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Sawn Timber Properties of Scots Pine As Affected by Initial Stand Density, Thinning and Pruning: A Simulation Based Approach

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The aim of this work was to analyze how different management schedules with varying initial stand density, thinning and artificial pruning of branches affect the quality, quantity and value of sawing yield in Scots pine (*Pinus sylvestris* L.). For this purpose, an integrated model system was employed and further developed to simulate: i) the three dimensional structure of the crown and stem of an average tree grown in a stand related to the changes in the within-stand light conditions as caused by the stand management, and ii) the sawing of logs into pieces and their quality grading based on the size and number of living and dead knots on the surfaces of sawn pieces. To maximize the quality of sawn timber, relatively dense stand is desired in the early phase of the rotation to reduce, especially in the lower part of stem, the growth of branches, and to increase the rate of dying and pruning-off of branches. In the later phase, a relatively sparse stand is desired to increase the self-pruning of branches and the occlusion of knots. However, in any case, artificial pruning is needed to maximize the knot-free zone of the stem. Also the value optimization of individual sawn pieces affects the quality and value of sawn timber. Because, only average tree was simulated, the differences between scenarios for stem volume were small. In the future, further model development is needed to analyze the development of crown and stem properties of trees with different status in a stand.

Keywords three-dimensional modeling, sawing simulator, knots, *Pinus sylvestris* L., shading
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List of symbols

General Symbols

i	section (or shoot) of the stem
t	simulation year

Modelling Self-Pruning of Dead Branches

ATot	total cross-section area of living branches (m^2) in a stand
SDensity	stand density (stems ha^{-1})
b	b=1..n refers to all living branches in a tree
BranchCrossSectionArea	cross-section area of a living branch (m^2)
ScalingFactor	scaling factor (0..1) for self-pruning of dead branches
A_1	parameter for ScalingFactor, maximum
B_1	parameter for ScalingFactor, shape parameter
C_1	parameter for ScalingFactor, minimum
N_1	parameter for ScalingFactor, shape parameter
MaxYears	unscaled value, indicating how many years a branch could be dead before self-pruning
A_2	parameter for MaxYears, maximum
B_2	parameter for MaxYears, shape parameter
C_2	parameter for MaxYears, minimum
N_2	parameter for MaxYears, shape parameter
BrDiam	diameter of a dead branch (mm)
YearsBeingDead	number of years which a branch has already been dead

Modelling the Stem Taper

VNS(i,t)	volume of new shoots (cm^3) above any section of the stem
D(i,t)	diameter (cm) of the stem at any section (or shoot i) of the stem at any year (t)
s	s = 1..n refers all the new shoots (both shoots in the stem and in the branches) above a particular section of the stem
D_s	diameter (cm) of a new shoot
L_s	length (cm) of a new shoot
$A(i,t)$	new cross-section area (cm^2) of the section of the stem at year t
A(i,t–1)	cross-section area (cm^2) at the previous year
ΔA(i,t)	increment of the cross-section area (cm^2) (i.e. area of the new annual ring)
VF	volume factor
ML	mean shoot length of the stem

1 Introduction

The effects of silvicultural management on the growth of trees and the consequent properties of stem and wood are established through the interaction between biological processes (i.e. height growth, radial growth of stem, crown development) and environmental conditions. Relatively small changes in the stem dimensions and, for example, in the number, size and status (e.g. live or dead) of knots affect the manufacturing and properties of the final wood products. Therefore, a thorough understanding of the development of the stem and branches, and further on knots in wood, as determined by silvicultural management (e.g. spacing, thinning and artificial pruning-off of branches) and environmental conditions (climate, site) is of importance in producing timber for different purposes.

For example, the competition for light tends to affect especially the allocation of growth, whereas competition for water and nutrients will influence more the growth rate than allocation of growth (Cannell et al. 1984, Nilsson and Gemmel 1993, Nilsson 1994). In Scots pine (*Pinus sylvestris* L.), this holds equally for the stem and branches, because their growth correlates well with each other (e.g., Mäkinen and Colin 1998, Mäkinen 1999); i.e. branch diameter can only be reduced at the expense of overall stem growth. Thus, early thinning or ample nitrogen supply combined with wide initial spacing may increase the number of branches and enhance their thickness on the stem of Scots pine, having thus, also implications for knots in wood products (Heiskanen 1965, Uusvaara 1974, Kellomäki and Tuimala 1981, Kärkkäinen and Uusvaara 1982, Kellomäki and Väisänen 1986, Turkia and Kellomäki 1987, Björklund 1997). On the other hand, especially by artificial pruning of dead branches in the lower part of the stem, the knot-free zone of the stem can be increased, and thus, consequently the value of the timber (Kellomäki et al. 1989, Uusvaara 1993, Petersson 1998).

As the lifespan of a branch is short compared to that of the stem it is difficult to relate the quality of sawn pieces experimentally to the dynamics of the branch population. Furthermore, the properties of logs (e.g. stem volume and straightness, number, size and quality of knots) and the pattern applied in sawing affect the quality of sawn pieces in grading (e.g. Nordic timber 1994). Therefore, several models have been developed in recent years, being capable 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, Loubère et al. 2004) 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, which are capable to simulate the structural development of stem and crown have been similarly developed to link stem and knot properties with the overall growth of trees (Oker-Blom et al. 1988, Kellomäki et al. 1989, Houllier and De Reffye 1996, Kellomäki et al. 1999). 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, Ikonen et al. 2003).

In the above context, the objective of this work was to analyze how different management schedules with varying initial stand density, thinning and artificial pruning of branches affect the quality, quantity and value of the sawing yield in Scots pine. For this purpose, an integrated model system was employed and further developed to simulate: i) the three dimensional structure of the crown and stem including both the branches on the stem and knots in the wood of an average tree grown in a stand related to the changes in the within-stand light conditions as caused by the stand management, and ii) the sawing of logs into pieces and their quality grading based on the number and size of living and dead knots on the surfaces of sawn pieces.

2 Integrated Model System

2.1 Three-Dimensional Growth Modeling

2.1.1 Basic Structure of the Model

The three-dimensional model for the growth of individual Scots pine (i.e. average tree in a stand), which was previously compiled by Kellomäki and Strandman (1995) and Kellomäki et al. (1999), has been further developed in this work. In the model, the tree growth is modeled 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 crown and stem is, thus, controlled by the generation, growth, death and pruning-off of the shoots and branches, with impacts on the stem and wood properties (Fig. 1).

The terminal shoots form the stem, while the shoots around the terminal shoots form the butt parts of the branches, which have direct effects on stem and knot properties in wood. 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. The formation of new shoots within the branch gradually ceases and the branch dies and eventually self-prunes.

