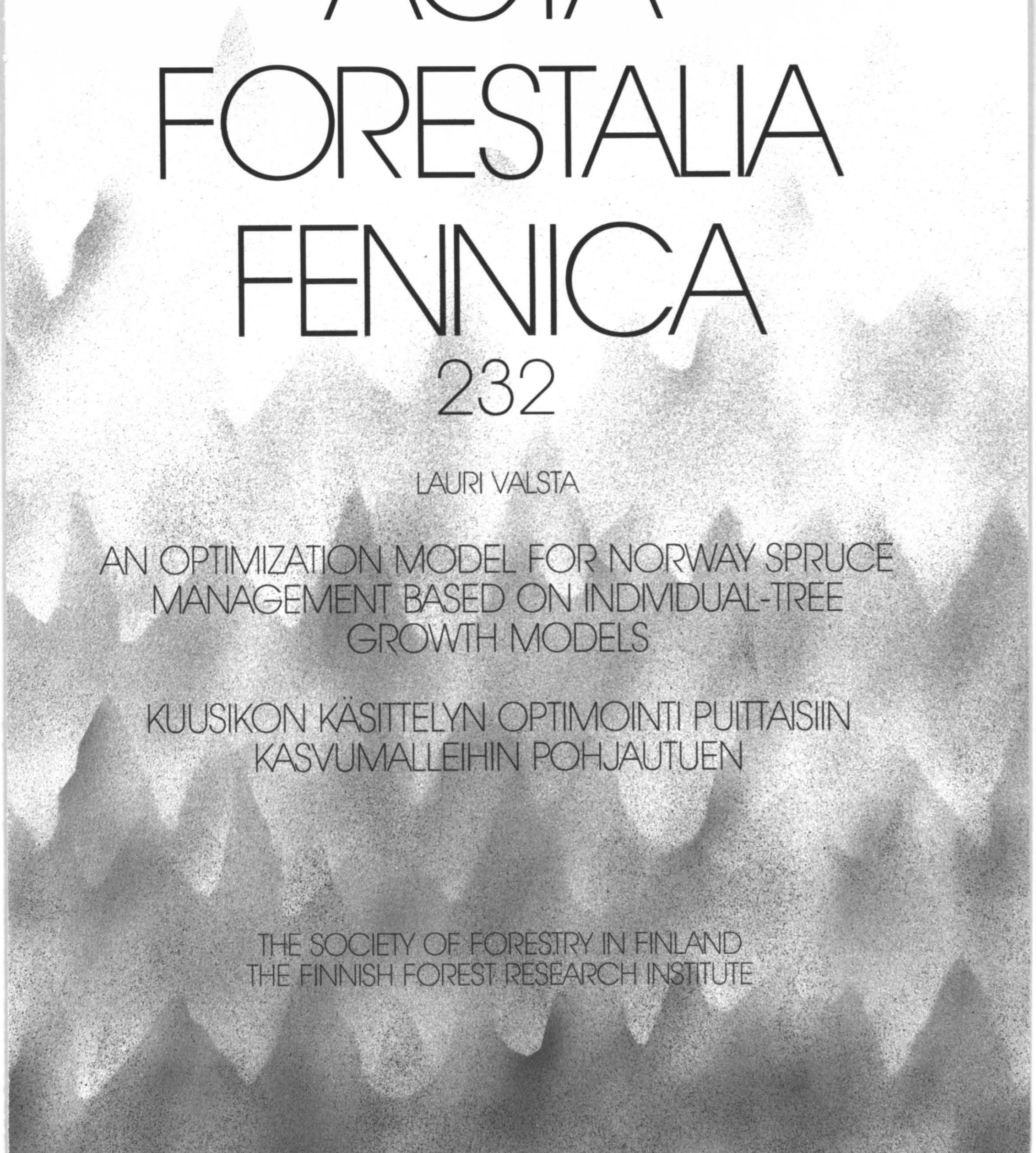

ACTA FORESTALIA FENNICA

232

LAURI VALSTA

AN OPTIMIZATION MODEL FOR NORWAY SPRUCE MANAGEMENT BASED ON INDIVIDUAL-TREE GROWTH MODELS

KUUSIKON KÄSITTELYN OPTIMOINTI PUITTAISIIN KASVUMALLEIHIN POHJAUTUEN

THE SOCIETY OF FORESTRY IN FINLAND
THE FINNISH FOREST RESEARCH INSTITUTE

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ACTA FORESTALIA FENNICA 232

AN OPTIMIZATION MODEL FOR NORWAY SPRUCE MANAGEMENT BASED ON INDIVIDUAL-TREE GROWTH MODELS

Kuusikon käsittelyn optimointi puittaisiin kasvumalleihin pohjautuen

Lauri Valsta

Approved on 28.10.1992

The Society of Forestry in Finland – The Finnish Forest Research Institute
Helsinki 1992

Valsta, L. 1992. An optimization model for Norway spruce management based on individual-tree growth models. Tiivistelmä: Kuusikon käsittelyn optimointi puittaisiin kasvumalleihin pohjautuen. Acta Forestalia Fennica 232. 20 p.

A nonlinear programming algorithm was combined with two individual-tree growth simulators consisting of distance-independent diameter and height growth models and mortality models. Management questions that can be addressed by the optimization model include the timing, intensity and type of thinning, rotation age, and initial density.

The optimum thinning programs were characterized by late first thinnings (at a dominant height of 15–17 m) and relatively high growing stock levels. It was optimal to thin from above, unless mean annual increment was maximized instead of an economic objective. In most cases, the optimum number of thinnings was two or three. Compared to a no-thinning alternative, thinnings increased revenues by 15–45 % depending on the objective of stand management. Optimum rotation was strongly dependent on the interest rate.

Hooke and Jeeves' direct search method was used for determining optimum solutions. The performance of the optimization algorithm was examined in terms of the number of functional evaluations and the equivalence of the objective function values of repeated optimizations.

Tutkimuksessa laadittiin metsikön käsittelyn optimointimalli yhdistämällä epälineaarisen ohjelmoinnin algoritmi kahteen simulaattoriin, jotka koostuivat puittaisista läpimitan ja pituuden kasvumalleista ja kuolemismalleista. Optimointimalli soveltuu harvennusten ajoituksen, voimakkuuden ja tavan sekä kiertoajan ja metsikön perustamistiheyden samanaikaiseen tarkasteluun.

Tuloksia laskettiin eteläsuomalaisille kuusikoille, lähinnä OMT:tä vastaaville kasvupaikoille, joissa puuston tiheys taimikonhoidon jälkeen oli n. 2000 kpl/ha. Laskelmissa käytettyjen taloudellisten tekijöiden arvojen vallitessa oli edullisinta harventaa puusto ensimmäisen kerran varsin myöhäisessä vaiheessa (15–17 metrin valtapituuden kohdalla). Suhteellisen korkeat puustopääomat (pohjapinta-ala 25–40 m^2/ha) olivat optimaalisia. Harvennusvoimakkuus riippui harvennusten lukumäärästä. Yläharvennus oli edullisin harvennustapa muulloin paitsi tilavuuskasvua maksimoitaessa. Optimaalinen harvennusten lukumäärä oli kahdesta kolmeen ja harvennukset lisäsivät tuottoja puunkasvatuksen tavoitteesta riippuen 15–45% kiertoajan kuluessa harventamattomaan vaihtoehtoon verrattuna. Korkokanta vaikutti voimakkaasti optimikiertoaikaan, joka vaihteli 70 vuodesta yli 110 vuoteen.

