

ACTA FORESTALIA FENNICA

Vol. 102, 1969

Determination of the optimum cutting policy for the forest stand by means of dynamic programming

Metsikön optimihakkuuohjelman määrittäminen dynaamisen ohjelmoinnin avulla

Pekka Kilkki and Unto Väisänen



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Tilaukset ja julkaisuja koskevat tiedustelut osoitetaan Seuran kirjastolle, Unioninkatu 40 B, Helsinki 17.

Publications of the Society of Forestry in Finland

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DETERMINATION OF THE OPTIMUM CUTTING POLICY FOR THE FOREST STAND BY MEANS OF DYNAMIC PROGRAMMING

METSİKÖN OPTIMIHAKKUUOHJELMAN MÄÄRITTÄMINEN DYNAAMISEN OHJELMOINNIN AVULLA

PEKKA KILKKI and UNTO VÄISÄNEN

HELSINKI 1970

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Seloste: Metsikön optimihakkuuohjelman määrittäminen dynaamisen ohjelmoinnin avulla.

1. INTRODUCTION

For many years, determination of the optimum cutting policy for a forest stand has interested forest scientists. In the main, the aim of economically oriented approaches to this problem has been that of finding the cutting policy that maximises the net present value of future revenues. Naturally enough, this aim has led to the application of marginal analysis, in determination of both the rotation and density of the growing stock (cf. DUERR and BOND 1952; NYSSÖNEN 1958; CHAPPELLE and NELSON 1964; BENTLEY and TEEGUARDEN 1965; KILKKI 1968 a).

However, marginal analysis has a definite drawback. Only the static optimum based upon the stand characteristics can be found, but not the route to be followed from a non-optimal situation to the optimum. For as long as logging was done manually, this problem did not assume any great importance. It paid to have even very light thinnings, and to have thinnings even only a few years before clear cutting. Consequently, the static optimum density and the fixed rotation were quite adequate guidelines for the treatment of a stand. Today, the mechanisation of forest work has radically changed the situation. Large machines call for large felling quantities, as otherwise the costs involved are too high. There thus exists permanent conflict between the requirement of preserving the static optimum, and that of reducing logging costs. This situation has led some forest scientists into a search for new methods in determining the optimum cutting programs for forest stands.

Dynamic programming (cf. HILLIER and LIEBERMAN 1968) gives the optimal routes to be followed, instead of certain static optima given by marginal analysis. Originally, dynamic programming was developed for transport problems. It is consequently quite natural that it has been applied to the technological problems of forestry (cf. VÄISÄNEN 1967). Nevertheless, it has been found that dynamic programming is also useful in optimisation of the cutting policies for forest stands. BRUN MADSEN (1964) has applied the method in determination of the optimum

density and rotation. AMIDON and AKIN (1968) have used dynamic programming for determination of the optimum density, and RISVAND (1969) has used it for determination of the optimum cutting policies. In view of the divergent circumstances in different countries, results obtained elsewhere are not directly applicable in Finland. Nonetheless, there remain several open questions which justify further studies of the applications of dynamic programming to forest stand cutting policy.

This study is aimed at discovery of the cutting program for a forest stand which maximises the net present value of future income from the stand. The income from the stand comprises the revenues from thinnings and clear cutting, and income from the tree generations which follow the first clear cutting.

Dynamic programming is applied in determination of the optimum cutting policy. It is then assumed that the development of the stand at a certain age depends only upon the stand characteristics at that moment. If this assumption is not sufficiently valid, dynamic programming is not an applicable tool in solving problems of this type.

There are five main questions to be answered in this study:

1. What is the influence of the rate of interest upon the cutting program?
2. Are there any differences in the cutting programs in regard to whether thinning from below or thinning from above is applied?
3. Which is more profitable, thinning from below, or thinning from above?
4. What is the influence of the logging costs upon the cutting programs? Logging costs in 1969, and the estimated logging costs in 1979 are compared.
5. What are the losses if the optimum cutting programs are not followed?

Calculations are made for even-aged Scotch Pine stands, aged from 50 to 100 years, in Southern Finland. The site is VT, in which the average growth is about 4 cu.m./ha/year excluding bark. Accordingly, the answers given here to the five questions stated above must strictly be limited to stands similar to these.