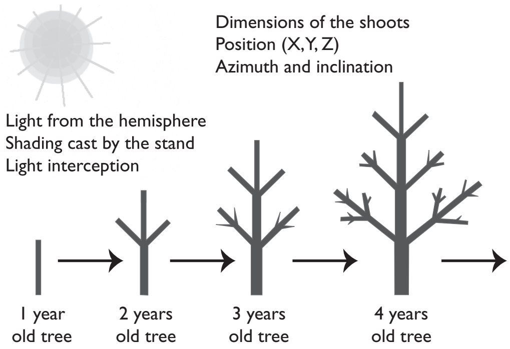

Fig. 1. Outlines of the growth processes applied in the model.

The number and dimensions (length and diameter) of daughter shoots are related to the light (direct and diffuse radiation) intercepted by the mother shoot and interception supply from other shoots (Kellomäki et al. 1999, Ikonen et al. 2003). The daughter branches are evenly distributed around the axis (azimuth), including a 10% random effect, however (Kellomäki and Strandman 1995) with certain initial inclination (i.e. angle between mother shoot and daughter shoot). This inclination angle of each branch, and thus, bending of branches downwards, is also changing during the life span of the tree due to the effects of gravitational forces (Kellomäki et al. 1999).

2.1.2 Modelling the Effect of Stand Density on the Growth of an Average Tree

In the further development of the growth model compiled by Kellomäki et al. (1999) it has been focused especially 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 knot properties in wood. In the model, a tree (object tree) growing in a stand receives light throughout the hemisphere, but only that not intercepted by the neighboring trees (shading trees), which are assumed to have the same crown structure as the simulated average tree. 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 stand density, affect the amount of radiation reaching each shoot, and thus, reduce the available light for the development of branches and stem. Fig. 2 outlines the procedure for calculating the shading caused by the stand on an object tree.

The shading caused by the stand is calculated in a one year timeframe. The living crown of the object tree in a particular year is divided dynamically into a maximum of 30 horizontal layers of equal depth (the height of living crown is divided by the number of layers). For each layer, the amount of light intercepted by the individual shoots is summed. The sum of the intercepted light in each layer in the object tree are then 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 to the bottom of the canopy. 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.

2.1.3 Modelling the Growth and Mortality of Branches and Self-Pruning of Dead Branches

In the model, the diameters of branches in the whorl and crown will develop (see more in details Kellomäki et al. 1999) in interaction with i) birth of a whorl, ii) initial length of branches, iii) growth of the branches, iv) solar radiation, v) interception of light by individual shoots and interception supply from other shoots, and vi) size and form of the crown. Also vii) shading caused by the stand affects the development of the branches and the crown, as presented above. In this version of the model, the branch growth was slightly modified in order to provide a more realistic distribution of branch diameters compared to the previous version (Kellomäki et al. 1999), in which the range of diameter distribution was too narrow. For this purpose, the light intercepted

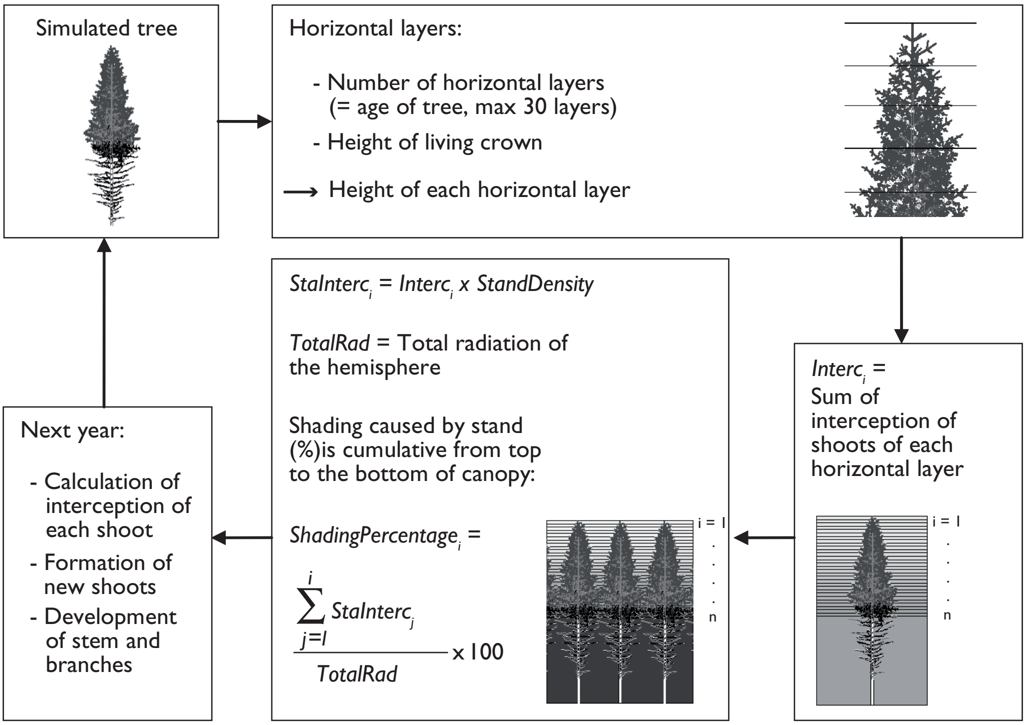

Fig. 2. Outlines for the calculation of the shading caused by the stand. Shading percentages for each horizontal layer are calculated in a one year timeframe using information regarding intercepted light by the shoots of the simulated average tree in the previous year and the stand density in the current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

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.

In reality, young branches have usually a high survival rate as regards shoots attached to the branches, but the survival rate decreases rapidly when branches are grown deeper in the canopy. On the other hand, the branches of a young Scots pine will also die earlier in a lower canopy than those of an older one. Therefore, in our model the survival of a branch is affected by 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). As a result, a branch will die when the percentage of the needle-covered shoots is less than that indicated by the theoretical rate of branch survival (Kellomäki et al. 1999).

In this version of the model, the self-pruning of dead branches is also modeled as a function of diameter of each dead branch (Kellomäki et al. 1999). However, compared to the previous model version, the self-pruning of dead branches was improved by taking into account the sheltering effect of living branches against snow load, wind or other factors affecting the rate of self-pruning (e.g. Heikinheimo 1953). For this purpose, the total cross-section area of living branches (ATot, m^2, based on the branch diameter at the point of insertion into the stem) in a stand year by year is calculated first, i.e.

$$\mathrm{ATot} = \mathrm{SDensity} \cdot \sum_{b=1}^{n} \mathrm{BranchCrossSectionArea} \qquad (1)$$

where SDensity is stand density (stems ha^{-1}), $b = 1..n$ refers to all living branches in the average tree and BranchCrossSectionArea is the cross-section area of each living branch (m^2). Second, a scaling factor (0..1) is calculated as follows:

$$\text{ScalingFactor} = \frac{A_1 - C_1}{1 + B_1 \cdot \text{ATot}^{N_1}} + C_1 \tag{2}$$

where $A_1 = 1$ (maximum), $B_1 = 2\,000\,000$ (shape parameter), $C_1 = 0.2$ (minimum) and $N_1 = -4.35$ (shape parameter). The parameter values were selected in such a way that in a dense stand the scaling factor is 1 and it decreases as the total cross-section area of living branches in the whole stand decreases (Fig. 3A). Third, the maximum number of years that the branch could be dead before self-pruning (MaxYears) is calculated, i.e.