Optimiratkaisut määritettiin Hooken ja Jeevesin suorahakumenetelmällä. Optimointialgoritmin toimivuutta arvioitiin funktioevaluointien lukumäärän ja toistettujen optimointien tavoitefunktion arvojen yhdenmukaisuuden perusteella.

Keywords: stand management, optimization, thinning, rotation, initial density, individual-tree simulator, Norway spruce, *Picea abies*.
FDC 174.7 *Picea abies* + 24

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Contents

1 Introduction

Controlling the amount and structure of the growing stock is one of the most important decisions in forestry. In practical decision-making, the true optimum treatment of a stand always depends on the rest of the forest property and the economic setting of the forest owner. Results concerning single, independent stands are, however, useful for management guidelines or comparative analyses where the effects of some economic or biological factors of stand management are studied.

At the present stage of forest modelling, regeneration optimization is deficient because of lack of usable models for stand regeneration and juvenile development. Considering individual stands, it is useful from optimization point of view to separate management questions regarding thinnings and final harvest from those dealing with regeneration.

The main decision problem in this study is the following: Assume that we have a young, established stand, free of competing vegetation. How should we treat the stand for the rest of the rotation? We are interested in the optimum combination of

- the number of thinnings
- the timing of thinnings
- the amounts thinned
- the types of thinnings (from below, from above)
- rotation
- pre-commercial thinning (tending)

Traditionally, these questions have been studied on the basis of field experiments incorporating sets of treatment regimes. At best, partial questions can be answered by these experiments consisting of a limited selection of treatment alternatives. To determine an optimum combination of many variables, we must resort to computer-based models. To accomplish this we need both a set of models that predict the development of any given stand subject to various treatments, a stand simulator, and a procedure for finding an optimum set of treatments, an optimization algorithm.

Thinnings have several economic effects. They affect the amount of capital invested in standing timber, the short and long term growth rates of standing trees, mortality due to different causes, the quality of remaining trees, future logging costs, and the optimum rotation. The complete effects of a thinning are not realized until the end of the rotation. Other decisions that may interact with thinnings include initial density, vegetation management, precommercial thinning, and fertilization.

One interesting management question is thinning type, i.e., whether one should thin the smaller or the larger trees of a stand. Thinning type has been a controversial issue in Finland, especially after the 1948 "Thinning Declaration" (Julkilausuma 1948). The thinning declaration banned thinnings from above because selection harvesting had led to devastation in Finnish forests and it was considered that the best way to improve thinning practices was to allow only thinning from below.

Finnish research on thinning types was not activated until the 1960s: the first results were published by Vuokila from temporary plots (1970) and remeasured plots (1977). Later measurements of the latter were reported by Mielikäinen & Valkonen (1991), who also computed monetary returns. Results from another set of experiments were reported by Hynynen & Kukkola (1989). Comparable studies in terms of biological conditions have been made in Sweden (Eriksson 1990). Regarding spruce stands, the Finnish and Swedish results suggest that thinning from above slightly reduces volume growth, compared to thinning from below. In present value computations, thinning from above was slightly superior (Mielikäinen & Valkonen 1991).

Finnish model-based analyses that include thinning type are limited to two. Both of them are based on whole-stand growth models and, as such, make simplifying assumptions about thinning returns and future growth relating to different thinning types. Kilkki & Väisänen (1969) used dynamic programming to determine the optimum thinning program for Scots pine stands and made separate analyses for thinning from below and above. Their results showed 2 to 12 % higher present values for thinning from above, when comparing optimum regimes of each thinning type. However, their analysis did not account for the increase in unit value of standing timber due to thinning from below, compared to thinning from above. Hämäläinen (1978) analyzed thinning types using a set of thinning alternatives based on the growth functions by Vuokila (1967) for Scots pine stands. In this study, as well, thinning type did not affect the growth of the stands and the results are clearly conditional. Thinning from below was more profitable when the interest rate was 2 % or less, whereas thinning from above was superior with interest rates of 3–5 %.

A Swedish study (Olsson 1986) utilizing individual-tree growth functions (Söderberg 1981 and Elfving 1982, ref. Olsson 1986) indicates that thinning from above is slightly superior under both a volume and a value criterion. However, the results for Norway spruce stands are based on only a few simulations.

The studies cited so far are based on roundwood market prices. If wood processing is taken into account in the computations, the results may be altered. This is because at least in Finland, roundwood market prices do not completely correspond to values derived from wood products, such as lumber. An example from Sweden is reported by Persson (1986) where log quality was considered as a pricing factor. This improved the profitability of thinning from above because most rapid diameter growth (resulting from thinning from below) was avoided and the tree rings did not become excessively wide.

Methods that have been used in other countries for optimizing thinning type include dynamic programming (Haight et al. 1985, Arthaud & Klemperer 1988, Torres-Rojo & Brodie 1988, Yoshimoto et al. 1990), nonlinear programming (Roise 1986b, Bare & Opalach 1987), and discrete time optimal control theory (Haight 1987, Solberg & Haight 1991). Given the large selection of species, growing conditions, and economic parameters, it is not reasonable to try to form an overall conclusion about the optimum thinning type. However, a pattern found in several of the studies is that thinning from below is optimal when maximizing the mean annual increment and thinning from above when maximizing discounted values. Most of the studies were made with various pine species. An optimum solution for Douglas fir, a species resembling Norway spruce, had a precommercial thinning from below and a commercial thinning from above (Roise 1986b).

The principal objective of the present investigation is to develop an optimization model for analyzing stand treatment options based on individual-tree, distance-independent growth models. A solution to this problem was first presented by Roise (1986a). (Kao & Brodie (1980) solved the same problem for a whole-stand growth model.) A model based on Finnish growth models (Mielikäinen 1985) was presented by Valsta (1987), but with limited numerical results. A more operational form of the optimization model was reported in Valsta (1992), but the main objective of that study was stochastic optimization. Using a deterministic version of the improved optimization model, the present study examines the effects of different elements of the optimization problem, such as the objectives of stand management, the number of available thinnings, the initial density, and the growth models. The numerical results concern examples of Norway spruce stands in southern Finland. The results are compared with previous research, as well as the present recommendations of a forestry extension organization in Finland. The performance of the optimization algorithm is also tested.

2 Stand simulators

2.1 Growth and mortality models

The growth models of the Finnish forestry planning system 'MELA' were chosen as the basic individual-tree, distance-independent growth simulator (Ojansuu et al. 1991). Optimization results may be strongly dependent on the growth models, and so for comparison, another set of models was chosen from the study by Mielikäinen (1985). The function forms of the models are presented in Appendix 1. Both sets of growth models have been estimated from temporary sample plot material. However, the MELA models have been extensively tested against repeated forest inventories and remeasured permanent plot data (Ojansuu et al. 1991).