2. DEVELOPMENT OF THE GROWING STOCK, AND REVENUE FROM THE CUTS

It is assumed that the volume growth of the stands follows a volume growth function calculated for Scotch Pine stands by KUUSSELA and KILKKI (1963, p. 27). The function takes the following form:

$$I_v = 11.38 t^{-1.230} 10^{-0.001309 v} v$$

where

I_v = current volume growth, cu.m./ha/year

t = age, years

v = volume, cu.m./ha

The volumes used in the function are expressed as solid measure excluding bark. By application of the percentages given by NYSSÖNEN (1965, p. 179) and the stem distribution series presented by VUOKILA (1967, p. 112), bark percentages were obtained for stands of different ages. These percentages were employed for transformation of the volumes into volumes including bark. All the volumes indicated later in this work include bark.

It is assumed that the structure of growing stock and removals is the same as that in VUOKILA's (1967) pine stands on site class III with medium treatment. Interpolation was used to arrive at the stem distribution series in five year intervals.

The value of the individual stem was calculated by means of the principles and value relationships presented by VÄSTERBO (1967), HEISKANEN (1968), and TUOVINEN (1968). The price of pine pulpwood by the long-distance transport route is assumed to be 20.00 Fmk per piled cu.m., and that of 7 inch sawlog 1.80 Fmk per cu.f. top. The relationship between sawlog size and value was calculated in accordance with the real milling values of timber, and not from the market price.

The values of growing stock and removals were arrived at by multiplication of the tree values by stem distribution series in each age class. The values of the growing stock before and after thinning were thus obtained. Straight lines passing through these two points provide an estimate of the relationship between the volume of the growing stock and its unit value when thinning from below is employed. These lines are indicated in figure 1. For the calculations, the lines were expressed in algebraic form. For

example, in the age class of 75 years the value function of growing stock is as follows:

$$y = 37.55 - 0.01260 x,$$

where

y = value of growing stock, Fmk/cu.m.

x = volume of growing stock, cu.m./ha

In the calculations concerned with thinning from below, the value of growing stock before and after thinning was calculated; the difference between these represents the value of the removal. For instance, if the volume at the age of 75 years is 200 cu.m./ha and the removal 60 cu.m./ha, the value of removal is:

$$200 \cdot (37.55 - 0.01260 \cdot 200) - 140 \cdot (37.55 - 0.01260 \cdot 140) = 7132.00 - 5010.60 = 2121.40 \text{ Fmk}$$

In thinnings from above, the value of the growing stock is assumed to be independent of the density; thus the value of the removal is the same as the value of the growing stock, and does not change with alteration in the removal volume. The unit values of the growing stock when thinning from above is applied correspond to the unit values of the growing stock of 150 cu.m./ha in figure 1.

The logging costs comprise the preparation and forwarding costs of pulpwood about 3 metres in length, and normal length sawlogs. In both cases, bucking is done without log-length measurement, and limbing is done roughly with a chain saw. The hauling distance in forwarding is 150 metres. In clear cuttings, tree length skidding and bucking at the landing are employed in cases where it is more profitable than the short wood method.

The costs of preparation and the primary transport were calculated for each tree size class in accordance with the tariffs of wage tables. The logging cost of each stand was calculated by multiplication of the costs by stem distribution series. The logging costs in 1969 are presented as a function of the value and amount of removal in tables 1 and 2.