$$\text{MaxYears} = \frac{A_2 - C_2}{1 + B_2 \cdot \text{BrDiam}^{N_2}} + C_2 \tag{3}$$

where $A_2 = 40$ (maximum), $B_2 = 1500$ (shape parameter), $C_2 = 1$ (minimum), $N_2 = -2.7$ (shape parameter) and BrDiam (mm) is the diameter of the dead branch (Fig. 3B). Finally, this maximum number of years is multiplied by the scaling factor and, as a result, the dead branch will be self-pruned, if the branch has already been dead (YearsBeingDead) for a sufficient period of time (Fig. 3C), as shown by the following formula:

$$\text{YearsBeingDead} \geq \text{MaxYears} \cdot \text{ScalingFacto}r \tag{4}$$

This implies that in more sparse stands the time needed for self-pruning of a branch with a certain diameter is shorter than of a branch with equal diameter in dense stand. In Fig. 3, the performance of Eqs. 2–4 is presented. The performance of Eqs. 2–3 are most sensitive to the shape parameters N_1 and N_2, respectively.

When the branches are self-pruned in the model, a short branch stub is left attached to the stem. The length of branch stub is calculated as a function of branch diameter (square root from the branch diameter). When the stem of the tree continues its diameter growth, the stubs are occluded during the following years and the stubs become the knots affecting the sawn timber quality.

2.1.4 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 radial growth in this section in the current year. In this version of the model, it was assumed that the radial growth of stem in any section is related to the formation of the new shoots (Fig. 4). The volume of new shoots (VNS(i,t), cm^3) above any section of the stem is:

$$\text{VNS}(i,t) = \sum_{s=1}^{n} \left(\pi \cdot \left(\frac{D_s}{2} \right)^2 \cdot L_s \right) \tag{5}$$

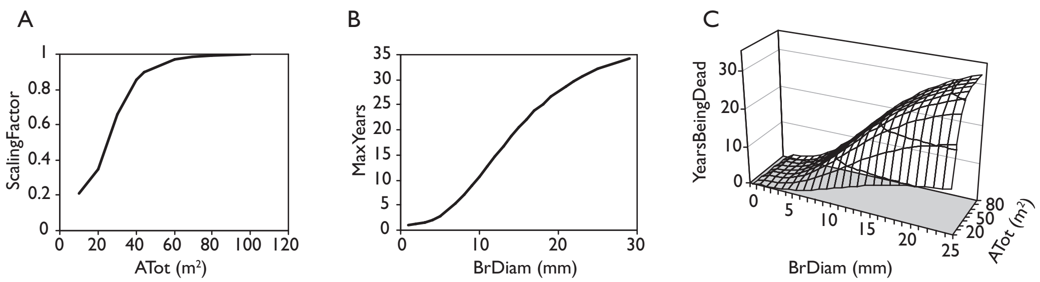

Fig. 3. The performance of Eqs. 2–4 for self-pruning of dead branches. The scaling factor as a function of the total cross-section area of living branches (m^2) in a stand (A), MaxYears (the unscaled value of how many years the branch could be dead before self-pruning) as a function of the diameter of the dead branch (mm) (B), and the scaled value on how many years the branch can be dead before self-pruning, when sheltering effect of living branches has been taken into account (C).

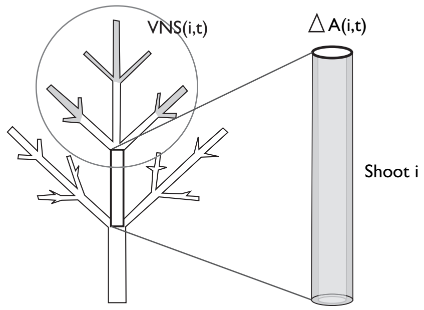

Fig. 4. The radial growth of the stem related to the formation of the new shoots. In shoot i a new annual ring has grown, of which area ($\Delta A(i,t)$) is related to the sum of the volume of the new shoots (VNS(i,t)) above the shoot i. These new shoots are presented with gray color inside the circle.

where s = 1..n refers all the new shoots (sections) (both shoots in the stem and in the branches) above a particular section of the stem, D_s (cm) the diameter of each new section and L_s (cm) the length of each new section. New cross-section area of the section of the stem at year t is:

$$A(i,t) = A(i,t-1) + \Delta A(i,t) \tag{6}$$

where $A(i,t–1)$ (cm^2) is the cross-section area at the previous year and $\Delta A(i,t)$ (cm^2) is the increment of the cross-section area (i.e. area of the new annual ring)

$$\Delta A(i,t) = \frac{\mathrm{VNS}(i,t)}{\mathrm{VF} \cdot \mathrm{ML}} \tag{7}$$

where VF is the volume factor with the value 2.5 and ML is mean shoot length of the stem (assumed to be 20 cm). New diameter of any section of stem can be calculated from new cross-section area, i.e.

$$D(i,t) = 2 \cdot \sqrt{\frac{A(i,t)}{\pi}} \tag{8}$$

2.2 Simulated Sawing

The three-dimensional growth model is linked to a sawing simulator (see more in details Ikonen et al. 2003), in which the simulated knot properties in wood and quality of the sawn pieces are related to the geometry and branch properties of stem and logs and the sawing pattern used to saw a given log. The sawing simulator employs the Nordic timber grading rules (Nordic timber 1994), which are mainly based on the occurrence of knots in the wood (the number, size and quality, i.e. sound or dead). Other parameters affecting the grading, such as the occurrence of pockets of resin and bark, slope of the grain, occurrence of resin wood, discoloration, insect damage and so on were excluded from the current version of the sawing simulator, since they could not be directly linked to the growth of trees or to silvicultural management.

The main grades used are A, B, C and D, in descending order. Grade A includes sub-grades A1–A4. A knot-based grading assumes that: i) each side of the piece will be graded separately, ii) the maximum values for the knot parameters (the number, size and quality) permitted on the worst one meter of the length of the sawn piece determines the grade, and iii) the grade of a sawn piece is decided on the basis of both the faces and edges. The current version of the sawing simulator differs from the previous version (Ikonen et al. 2003) in such a way that also wanes (sawn pieces with parts of surfaces not touched by the saw) are included in assessing the total amount and value of sawing yield as facilitated by the grading rules.

The part of the stem to be cut into saw logs is defined by the height of the stump (felling height) and the diameter of the stem fulfilling the minimum top diameter for a log acceptable for sawing. Thereafter, the stem between these points can be cut into logs of varying length (lengths beginning from 3100 mm, increasing in 300 mm modules, longest allowed log length 6100 mm) (Nordic timber 1994). The stem is characterized by the number of logs obtainable for sawing, the length of the logs, their top and butt diameters, stem volume and taper. The wood for sawing is characterized by knots (i.e. sound or dead; number, size and location of knots in wood). Sawing proceeds following the Nordic practice (Nordic timber 1994), i.e. first the block in the centre of log is cut (centre yield), and secondly, the centre and side yields are sawn into pieces as defined by the selected sawing pattern (i.e. dimensions 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. In this study, the optimization includes only maximizing the value of an individual sawn piece (with the assumptions mentioned above), the sawing simulator neither optimizes the total value of sawn timber nor automatically tries to find out the optimal log lengths nor sawing pattern. However, because the unit prices used for different grades and dimensions of sawn timber were available only from one local dealer of sawn timber, they should be taken as estimates on how the quality and size of dimensions may affect on the value differences (and thus ranking) between different management scenarios.