The basic mortality model chosen (Haapala 1983, also used by Ojansuu et al. 1991) predicts individual tree mortality in managed stands free of large scale mortality. The model does not apply to stands at limiting densities. Another model (Hynynen 1991) identifies the self-thinning curves based on stand level variables. Because of lack of comprehensive data, the two models given above do not predict mortality reliably for older stands with less than 500 trees per hectare. These conditions are found by the optimization algorithm and taken advantage of. To handle these cases, live crown ratio is linked to mortality. This is achieved by combining a live crown ratio model (Mielikäinen 1985, Equation 17) with two ad hoc models. It should be noted that the crown ratio model is used for a purpose not intended by Mielikäinen (1985, p. 28–29). This is done because no other models are available. The mortality models are described in more detail in Appendix 1.

2.2 Thinning model

The thinning model defines the number of trees cut in each diameter class, and it is the same as reported in Valsta (1992). Being essential for the thinning type analysis, the model description is repeated here.

The present thinning type model was designed with the idea of being able to vary the accuracy and the number of variables required. To achieve reliable solutions with the available nondifferentiable optimization algorithms, the number of decision variables must be kept to the minimum. This can be done by specifying thinnings by groups of diameter classes (Haight & Monserud 1990, Yoshimoto et al. 1990), by removing trees from below or above (Haight et al. 1985, Haight 1991), or by using a diameter distribution function with its parameters as decision variables (Bare & Opalach 1987).

In the present study, a piecewise linear function defines thinning intensities as a function of tree diameter, relative to the smallest and the largest diameters of the stand at time of thinning. Thinning parameters define thinning rates (percentages of trees cut) at the corner points of the piecewise linear function. At one extreme, there may be only one thinning parameter, and the thinning rate is constant across all tree diameters. At the other extreme, there may be a thinning parameter for each diameter class. As an example, suppose that we wish to use three parameters, p_1, p_2, and p_3, to define a thinning. They denote thinning rates at the minimum, midpoint, and maximum tree diameter, d_{min}, d_{mid}, and d_{max}, respectively. Thinning rates for other diameters are computed using linear interpolation. An example of the thinning specification is shown in Fig. 1, with three parameters to define the thinning intensities for different diameters. The first and last parameter always refer to the smallest and largest diameter of the stand at time of thinning.

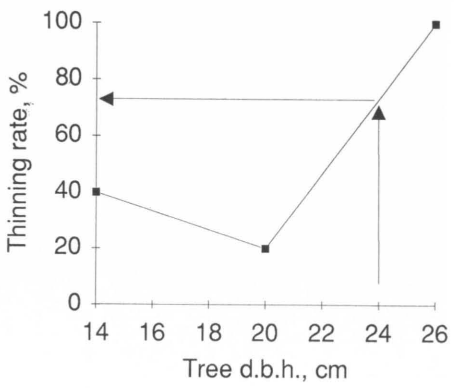

Fig. 1. Thinning specification based on three parameters for a stand with minimum and maximum breast height diameters of 14 and 26 cm, respectively. For example, the thinning rate for 24 cm trees is 73 %.

2.3 Yield models and economic data

Tree total volumes and volumes by wood assortment are computed based on the models by Laasasenaho (1982) using computer programs by Laasasenaho & Snellman (1983). Wood assortment volumes are based on tree dimensions only – no deductions due to defects are made. The amount of sawtimber produced is thus overestimated but the importance of this bias is reduced by the small difference between the road side prices of spruce sawlogs and pulpwood.

Logging costs are based on the Finnish logging and hauling work tariffs (Valsta 1992). The tabulated tariff values were smoothed to form equations of total logging cost as functions of average tree size and total volume harvested. The models are given in Appendix 1.

Road-side values for spruce sawlogs and pulpwood are 210 and 180 FIM/m^3, respectively. Regeneration costs are assumed to be 4300 FIM per hectare. When initial density (trees/ha) is a decision variable, regeneration cost (FIM/ha) is computed as:

$$\text{cost} = 1800 + 1.25 \text{ density} \qquad (1)$$

Soil expectation value is computed based on a series of equal rotations. All costs and revenues are discounted to stand age 0, and then transformed to an infinite series using coefficient $(1 + i)^T / [(1 + i)^T - 1]$, where i is the decimal interest rate and T is rotation length.

2.4 Restrictions of the models

The model set employed causes some important factors to be ignored in the analysis. These include

- improvement of stand quality by thinnings
- spatial distribution of trees and skid roads
- logging damage to remaining trees

Also, the growth models are used for predicting growth in stands thinned from above, whereas the sample trees were taken from stands thinned mostly from below. Further, risk and uncertainty are not accounted for: growth and mortality of trees are deterministic, prices and costs are known and constant over time.

2.5 Plot data for simulation

Measurements of three experimental plots are used as starting points for stand simulation (Table 1). The plots were established and are managed by the Finnish Forest Research Institute, Department of Forest Production. All plots are of planted Norway spruce. The diameter distributions of the initial stands are shown in Fig. 2 and the complete listings by diameter class are given in Appendix 2. The diameter distribution of plot 11302 was expanded by duplicating diameter classes 1 to 4 cm in order to give more room for thinning type optimization. Tree height values are based on sample tree measurements.

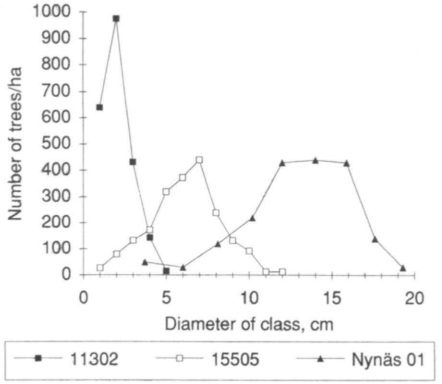

Fig. 2. The diameter distributions of plots 11302 (14 years old), 15505 (21 years old), and Nynäs 1/01 (40 years old).

Table 1. Characteristics of the three plots used as initial stands. For symbols, see App. 1.

Plot number	$H100$	Age	D_{ba}	$Hdom$	Basal area	Trees/ ha
11302	28	14	2.8	3.4	0.8	2208
15505	29	21	7.4	7.3	6.8	2038
Nynäs 1/01	29	40	14.4	14.8	37.0	1890

3 Optimization method

The optimization method is a deterministic version of the one applied by Valsta (1987, 1992). The basic approach is after Kao & Brodie (1980) and Roise (1986a). Fig. 3 shows the overall structure of the simulation-optimization model. The stand growth simulator is depicted as a black box to reflect the fact that the optimization algorithm knows of the simulator only by the objective function values it obtains in return for decision variable vectors.

Hooke and Jeeves' (1961) direct search method is used as the optimization algorithm. It is classified a derivative free, multidimensional search method for unconstrained nonlinear programming (Bazaraa & Shetty 1979). Compared to other alternatives, it has performed well with whole-stand and individual-tree growth models (Roise 1986a, Linkosalo 1991).

