in the outer part of the stem and lowest in the top part, which was opposite to the early wood percentage predictions. This result is in agreement with many previous findings, in which wood density and fibre length has been found to increase and early wood percentage decrease as a function of cambium age and distance from pith to bark, and wood density and fibre length to decrease and early wood percentage to increase from stem base to tree top, in coniferous tree species such as Scots pine (Wilhelmsson et al. 2002, Ekenstedt et al. 2003, Peltola et al. 2007).

The largest effects of tree status in a stand and management on tree growth and distribution of wood properties along the stem can be seen mainly near the stem base. This may at least partly explain why differences in the average fibre length of the whole stem in suppressed and dominant trees grown in unthinned and thinned stands at the time of final cutting were not found. However, the relatively small differences found in suppressed trees, especially between average properties of the whole stem and the inner part of the stem at the time of final cutting, was also due to the fact that in a relatively small stem, most of the volume of the stem belonged to the inner part. If the stem diameter was rather large, the effect of the inner part on the whole stem average would diminish. The average early wood percentage was also significantly higher and wood density and fibre length significantly lower at the time of first thinning compared to second thinning and the difference increased at the time of final cutting. The difference in growth and consequently in wood properties, such as wood density between dominant and suppressed trees, also increased over time especially in the unthinned stand when the size of trees increased, as was suggested previously also by Molteberg and Hoibo (2007) in Norway spruce.

5.3 CONCLUSIONS

This study covered the whole wood supply chain from forest (growth of trees) to end-products (sawn timber). It utilized partly the existing model systems originally developed by the others, but the models dealing with crown and stem structure of trees were further developed in these model systems. It was also tested how the theoretical assumptions held true in stands of varying ages and densities. Thus, this study created new information related to the detailed mechanistic modelling on crown and stem structure, as well as statistical modelling on wood properties. The new properties and functionalities of the models increase our understanding on tree growth and stem and wood properties.

In this study, it was found that to maximize the quality of sawn timber, trees should be grown at relatively narrow spacing (up to 5 000 stems ha^{-1}) at the beginning of the rotation to reduce the growth of branches, and towards the end of rotation trees should be grown in relatively sparse stands (e.g. 500 stems ha^{-1}) to make the self-pruning of branches more intensive (due to smaller branches and effect of wind and snow loading) and occlusion of knots faster (due to faster diameter growth), and volume growth of the stem larger (Paper III). It was also noticed, that artificial pruning of branches is needed to maximize the knot-free zone of the stem.

The work shown in Papers IV and V demonstrated also that the properties of raw material vary depending on which development phase of stand stems are harvested (e.g. from young or mature stands), or on management (e.g. initial spacing and thinning) and tree status in a stand (dominant or suppressed) or which parts of the stem are considered (e.g. whole stem, butt log or logging residue). Thus, it is important to have proper knowledge regarding the distribution of diameter growth and wood properties (such as early wood percentage, wood density and fibre length) along the stem and the effects of management and tree status on these properties over the whole rotation.

So far, the development of three-dimensional growth modelling with implications for simulated sawing has been done independently of the corresponding modelling of growth distribution and wood properties along the tree stems related to the growth of trees predicted by the process-based growth and yield model. Therefore, at the moment these different modelling approaches can be used to study relatively different research questions. However, in the future the integrated use of models, such as demonstrated in this work, especially in Papers III and V, could offer means to study in detail how environmental conditions (such as various site types or climate change), forest structure and silvicultural practices (such as spacing, thinning, pruning and fertilization) affect the quantity and properties of stem wood produced over the whole rotation. The need for this kind of integration of wood quality models with growth and yield models is emerging and will become increasingly important in the future, when more intensive forest management (e.g. heavy thinning and fertilization) and value-added wood utilization are aimed for in forestry.

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