2.3 Demonstration of the Integrated Model Performance

The performance of the integrated model will be demonstrated in this work through simulations on how different silvicultural management schedules may affect the quality, quantity and value of the sawn timber. The growth of average tree grown in a stand is simulated in an even-aged Scots pine stand representing a relatively poor site fertility type in southern Finland (latitude 62°N) over a fixed rotation length of 100 years. However, the results for the simulated trees are compared only at the end of the 100 year simulation period. Altogether 12 different alternative management scenarios were applied in the simulations. They were adopted based on current forest management practices applied in Scots pine in Finland, i.e. including a range of possible alternatives for Scots pine management, including differences in initial stand density and thinnings (i.e. number and intensity) with or without artificial pruning of branches (Table 1).

Management scenarios 1 and 2 represented stands with an initial stand density of 2500 stems ha^{-1}, with first thinning being at the age of 45 years. Scenarios 1 and 2 differ from each other in that sense that scenario 1 has two later commercial thinnings at ages 65 and 85, whereas scenario 2 has one at age 70. Scenarios 3 and 4 represented stands with an initial stand density of 5000 stems ha^{-1}, tending of the seedling stand occurred at the age of 15 years into a stand density of 2500 stems ha^{-1} (at height of 2.8 m). Scenarios 5 and 6 are like scenarios 3 and 4, but the tending of the seedlings was done as late as at the age of 30 years into a stand density of 2500 stems ha^{-1} (at height of 6.9 m). Scenarios 7–12 differ from counterparts 1–6 only with artificial pruning conducted along with first commercial thinning at age 45 (stems were pruned to the height of 5.35 m at tree height of 10.7 m). The purpose of the artificial pruning of branches to a particular height was to get comparable results from each simulation supposing that the butt log will be 5.2 meters long, the next log 4.9 m long and the third log to the height where log top diameter is at least 14 cm. Felling height of the stem (height of the stump) was always 10 cm. In this study, the effects of different management scenarios on the simulation results were compared only on the basis of the results attained from the final cutting.

Many features of the growth model include a random effect, e.g. the annual growth of the length of stem had ±10 % randomness from the theoretical calculated length, having implications also on the development of the crown, for example. Therefore, in order to ensure that the results would reveal properly the effects of differences between management scenarios, instead of the effects of randomness, we first studied how many repeated simulations would be needed to stabilize the mean values and standard deviations of the sawing results. Based on that work, we did finally use 10 repeated simulations in each management scenario.

All simulated trees were sawn by applying the grading, which optimized 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 a better comparison

Table 1. Management scenarios applied.

Scenario: initial stand density	Timing and post-thinning stand density (stems ha^{-1})					
	Pre-commercial thinning		Commercial thinnings			
	Year 15	Year 30	Year 45	Year 65	Year 70	Year 85
1: 2500			1100	800		500
2: 2500			1100		500	
3: 5000	2500		1100	800		500
4: 5000	2500		1100		500	
5: 5000		2500	1100	800		500
6: 5000		2500	1100		500	
7: 2 500			1100, Pruning	800		500
8: 2500			1100, Pruning		500	
9: 5000	2500		1100, Pruning	800		500
10: 5000	2500		1100, Pruning		500	
11: 5000		2500	1100, Pruning	800		500
12: 5000		2500	1100, Pruning		500	

Note: In all scenarios a clear cut was done at the end of rotation at the age of 100 years.

between different schedules (this could be also seen later in Fig. 8). 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). The default values of thickness of sawn pieces could be changed by the user, but in this study the defaults were preferred. Dimensions of sawn pieces were, therefore, dependent on the log dimensions, the sawing pattern, and the value optimization of individual sawn pieces.

3 Simulation Results

3.1 Performance of the Growth Model

We use here two different kind of management scenarios to demonstrate the performance of the growth model, especially in terms of shading caused by stand as affected by forest management (spacing, thinning and artificial pruning) and how the forest management affected the development of shoots and branches in the crown. The first management scenario (number 12) used for this purpose gave the best results in sawing (see in more details later) and the latter one (number 1) the worst results, respectively. In management scenario 12 with artificial pruning of branches, the stand at the beginning of the rotation was very dense (5000 stems ha^{-1}), but turned sparser towards the end of the rotation (see Table 1). Management scenario 1, in which pruning was not applied, had quite a sparse initial stand density (2500 stems ha^{-1}), but in the later phase of the rotation the density was kept higher than in some other scenarios (see Table 1).

In the example shown for management scenario 12, the shading percentage shows the maximum value of 60% just before tending of the seedling stand (into stand density of 2500 stems ha^{-1}) in year 30. However, as a result of the 45% decrease in stand density, the shading percentage decreases immediately to 31% (Fig. 5). In the corresponding example for management scenario 1, with a smaller initial stand density, the shading percentage in the same year was 44% (the scenario includes no thinning in that year, having 2443 stems ha^{-1}). This implies that for scenario 1 the shading percentage (with smaller stand density) becomes larger as a result of slightly 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