Hooke and Jeeves' direct search algorithm operates using two search modes: exploratory search and pattern search. Given a base point, exploratory search examines points around the

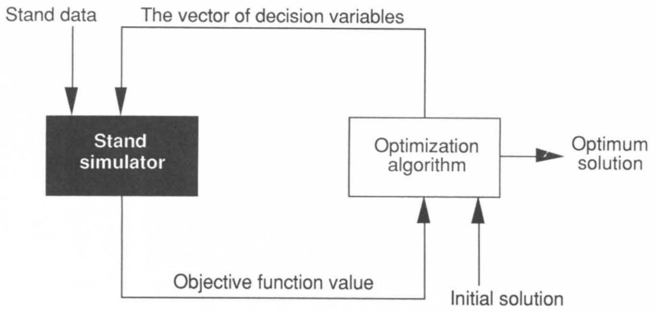

Fig. 3. The structure of the optimization-simulation model.

base point in the directions of coordinate axes. Pattern search moves the base point in the direction defined by the previous base point and the best point of exploratory search. An example of the algorithm operation is seen in Fig. 4, where the function $y = (x_1 - 2x_2)^2 + (x_1 - 2)^4$ is minimized. The points generated, joined with line segments, are labelled. The initial point is (10,10). The short horizontal and vertical moves are the exploratory searches and the longer jumps are the pattern searches. The first ten pattern moves lead to point (2.4,1.2) with a function value 0.0256, while the true optimum is at point (2,1) with a function value 0.

The vector of decision variables consists of times between forest operations and information on how the operation is executed, e.g., thinning percentages at different tree diameters, or the number of plants per hectare. When optimizing the rotation, two thinnings defined by three parameters (thinning percentage for the smallest, medium-sized, and the largest trees), and initial density, the vector of decision variables is, e.g.:

(14.2,	time from the last thinning to the final cut
29.9,	time from the start of the simulation to the first thinning
0.00,	first thinning, thinning percentage for the smallest trees
51.1,	first thinning, thinning percentage for medium-sized trees
100.0,	first thinning, thinning percentage for the largest trees
14.5,	time from the first thinning to the second (last) thinning
0.00,	second thinning, thinning percentage for the smallest trees
70.2,	second thinning, thinning percentage for medium-sized trees
100.0,	second thinning, thinning percentage for the largest trees
2200)	trees per hectare

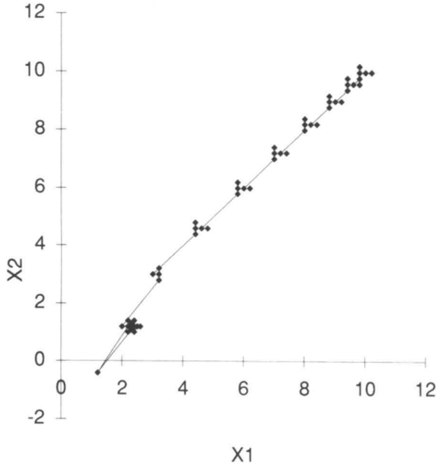

Fig. 4. Sequence of points on plane x_1x_2 generated by Hooke and Jeeves' algorithm when minimizing the function $y = (x_1 - 2x_2)^2 + (x_1 - 2)^4$ from initial point (10,10).

This is the optimum solution with 3 % discount rate for plot 11302 with MELA growth models (two thinnings).

4 Results

4.1 Optimum thinning programs for different goals of stand management

Unless otherwise stated, the results presented are based on the MELA growth models (Ojansuu et al. 1991) and plot 15505 tree list as the initial stand. Stand volume development in the optimum thinning programs is shown in Fig. 5 for maximizing volume production, i.e., mean annual increment (M.A.I.), as well as soil expectation values at 1, 3, and 5 % interest rate. Thinnings were defined by three parameters and a maximum of four thinnings are considered.

As anticipated, the higher the interest rate, the shorter the rotation, and the earlier, the fewer and the heavier the thinnings. The solution for maximum M.A.I. with 4 thinnings produced 10.2 m^3/ha/yr in a 96-year rotation. Thinning intensity varied from 20 to 27 % of volume, and thinnings both captured mortality and removed larger trees. For an unthinned stand (not shown in Fig. 5), the optimum rotation was 71 years with an M.A.I. of 8.7 m^3/ha/yr. 21 % of the trees (35 m^3/ha) died during the rotation. Although thinnings can not increase periodic volume increment in a stand, they can increase the total volume harvested per year during the rotation. A part of the increase results from a longer optimum rotation in the thinning case. Then, a proportionally shorter part of rotation is used by the young stand period where volume growth is small.

4.2 Optimum thinnings and rotation for different numbers of thinnings

The optimization of thinnings and rotation for each number of thinnings constitutes a different problem with a corresponding number of variables. The number of thinnings is therefore a parameter given to the computer program at the outset. Optimum solutions for 1, 2, and 3 thinnings are shown in Fig. 6 in terms of stand basal area and dominant height. According to expectations, thinning intensity decreased with an increasing number of thinnings. The time of the first thinning was about the same in all cases. Dominant height was reduced at the time of thinning because the thinnings were from above.

The optimum rotation age increased with the

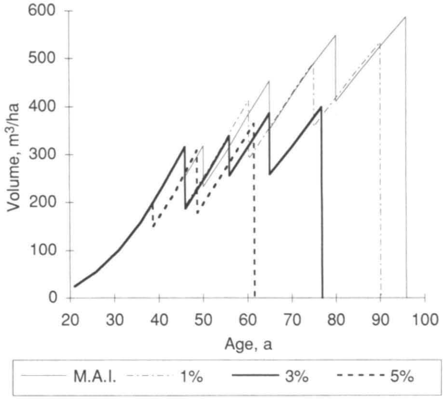

Fig. 5. Optimum thinnings and rotation for different objectives: maximum Mean Annual Increment (M.A.I.), and maximum soil expectation value at 1, 3, and 5 % discount rate. Thinnings are defined by three parameters.

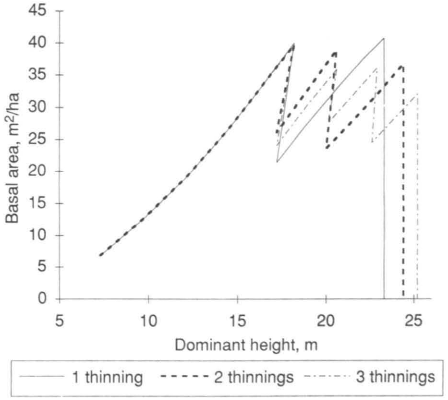

Fig. 6. Basal area development in the optimum thinning programs with 3 % interest rate for one, two, and three thinnings.

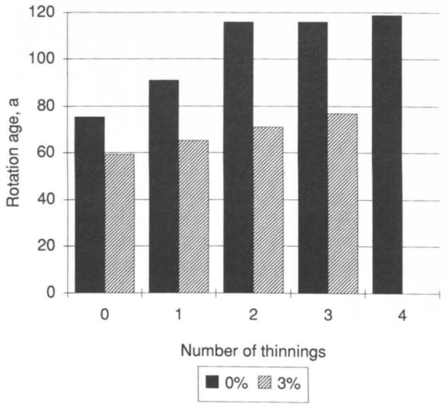

Fig. 7. Optimum rotation age for different numbers of thinnings for average annual net cash flow (0 %) and 3 % soil expectation value.

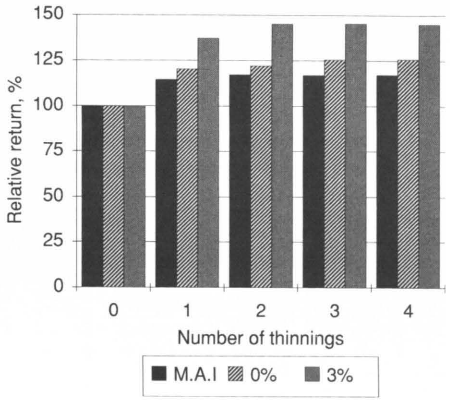

Fig. 8. Relative returns in relation to the number of thinnings for different objectives: maximum mean annual increment (harvested), average annual net cash flow (0 %), and soil expectation value with 3 % interest rate.

number of thinnings (Fig. 7). The effect was stronger with no discounting (0 %, i.e., forest rent case). The average diameter at final harvest was only slightly increased by thinnings: with a 3 % interest rate it amounted to 18, 21, 22, and 23 cm for 0, 1, 2, and 3 thinnings, respectively.

Returns to thinning were notable with all the criteria used and more so with a greater interest rate (Fig. 8). However, most of the gain was achieved with just one thinning. Optimum regimes with two to four thinnings produced about the same return. The fact that the returns were almost constant for regimes with two, three, or four thinnings may not hold for other (suboptimal) thinning regimes.

4.3 Optimum thinning type and initial density

The optimum thinning type (thinning from below/above, or low/high thinning) was affected by the objective of stand management and by stand density. In Fig. 9, thinning type is defined as the ratio of average diameter of trees thinned to average diameter of all trees (arithmetic averages), denoted by d/D. The ratio d/D < 1 implies thinning from below and d/D > 1 indicates thinning from above. With an economic objective, thinning from above was optimal in most situations.

When maximizing volume production, both the smallest and the largest trees were thinned. The first thinning was from above which was exceptional in view of other results for the same objective. The optimum regimes with one or two thinnings (not shown in Fig. 9) did not include thinnings from above but employed thinnings from both ends of the diameter distribution.

The optimum thinning program depends on the initial density. The basal area development in optimum thinning regimes with different initial densities is shown in Fig. 10. Soil expectation value was computed using density independent regeneration costs because initial density was not a decision variable in this analysis. Natural regeneration would be an appropriate assumption in this case.

Precommercial thinning was profitable only for the stand with 4400 trees per hectare. About 1000 trees (average d.b.h. 3.4 cm) were removed at a cost of 760 FIM/ha at 15 years. This reduced mortality during the following 25 years (the time up to the first commercial thinning) from 10 % to 3 %.

The time of the first commercial thinning was set in the optimum solution by the optimization algorithm so that adversely high growing stock levels were avoided. The optimum number of commercial thinnings was 2 for 1100 trees/ha and 3 for 2200 trees/ha, and 2 for 4400 trees/ha.

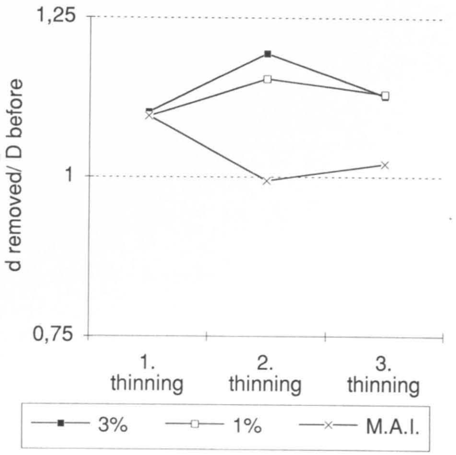

Fig. 9. Optimum thinning type (d/D -ratio) when maximizing soil expectation value with 1 % and 3 % interest rate, and M.A.I. in three-thinning regimes. Thinnings are defined by three parameters.

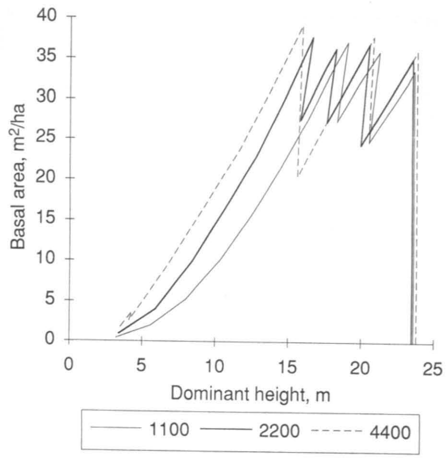

Fig. 10. Basal area development following different initial densities in optimum thinning regimes (3 % discount rate). Numbers of trees by diameter class of plot 11302 are multiplied by 0.5, 1.0, and 2.

The regime for the greatest density included one precommercial thinning, too. The thinning interval and intensity were also affected by the initial density. In most cases, the basal area before thinning was between 35 and 40 m²/ha.

Initial density was optimized by adding it to the vector of decision variables. Density optimization was made for stands based on the tree list of plot 11302 which is a 14 years old plantation at the beginning of simulation. Different initial densities were generated by multiplying the trees-per-hectare values of the tree list by the initial density decision variable. Establishment costs were computed according to Eqn. (1). Because of the lack of empirical basis of Eqn. (1), the purpose of the results is only to present the methodology of optimizing initial density (planting density) using the present algorithm.

An increasing interest rate decreased the optimum initial densities (Fig. 11). Rotation length was also clearly affected by the interest rate. The runs were made so that two thinnings were possible but optimization set one of them to zero in the 4 and 5 % interest rate cases. The soil expectation value was –46 FIM/ha at 5 % interest rate, which is the approximate maximum internal rate of return obtainable based on the present models and parameter values.

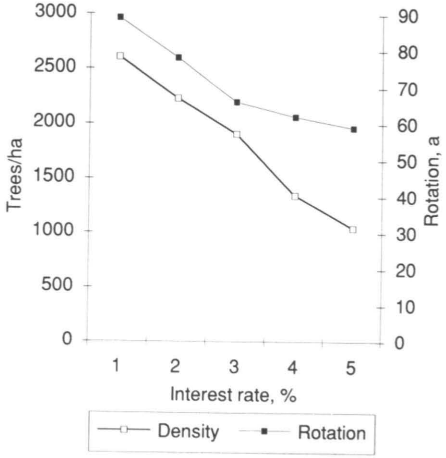

Fig. 11. Optimum initial density and rotation age of each solution in relation interest rate. Two thinnings with one thinning parameter are available.

4.4 Behavior of the optimization algorithm

The number of variables *N* in the problem of optimizing thinnings and rotation is given by $N = 1 + nt * (1 + np)$, where *nt* is the number of thinnings and *np* is the number of thinning parameters. The larger the number of variables, the slower the convergence to an optimum solution. The performance of the algorithm in optimizing stand management is shown in Fig. 12 for three different optimization problems: no thinnings (rotation length only), one thinning defined by three parameters, and two thinnings defined by three parameters. The number of variables to be optimized is 1, 5, and 9, respectively. Contrary to Fig. 4, Fig. 12 shows only the pattern search moves; the points generated by exploratory searches are not plotted.

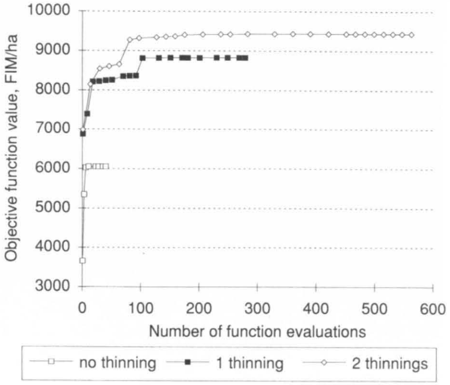

Fig. 12. Convergence of Hooke and Jeeves' algorithm in three optimization problems involving 1, 5, and 9 variables.