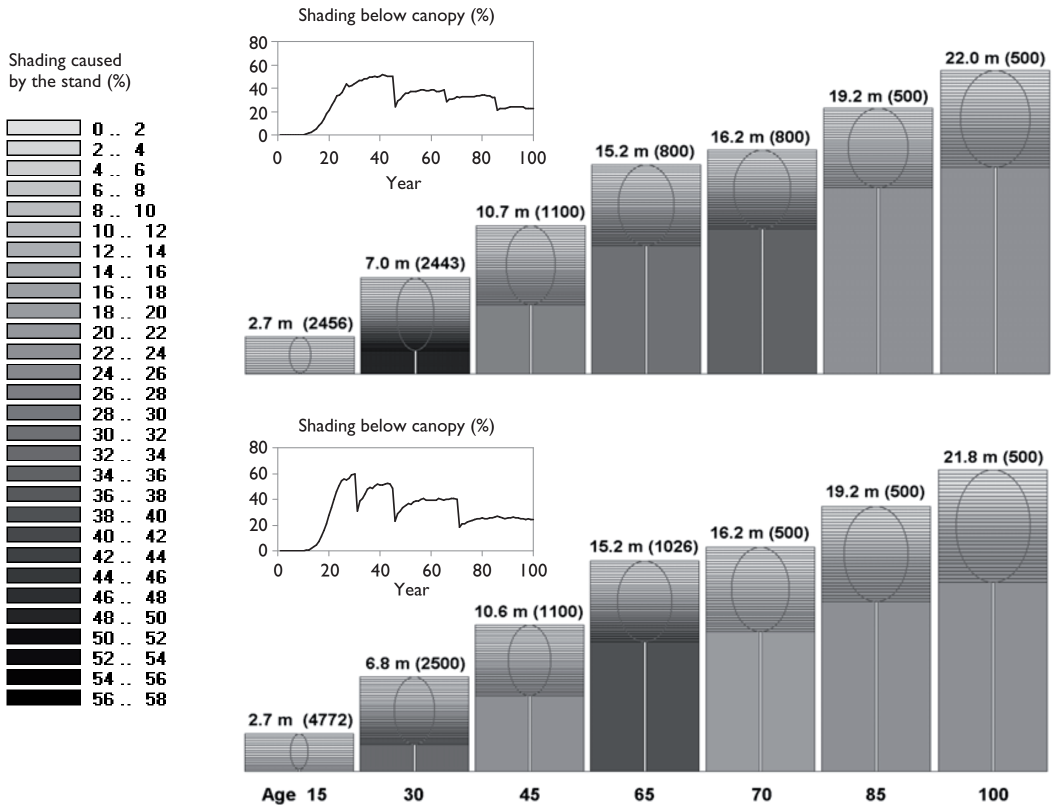

Fig. 5. Example of shading caused by the stand. Examples of iterations have been taken from management scenario 1 (top) and 12 (bottom). The presented shading percentages (in the gray scale images) are post-thinning values for each horizontal layer. The presented years are those in which at least one management scenario includes thinning in that particular year. Also height of the tree (m) and post-thinning stand density (stems ha^{-1}, in parentheses) have been presented. Shading percentages below canopy are presented in the charts.

the corresponding values were 1026 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% (Fig. 5). At the end of the rotation from years 85 to 100 the shading percentages in both examples were quite similar implying that growing conditions were alike in both cases (both quite sparse stands). In Table 2, the post-thinning shading percentages below the canopy are presented as an average of the 10 simulations in addition to these two management scenarios, also for all other management scenarios used in this work.

Regardless of the management scenario considered, at the beginning of the rotation the number of shoots with living needles is increasing rapidly. Consequently, the shading caused by the stand is increasing rapidly, especially in the dense stand (Figs. 5 and 6). When the canopy closes, the formation of new shoots decreases and the amount of shading caused by the stand levels off. The leveling-off is faster in stands with higher density than in the stands with lower density. Thinning reduces shading, which accelerates the formation of new shoots. This can be seen, for example, in Fig. 6, where the shading percentages below the canopy are quite the same in year 45 (see also Table 2), but the development of shading and the number of shoots with living needles differ from each other (especially between years 20 and 40).

Table 2. Shading caused by stand: post-thinning shading percentages below the canopy.

Scenario	Shading caused by stand [a] (%)						
	Year 15	Year 30	Year 45	Year 65	Year 70	Year 85	Year 100
1	9	46	25	30	33	21	23
2	9	46	25	40	19	26	23
3	9	45	24	30	34	21	24
4	9	46	24	40	19	26	24
5	17	31	24	30	34	22	24
6	16	31	24	40	19	26	24
7	10	45	25	30	33	21	23
8	9	45	24	40	19	26	23
9	10	46	24	30	33	21	24
10	10	46	24	39	19	25	23
11	16	30	23	29	33	21	24
12	15	30	23	39	19	25	24

[a] Shading percentages shown are post-thinning values for each management scenario as an average of 10 iterations, taken from the ground level (below the canopies).
Note: The presented years are those in which at least one management scenario includes thinning in that particular year.

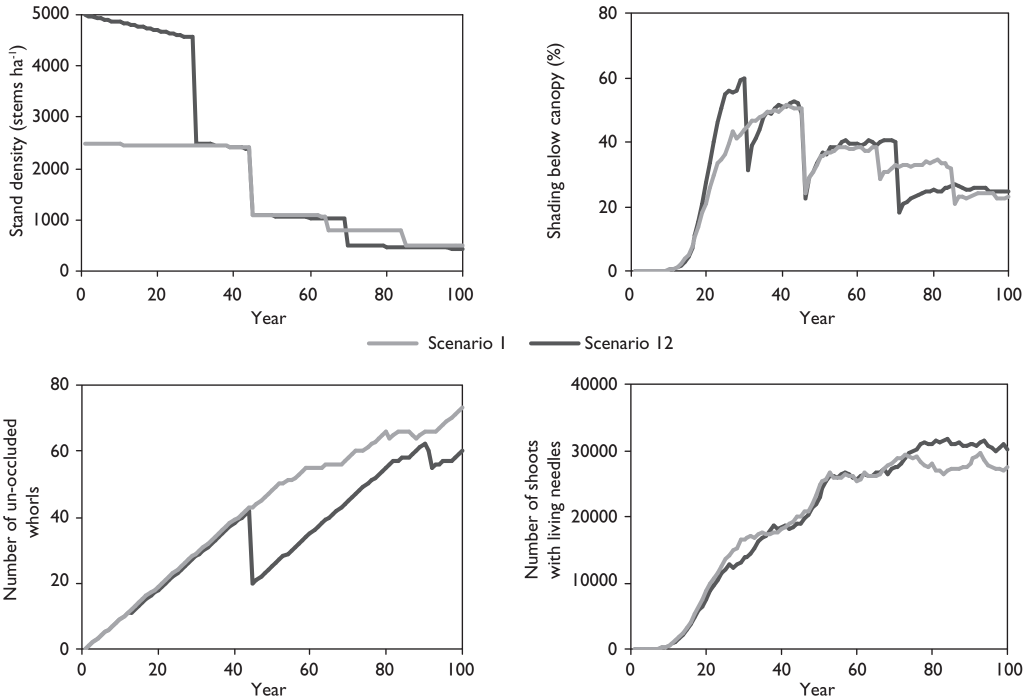

Fig. 6. Examples of iterations of management scenarios 1 and 12 for the interaction of development of stand density (stems ha^{-1}), shading caused by the stand in terms of shading below canopy (%), number of all un-occluded whorls on the stem, and number of shoots with living needles. The number of whorls includes all whorls which have at least one branch, either a living or dead branch or an un-occluded branch stub.

Table 3. Average tree level and stand level results of sawn pieces of simulated sawing of each management scenario.