The experience of the author has been that the time variables (times between cuttings) are much more time-consuming to optimize than the variables for thinning intensities. This can be seen in Figs. 13 and 14 which are based on the growth models by Mielikäinen (1985). The thinning parameters produce smooth response surfaces (Fig. 13) whereas the time variables (times between cuttings) create less regular surfaces (Fig 14). When the stand is subject to excess mortality, the surfaces become very uneven. This phenomenon is starting to show up in Fig. 13 when both thinning percentages are close to zero and the growing stock of the unthinned stand exceeds the self-thinning limit.

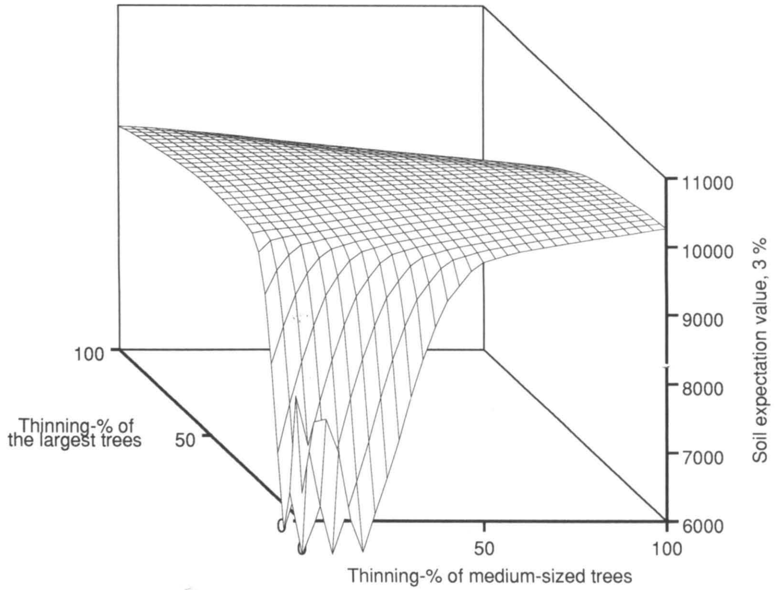

Fig. 13. Response surface generated by two thinning intensity variables around the optimum solution for maximizing 3 % soil expectation value; one thinning defined by 3 parameters in the regime; growth models by Mielikäinen (1985).

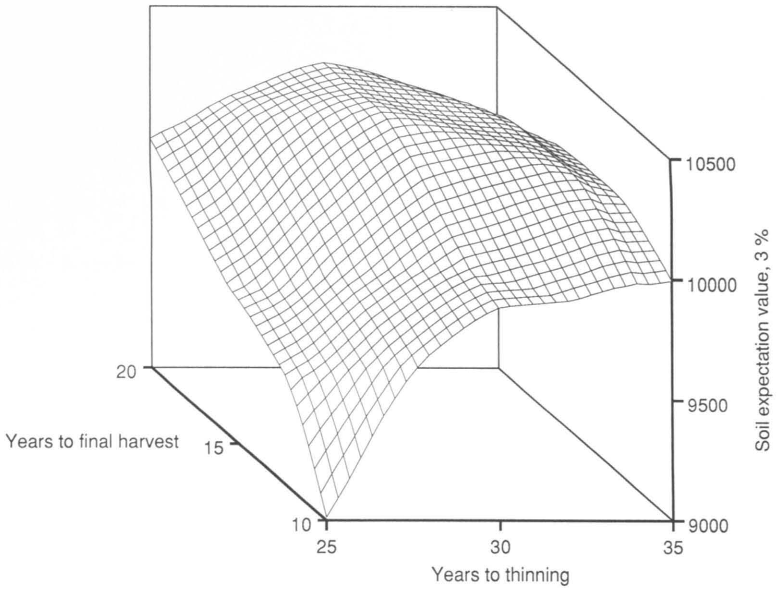

Fig. 14. Response surface generated by two time variables around the optimum solution for maximizing 3 % soil expectation value; one thinning defined by 3 parameters in the regime; growth models by Mielikäinen (1985).

The most important idea behind the approach of defining thinnings for optimization is to allow flexibility in the number of parameters required to describe thinning type. This number should be large enough so that thinning type can vary adequately. On the other hand, computational load suggests a minimum number of parameters. A reasonable compromise was found by number three, which has been used in the analyses reported. Fig. 15 illustrates the effect of the number of thinning parameters in a one thinning regime when maximizing 3 % soil expectation value. The maximum value, 12, assigns a thinning parameter for each diameter class (when the number of parameters equals the number of diameter classes, thinning rates are no longer a function of diameter, instead, the model uses separate thinning rates for each diameter class in the order of increasing diameters). Basically, the smallest and largest diameters are harvested, except that the two smallest classes are left because they have no commercial value at the age of thinning. The thinning defined by two points is already from above, a fact that is seen clearly in the case of 5 or 12 points. In this example, three points gives a reasonable approximation of the more accurate solution. The objective function values for the solutions based on 12, 5, 3, and 2 thinnings are, 10384, 10201, 10009, and 9646 FIM/ha, respectively, and in percentage, 100, 98, 96, and 93.

The two growth model sets used in this study, based on Ojansuu et al. (1991) and Mielikäinen (1985), turned out to be unequal tasks for the optimization algorithm. The data for comparison were produced by five replications of optimization runs starting from different random initial solutions. Four problem set-ups, i.e., combinations of the numbers of thinnings and thinning parameters, corresponding to different numbers of variables to be optimized, were formed. The standard deviations of objective function values were computed for each problem set-up. The standard deviations for solutions obtained using the MELA model (Ojansuu et al. 1991) were larger than those based on growth models

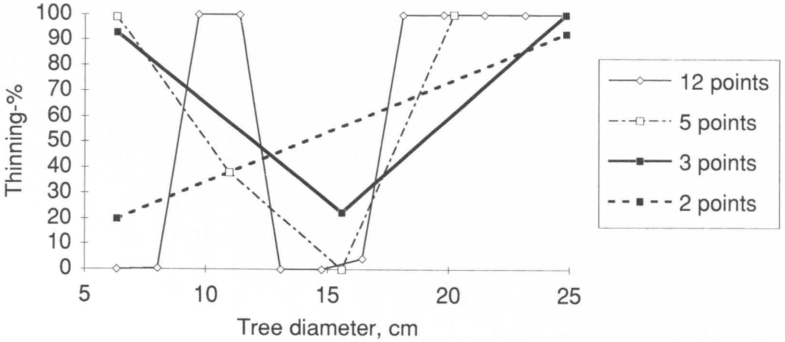

Fig. 15. The effect of thinning specification on the optimum thinning pattern in one-thinning regimes with the objective of maximizing 3 % soil expectation value.

by Mielikäinen (1985) (Fig. 16). The relations in the MELA growth models produced less smooth surfaces which caused more differences between the solutions that were reported as optimal in repeated optimization runs.

Fig. 17 shows the MELA model in a situation parallel to that of Fig. 14. For example, the sharp ridge located at time to thinning equal to 25 years is somewhat problematic for the optimization algorithm. Note that the thinning intensity variables change the location and shape of the ridge and they are optimized simultaneously.

Another feature of the MELA models that showed up in the response surfaces is that the diameter growth models have the maximum diameter of the stand as an independent variable. A decrease in that variable increases growth. When the diameter class with greatest trees is completely removed, the remaining trees get a growth boost. This creates a jump in the objective function value right at the edge of the feasible region of thinning intensity variables.