Scenario	Stem properties			Sawing yield and value of sawn pieces of the stem							Sawing value of sawn pieces of the stand	
	Height (m)	Dbh (cm)	Volume (m^3)	Value (€ m^{-3}) [a]		Total value (€) [a]		Sawing yield [b] (%)		Quality frequencies [c] of butt logs (A/B/C)	Total value [d] (€ ha^{-1}) [a]	
				Butt log	All logs	Butt log	All logs	Butt log	All logs		Butt log	All logs
1	22.1	22.7	0.490	157 (51%)	143 (67%)	20 (51%)	38 (66%)	62	61	1.9/2.6/3.5	9791 (50%)	18990 (65%)
2	22.1	23.0	0.501	166 (54%)	147 (69%)	21 (54%)	40 (69%)	61	60	2.4/2.0/3.6	10282 (53%)	19792 (68%)
3	22.1	22.7	0.488	167 (54%)	147 (69%)	21 (54%)	39 (67%)	62	61	2.1/3.2/2.7	10399 (53%)	19530 (67%)
4	22.2	23.0	0.507	174 (56%)	150 (70%)	22 (56%)	41 (71%)	60	60	2.9/1.6/3.5	10819 (55%)	20495 (70%)
5	22.1	22.7	0.491	188 (61%)	157 (74%)	22 (56%)	41 (71%)	59	60	3.7/1.4/2.9	11209 (57%)	20526 (70%)
6	22.2	22.9	0.504	185 (60%)	155 (73%)	22 (56%)	41 (71%)	58	59	3.6/1.3/3.1	11000 (56%)	20607 (71%)
7	22.2	22.8	0.492	261 (85%)	191 (90%)	32 (82%)	51 (88%)	61	60	6.1/1.9/0.0	16060 (82%)	25334 (87%)
8	22.1	23.0	0.506	272 (88%)	197 (92%)	35 (90%)	55 (95%)	63	61	6.3/1.7/0.0	17563 (90%)	27297 (94%)
9	22.2	22.8	0.495	267 (87%)	194 (91%)	33 (85%)	52 (90%)	61	60	6.3/1.7/0.0	16493 (84%)	25824 (89%)
10	22.2	23.0	0.506	268 (87%)	194 (91%)	34 (87%)	54 (93%)	62	61	6.0/2.0/0.0	17065 (87%)	26794 (92%)
11	22.1	22.5	0.487	296 (96%)	207 (97%)	36 (92%)	54 (93%)	61	60	6.5/1.5/0.0	17881 (91%)	27062 (93%)
12	22.0	22.9	0.503	308 (100%)	213 (100%)	39 (100%)	58 (100%)	62	61	6.4/1.6/0.0	19560 (100%)	29179 (100%)

[a] In parentheses relative value in percents.
[b] Sawing yield (%) is volume of sawn pieces divided by volume of the log multiplied by 100.
[c] Quality frequencies shows the number of sawn pieces in each main grade.
[d] 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).
Note: The results are average values of 10 iterations of each management scenarios from final cutting (at the age of 100 years).

3.2 Effects of Management Scenarios on Properties of Sawn Timber

Management scenarios used in this study (see Table 1) had variation in i) initial stand density (2500 and 5000 stems ha^{-1}), ii) timing of pre-commercial thinning (either year 15 or 30, post-thinning stand density of 2500 stems ha^{-1} in both cases), iii) whether artificial pruning of branches was used or not, and also iv) thinnings in the latter part of the rotation. However, final stand density was 500 stems ha^{-1} in all scenarios. For example, when management scenarios 1, 2, 7 and 8 represented initial stand density of 2500 stems ha^{-1}, the other scenarios had as a initial stand density 5000 stems ha^{-1}. In scenarios 5, 6, 11 and 12, the stands were also rather dense in the first 30 years, supposing that branches remained rather small and self-pruned faster. In scenarios 2, 4, 6, 8, 10 and 12, the final stand density of 500 stems ha^{-1} was achieved earlier than in the other scenarios as a result of earlier last thinning, and therefore the stems grew slightly larger and the branches were self-pruned also slightly earlier than in other scenarios. In scenarios 7–12, the management differed from scenarios 1–6 only with pruning (see Table 1). Despite of large differences especially in initial stand density, but also in stand density before first commercial thinning between some scenarios, the stem volume was not sensitive to these differences, because only so called average tree of stand was simulated. On the other hand, as a result of higher initial stand density in the early phases of the rotation with delayed tending of the seedling stand, the quality of sawn timber was higher (Table 3, Fig. 7). 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.

The value optimization of the individual sawn pieces (in more details later), 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 with smaller lengths and sometimes even with 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 from management scenarios 5 and 6 (Fig. 7). 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, 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.

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 slightly 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 from each management scenario differed from each other only slightly, the inner quality of 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. The second and the third logs had, in general, quite similar yield in all scenarios. This was, because of the high frequency of sound and dead knots of these logs.

3.3 Effects of the Value Optimization of Individual Sawn Pieces on Dimensions and Quality Grading of Sawn Pieces

The dimensions of the sawn pieces depend on the log dimensions, the sawing pattern, and the value optimization of individual pieces. In this work, two simulations were selected to demonstrate more in details the effect of value optimization (Table 4 and Fig. 8). The example simulation of

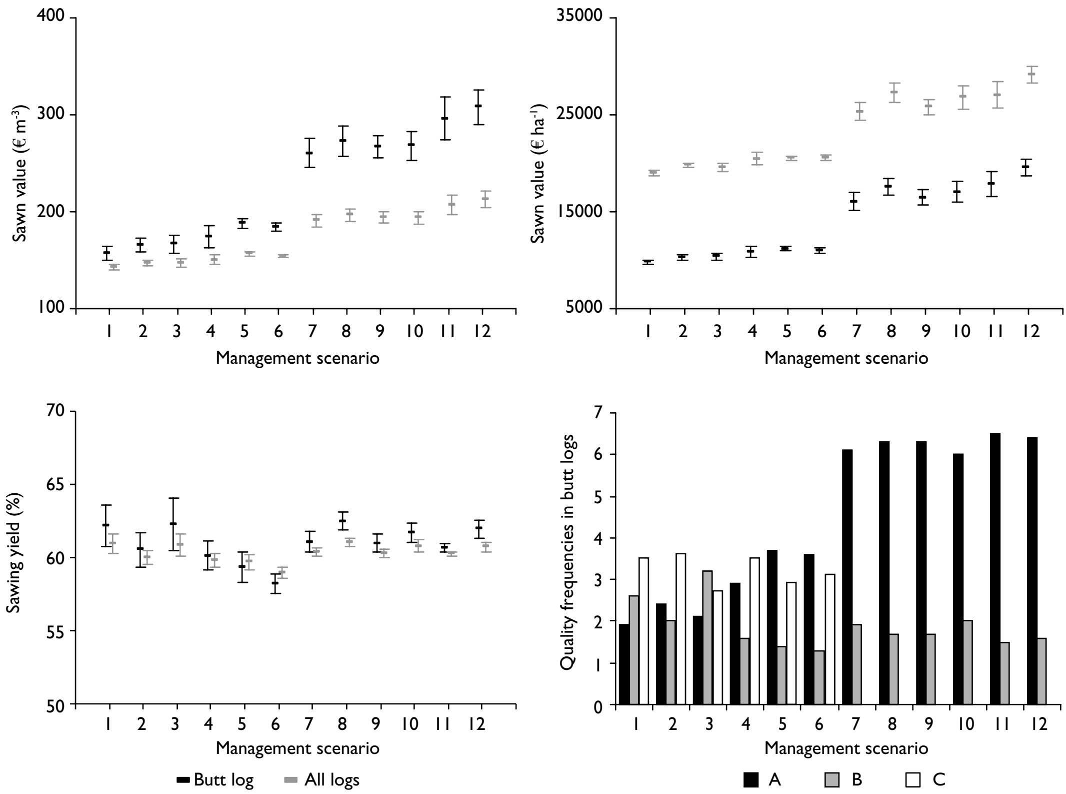

Fig. 7. Mean values and 95% confidence intervals for the sawn value (€ m^{-3}) from the stem, sawn value (€ ha^{-1}) from the stand, sawing yield percentage of the stem and quality frequencies (of quality classes) in butt logs of sawn timber in each management scenario.