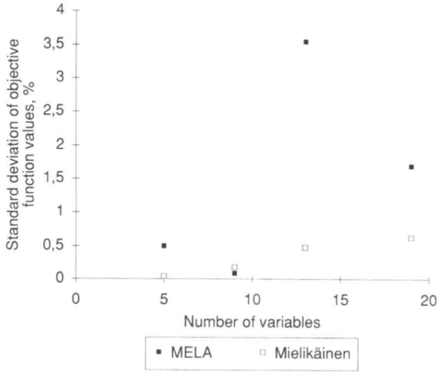

Fig. 16. Effect of the number of variables to be optimized on the variability of objective function values, based on repeated optimizations of two different growth simulators.

5 Discussion

The purpose of presenting numerical results on optimum thinning regimes in this report is to show the capabilities of the optimization model. Because many of the models for stand development in this study are not completely satisfactory and the biological data are limited in many respects, the results should be considered to be demonstrational rather than normative. The general trends shown may be taken as hypotheses for further studies or for consideration by practitioners. Most of the optimum results reported by this study are based on maximizing soil expectation value.

Finnish organizations for private forestry (Central Forestry Boards "Tapio" and "Skogskultur") have designed guidelines for profitable thinning practices. The goals behind these recommendations have not been stated explicitly (Tapion taskukirja 1991). In a study based on permanent plot measurements (Valsta 1982), it was found that the treatment closest to guidelines was most profitable with 2–3 % interest rate. However, there were only four alternative treatments in the permanent plots, none of which correspons to the optimum solutions found in the present study. Compared to the guidelines (Tapion taskukirja 1991), the optimum thinning regimes of the present study involve higher growing stock levels, especially during the first two thirds of the rotation, and heavier thinnings (Fig. 18). The first thinning is scheduled more than 10 years later than in the guidelines. The 3 % soil expectation value resulting from the guidelines (8 142 FIM/ha) was 23 % lower than the optimum soil expectation value (10 575 FIM/ha).

Thinnings that are late, heavy, or from above may expose the stand to windfall or snow break. The simulation model used in the present study did not include this risk. If models are available, such factors could be taken into account, but best within a stochastic optimization model (e.g., Valsta 1992).

A recent Finnish project studied the economics of thinning at stand, forest, and national level (Harvennushakkuiden ... 1992). Based on inventory data and the MELA simulator (Ojan-

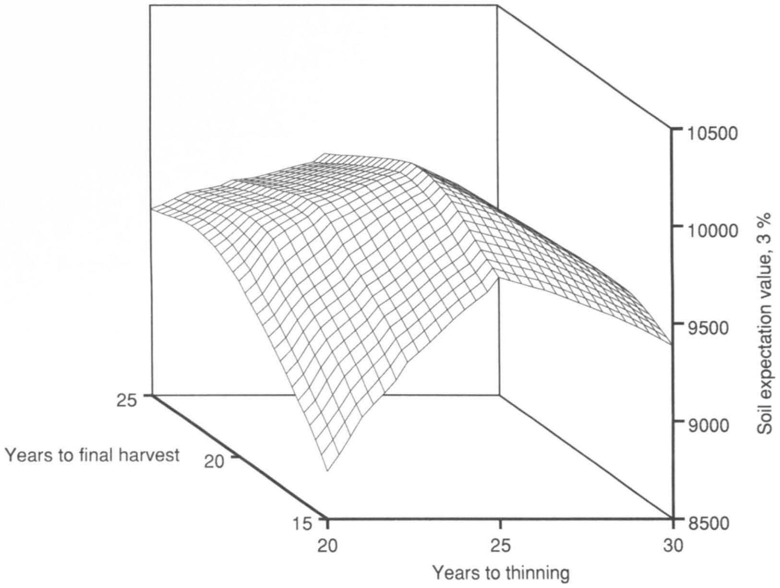

Fig. 17. Response surface generated by two time variables around the optimum solution for maximizing 3 % soil expectation value; one thinning defined by 3 parameters in the regime; growth models by Ojansuu et al. (1991).

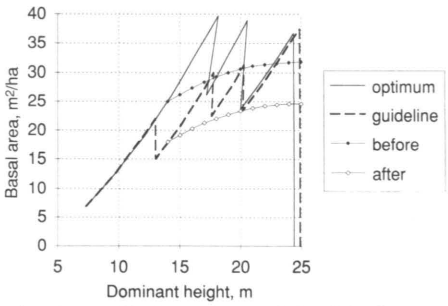

Fig. 18. Two-thinning optimum solution (3 % discount rate) compared to the solution based on the guidelines of Central Forestry Board Tapio. The curves "before" and "after" are the recommended basal areas before and after thinning, respectively.

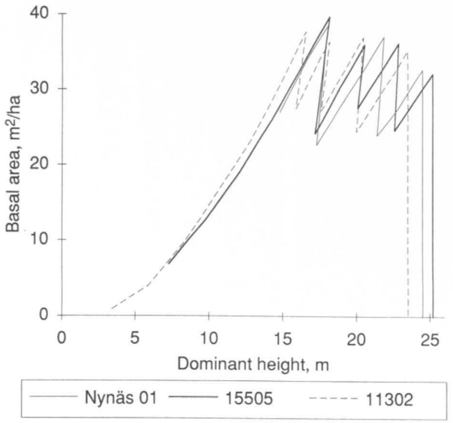

Fig. 19. Optimum thinning programs for three initial stands.

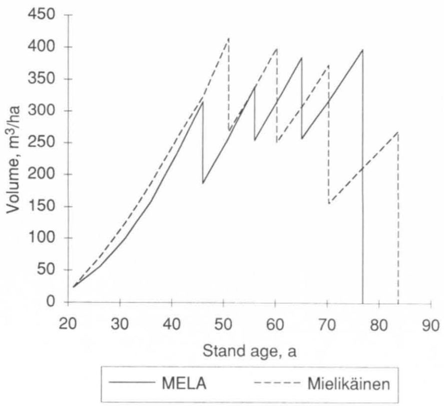

Fig. 20. Volume development in optimum solutions by two individual-tree growth simulators.

suu et al. 1991), the project reported thinning guidelines. The guidelines included in the 1992 report concern a less fertile site than the plot data of this study. The results are therefore only partially comparable.

The optimum thinning program of the present study had higher growing stock levels and the thinnings were scheduled later, compared to the 1992 report (Harvennushakkuiden... 1992). As a result, the average diameter at final harvest was only 20–22 cm in the present study. Also, there was no sawlog price premium on diameter and only logging costs depended on tree size. Thus, there was no incentive to enhance diameter growth. Tree volumes were already large enough from the logging cost point of view at 20–22 cm d.b.h., because the trees were about 22 m tall. The optimum rotation length was about the same in the two studies.

Optimum thinning programs stemming from three different plot data are shown in Fig. 19. The plots represent approximately the same site quality, $H_{100} = 28–29$. The undisturbed development of the stands (based on the MELA growth model) was quite similar in terms of basal area and dominant height. The optimum thinning programs exhibited a common ground: the first thinning is performed when the basal area is 37–40 m²/ha. Later, thinnings are done at somewhat lower basal areas. The thinnings were heavier for the plot "Nynäs 01" as the optimum program contains only two thinnings. Thinning was from above in all cases.