Table 4. 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 of sawn pieces 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
4E [a]	219	169	26	46	58	59	4/4/0	4/4/12
11A [b]	338	227	41	59	61	60	8/0/0	8/0/12

[a] The 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] The simulation 11A is the first simulation of 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.

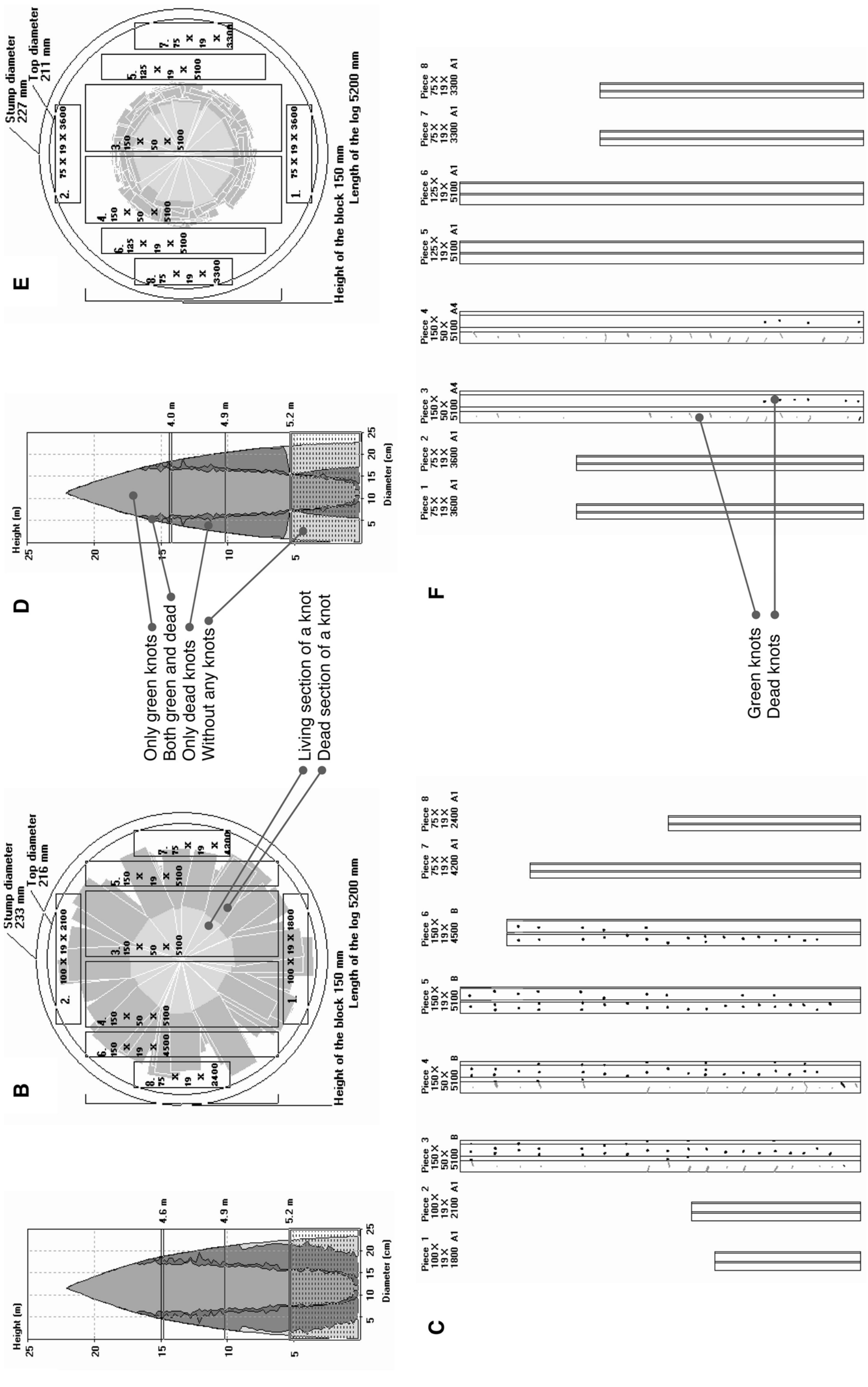

Fig. 8. Example of results of sawing of two simulated trees (final cuttings) from management scenarios 4 (left: without pruning) and 11 (right: with pruning). Figures A and D present form and knottiness of the stem, and cutting of logs. Figures B and E present used sawing pattern of the butt logs and knottiness. Figures C and F present dimensions and quality classes of sawn pieces of butt logs as well as knots on the surfaces of faces and edges of the pieces.

management scenario 4 is named "4E" and the example simulation of management scenario 11 is named "11A".

The volume of the stem in simulation 11A is only slightly smaller than that in simulation 4E, despite of different timing in the tending of the seedling stand (in 11A at the age of 30 and in 4E at the age of 15) and last thinning (in 11A at the age of 85 years and in 4E at the age of 70). But, the quality 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 (Table 4).

In the sawing of the butt logs, the same sawing pattern was used regardless of simulation, i.e. height of the center 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 and so on). The width of the sawn pieces is larger in the pieces 1, 2, 5 and 6 in the tree grown without pruning, but the lengths of the pieces are larger in pieces 1, 2, 6 and 8 from the pruned stem (only piece number 7 is shorter). The knottiness of sawn pieces from the log of the pruned stem is much less than the knottiness of the un-pruned one, as could be expected. This allows the sawing simulator to saw longer pieces without any knots and without any wane leading to only a 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 (Fig. 8). 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 a higher quality and to maximize their value. The same effect of value optimization (shortened length) is demonstrated by piece 6 from the 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.

4 Discussion and Conclusions

In this study, a structural growth model developed previously by Kellomäki et al. (1999) for individual Scots pine (an average tree in a stand) was further developed and integrated to a sawing simulator in order to analyze more in details the effects of silvicultural management on the stem and knot properties in wood with consequences on the quality of sawn pieces. In the model, the effects of stand density, thinning and pruning on the properties of stem and knots are modeled through the development of the stem and crown interacting with shading caused by the stand. As a result of this, the development of shading controls the formation of new shoots, and thus, affects the development of the crown. In the previous version of the model (Kellomäki et al. 1999) internal shading of a crown of a tree was used, i.e. shoots shaded each other depending on the direction of the radiation. In this model version, the effect of internal shading is not taken into account, but shading caused by the stand is applied instead. Thus, the modified model is simpler in this aspect, nevertheless it enables the size and structure of the crown and the stand density to be taken into account when calculating the growth of the average tree in a stand. However, because only the growth and properties of so called average tree was simulated, there could not be expected large differences in tree size despite of differences in management scenario applied. The situation would be different if trees with different tree status in a stand (from suppressed to dominant trees) would be considered in analyses, as well as different thinning types, for example (see e.g. Peltola et al. 2007, Ikonen et al. 2008).