The optimum solutions produced by the two growth simulators of this study were similar in terms of the number of thinnings and thinning type (Fig. 20). On the other hand, the optimum rotation differed by 7 years and the growing stock levels after thinning behave dissimilarly. The last thinning in the solution for Mielikäinen's (1985) growth models was unrealistically heavy, 58 % of volume. This solution indicates the absence of history variables in the growth and mortality models.

Considering the same tree species and similar growing conditions, the optimization study by Solberg & Haight (1991) comes closest to the present study in terms of comparability. In their study, the optimum number of thinnings varied between 2 and 4. The optimum thinning type was always thinning from above and "the thinnings are made at a relatively high age". These results are very similar to those of the present study.

According to Solberg & Haight (1991), the optimum planting density decreased strongly with increasing interest rate (from 2900 to 1050 with interest rate from 2 to 4 %, respectively). The present study shows somewhat smaller change for the same interest rates, from 2230 to 1349. The optimum rotation decreased from 90 to 70 years while the change in the present study is from 78 to 62 years. Although the numerical values differ, the overall results are quite comparable.

There could be many desirable improvements to the present optimization model. The most important ones concern the stand growth simulator: its biological realism is deficient in several respects. Areas of major simulator development include: (1) a history variable, such as crown ratio, that would carry on the past growing conditions especially when dense stands are thinned relatively late; (2) more reliable growth predictions for trees in lower crown classes; (3) models for relating regeneration investment to early stand development. Also, the results presented here concern limited data in terms of costs and prices, site quality, and initial stand structure. Recommendations to practitioners should be based on a much wider set of analyses.

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Total of 39 references

Appendix 1. Forms of the equations of the simulators.

List of symbols:

e = base of the natural logarithm
k, m, β_i = parameters
BA = stand basal area
ba = tree basal area
BA_{above} = basal area sum of trees larger than the subject tree
ba_{max} = basal area of the largest tree in the plot
cr = live crown ratio, %
d = tree d.b.h.
D_{ba} = basal area weighted average stand d.b.h.
h = tree height
H_{100} = site index (dominant height at 100 years)
H_{dom} = dominant height of stand (average height of the 100 thickest trees/ha)
i_{ba} = tree basal area growth in the coming 5-year period
i_d = tree d.b.h. growth in the coming 5-year period
$i_{d_{ref}}$ = tree d.b.h. reference growth in the coming 5-year period (a tabulated function of d and BA)
i_h = tree height growth in the coming 5-year period
LC_{FH} = final harvest logging cost per cubic meter
LC_{TH} = thinning logging cost per cubic meter
ln = natural logarithm
N = number of trees per hectare
P = probability of death in the coming 5-year period, fraction
t = tree age at breast height
TS = temperature sum (day degrees)
v_{tot} = total volume cut per hectare
$\overline{v}$ = average tree volume in a cutting

1. The MELA growth models (Ojansuu et al. 1991)

Tree diameter increment (Eqn. 4.6.1a):

$$i_d = \beta_0 (1 + \beta_1 TS)^{\beta_2} (i_{d_{ref}} t^{\beta_3} + \beta_4 d) \tag{A.1}$$

Tree height (Eqns. 4.7.1 and 4.7.2):

$$h = \beta_0 (\beta_1 + TS)^{\beta_2} (ba / ba_{max})^{\beta_3} (1 - e^{-kt})^{\frac{1}{1-m}} \tag{A.2}$$

2. Growth models by Mielikäinen (1985)

Tree basal area increment (Eqn. 42):

$$i_{ba} = \beta_0 d^{\beta_1} t^{\beta_2} BA^{\beta_3} H_{100}{}^{\beta_4} (h / H_{dom})^{\beta_5} \tag{A.3}$$

Tree height increment (Eqns. 55 and 56):

$$i_h = \beta_0 h^{\beta_1} H_{100}{}^{\beta_2} (h / H_{dom})^{\beta_3} \tag{A.4}$$

Tree live crown ratio (Eqn. 17)[1]:

$$cr = \beta_0 d^{\beta_1} t^{\beta_2} e^{\beta_3 (h/d)} BA^{\beta_4} \tag{A.5}$$

Ad hoc model for large basal areas:

$$cr = \begin{cases} cr & \text{if } BA < 40 \\ cr\left(1 - \left(\dfrac{BA-40}{20}\right)^2\right) & \text{if } 40 < BA < 60 \end{cases} \tag{A.6}$$

3. Mortality models (used by both simulators)

Tree mortality (Ojansuu et al. 1991):

$$P = \frac{1}{1 + e^{\beta_0 + \beta_1 d + \beta_2 BA + \beta_3 BA_{above}}} \tag{A.7}$$

Stand self-thinning curve (Hynynen 1991):

$$\ln D_{ba} = \beta_0 + \beta_1 \ln H_{100} + \beta_2 \ln H_{100} \ln N \tag{A.8}$$

Ad hoc model for small crown ratios:

$$P = \begin{cases} P & \text{if } cr > 30 \\ \max\left[P, \left(\dfrac{30-cr}{10}\right)^2\right] & \text{if } 20 < cr < 30 \end{cases} \tag{A.9}$$

4. Logging cost models (Valsta 1992):

Logging costs in thinning:

$$\begin{aligned} \ln LC_{TH} = {} & 5.410 - .05217 \ln \overline{v} + .02429 (\ln \overline{v})^2 \\ & - .4451 \ln v_{tot} + .03969 (\ln v_{tot})^2 \end{aligned} \tag{A.10}$$

Logging costs in final harvest:

$$\begin{aligned} \ln LC_{FH} = {} & 5.230 - .05976 \ln \overline{v} + .02076 (\ln \overline{v})^2 \\ & - .3840 \ln v_{tot} + .03273 (\ln v_{tot})^2 \end{aligned} \tag{A.11}$$

---

[1] The original equation includes the variable 'birch-% of basal area'. It was assumed constant (21.0, the minimum of the range of the original data) and its effect is included in parameter β_0.

Appendix 2. Plot data.

Table 1. Diameter distribution of plot 11302.

Diam. class no.	D.b.h. (cm)	Height (m)	Trees/ha
1	1.0	1.7	320
2	1.0	1.7	320
3	2.0	2.0	488
4	2.0	2.5	488
5	3.0	2.6	216
6	3.0	2.7	216
7	4.0	3.1	72
8	4.0	3.4	72
9	5.0	3.6	16

Table 2. Diameter distribution of plot 15505.

Diam. class no.	D.b.h. (cm)	Height (m)	Trees/ha
1	1.0	1.5	27
2	2.0	1.7	80
3	3.0	2.5	133
4	4.0	3.3	173
5	5.0	4.6	320
6	6.0	5.3	373
7	7.0	6.5	440
8	8.0	6.3	240
9	9.0	6.6	133
10	10.0	7.3	93
11	11.0	7.0	13
12	12.0	7.6	13

Table 3. Diameter distribution of plot Nynäs1/01.

Diam. class no.	D.b.h. (cm)	Height (m)	Trees/ha
1	3.7	4.3	50
2	6.0	6.7	30
3	8.1	8.8	120
4	10.2	10.6	220
5	12.0	11.9	430
6	14.0	13.0	440
7	15.9	13.9	430
8	17.6	14.6	140
9	19.3	15.2	30

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