In this model version, the effect of stand density (and size and structure of the crown) on self-pruning of branches was modeled through calculating the cross-section area of living branches in a stand assuming that living branches protect dead branches from self-pruning in dense stands (where exists less snow and wind loading, for example). The model behavior is in this sense in line with the previous findings by e.g. Heikinheimo (1953), in which the self-pruning of branches (and occlusion rate) was found faster in thinned stands compared to unthinned ones.

In general, a clear correlation exists between the thickness of the annual growth ring in Scots pine and the growth of branches and knots (Hakkila 1966, Uusvaara 1974). Consequently, the quality of sawn pieces is inversely related to the radial growth rate of the stem (Uusvaara 1974, 1985, Jäghagen and Lageson 1996). Thus, the initial stand density, timing and intensity of tending of seedling stand and thinning affect both the development of stem and branches, and concurrently knots in the wood, over the whole lifespan of the tree. On the other hand, the quality and value of sawn timber is also affected by the interaction of tree height, stem diameter and taper of the stem, number and length of logs, knottiness, and the sawing pattern as well as the unit prices used for sawn pieces in various quality and dimension classes.

In this study, the quality grading used in the sawing simulator follows the grading rules that are common for the Nordic countries (Nordic timber 1994). However, only some of the rules were taken into account, i.e. the occurrence and properties of knots on the surfaces of sawn pieces since these parameters are directly related to the growth of trees and are affected by management. Blue stain, discoloration, insect damage and related defects in wood were not considered in the sawing simulator, because they are more or less random defects that lie beyond the mechanistic modeling of growth. Furthermore, the unit prices used in this work for different grades and dimensions of sawn timber could be taken as most appropriate for relative ranking of different scenarios, but not as accurate values because they were provided only by one local dealer of sawn timber (absolute values range also from year to year and depending on demand of sawn timber). In this work, the average value used of grade A was 334 € m^{-3} (ranging between A1–A4), when the corresponding values for grade B and C were 161 € m^{-3} and 130 € m^{-3}.

This work concentrated to analyze how management affects the quality of timber in final cutting, and not in details the profitability of management (incomes, costs and interest rate) over the whole rotation. Thus, in this study, the management scenarios were compared only on the basis of the results attained for the logs from the final cutting. Moreover, to facilitate the comparison of several management scenarios, the same log lengths were used for butt logs (5.2 m) and for the second logs (4.9 m) of the stems. Also the sawing pattern (the height of the center block) was taken to be the same for all butt logs and the stems were pruned to the same height, when pruning was applied. As a result, we found that the variations in sawing results between management scenarios were mainly due to the differences of the sawn pieces from the butt logs. Also the value optimization of individual sawn pieces led to smaller lengths and sometimes even to smaller widths of sawn pieces. This resulted in a higher quality (€ m^{-3}), but smaller utilization of the log volume, which in turn led to a smaller sawing yield percentage.

Management scenario 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 compared to the other scenarios. In this scenario, the stand was very dense (5000 stems ha^{-1}) at the beginning of the rotation, but turned sparser towards the end of the rotation, and it included artificial pruning of branches. Scenario 11 (the last thinning was made later) gave similar results. Among the scenarios with the lowest quality of sawn pieces was scenario 1, in which pruning was not applied. This scenario represents quite sparse initial stand density (2500 stems ha^{-1}), but in the later phase of the rotation the density was higher than in some other scenarios. Compared to scenario 1, scenario 8 showed good results, even if it had relatively sparse stand throughout the rotation. This result was mainly due to pruning (leading to good sawn timber quality), but it was also due to slight differences in volumes of the stem, which led in this case to a slightly higher sawing yield percentage. Also the sawing pattern seemed to be optimal for the stems of this scenario.

Previous studies exist also in different tree species on the simulated sawing, including Scots pine (and other pine species) and Norway spruce (*Picea abies* (L.) Karst.). However, they are based on use of different management scenarios and in many cases different sawing patterns, in addition to different values for the grades and dimensions of sawn pieces (see e.g. Chiorescu and Grönlund 2000, Nordmark and Oja 2004, Uusitalo et al.

2004, Moberg and Nordmark 2006, Pinto et al. 2006, Kantola et al. 2008). Therefore, it is very difficult if not even impossible to compare different studies to each other. However, similar to this study, also for example Kantola et al. (2008) found in Norway spruce relative small differences (<8%) in the volume yield (m^3 ha^{-1}) of sawn goods resulting from sawlogs available from final cutting (with different thinning scenarios, including unthinned, normal and intensively thinned).

In our study, the percentages of the number of sawn pieces in each main grade of butt logs varied between 24–46% (quality A), 16–40% (quality B) and 34–45% (quality C) on the average in scenarios without artificial pruning of branches and 75–81% (A), 19–25% (B) and 0% (C) in scenarios with artificial pruning. Previously, Uusitalo et al. (2004) have also studied Scots pine timber quality based on field experiments (with 100 Scots pine stems taken from 6 stands from southwestern Finland in 2001). In their study, the portion of grade in butt logs varied between 20–90% in A grade (average 60%), 9–78% in B grade (average 40%) and 0–8% in C grade (average 0.2%), being thus different than in this simulation study of an average tree. In our study sawing yield percentage varied between 58–63% from butt logs and between 59–61% from all logs (Table 3). As a comparison, in the study by Chiorescu and Grönlund (2000), the simulated sawing yield percentage was in some degree smaller than in this work, but very close to the sawmill's volume recovery in Scots pine, being 48%.

To conclude, the simulations done in this study showed that relatively dense stand at the beginning of the rotation is needed in order to reduce the growth of branches and to increase the quality of sawn timber. During the later phases of a rotation, relatively sparse stands are preferable in order to make the self-pruning of branches more intensive (due to smaller branches and effect of wind and snow loading), the occlusion of self- or artificially pruned branches faster (due to faster diameter growth). It was also noticed that the effect of artificial pruning was significant on the quality of sawn timber, i.e. artificial pruning is needed in order to increase the knot-free zone of the stem. In addition to management, the selected sawing pattern (i.e. dimensions of logs and sawn pieces) and value optimization of individual sawn pieces significantly affected the quality and value of sawn timber. However, because only average tree was simulated in a stand, the differences between scenarios in terms of stem volume were rather small. Thus, cautious has to be considered if the findings in this study will be generalized to the stands with large tree size variation. In the future, further model development is needed in order to analyze simultaneously the development of crown and stem properties of trees with different status (from suppressed to dominant) in a stand as affected by silvicultural management with implications on simulated sawing.

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