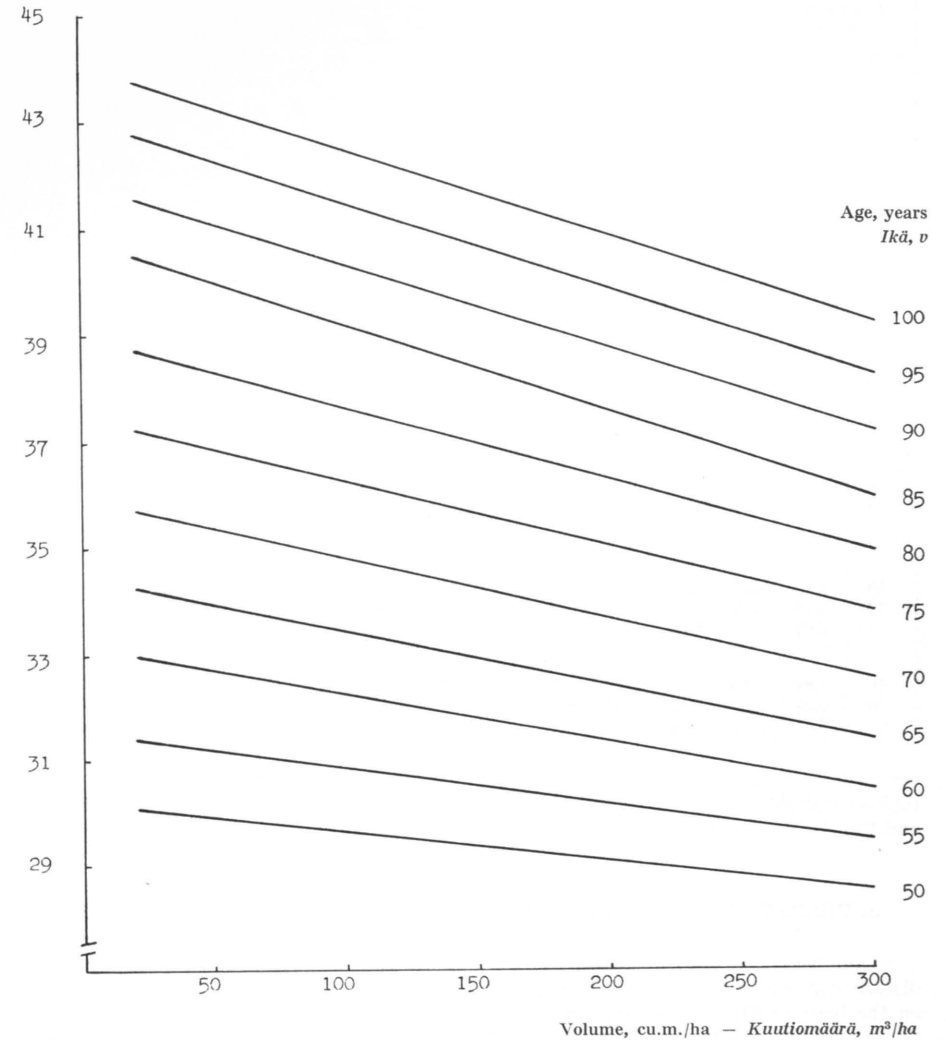
The logging costs in 1979 were calculated in the same way as those for 1969. It is supposed that the logging costs in final cuttings of the old stands will not rise from the present level, or if they do rise, the timber prices will

Figure 1. Unit value of the growing stock as a function of age and volume.

Kuva 1. Puuston arvon riippuvuus iästä ja kuutiomäärästä.

Value of growing stock, Fmk/cu.m.

Puuston arvo, mk/m³



rise to the same extent. This requires completely mechanised logging in 1979. In young thinning stands it is probable that mechanisation will not make any rapid advances. It

is supposed that the manual shortwood method will be applied in 1979, and primary transport done by the forwarder. It is taken that the costs of this method will rise by 4 per

Table 1. Relationship between thinning costs and the values of removals and volume to be cut.
Taulukko 1. Harvennushakkuukustannusten riippuvuus poistuman arvosta ja leimikon tiheydestä.

Volume, cu.m./ha Kuutiomäärä, m ³ /ha	Value of removals, Fmk/cu.m. — Poistuman arvo, mk/m ³								
	28	29	30	31	32	33	34	35	
	Costs, Fmk/cu.m. — Kustannukset, mk/m ³								
	Year 1969 — Vuosi 1969								
10	10.44	9.57	9.20	8.92	8.69	8.51	8.33	8.19	
30	8.75	7.88	7.51	7.23	7.00	6.82	6.64	6.50	
50	8.29	7.42	7.05	6.77	6.54	6.36	6.18	6.04	
70	8.02	7.15	6.78	6.50	6.27	6.09	5.91	5.77	
90 +	7.88	7.01	6.64	6.36	6.13	5.95	5.77	5.63	
	Year 1979 — Vuosi 1979								
10	15.50	14.31	13.60	12.92	12.43	12.00	11.62	11.32	
30	13.50	12.31	11.60	10.92	10.43	10.00	9.62	9.32	
50	12.50	11.31	10.60	9.92	9.43	9.00	8.62	8.32	
70	11.90	10.71	10.00	9.32	8.83	8.40	8.02	7.72	
90 +	11.50	10.31	9.60	8.92	8.43	8.00	7.62	7.32	

Table 2. Relationship between clear cutting costs and the values of removals and volume to be cut.
Taulukko 2. Paljaasihakkuukustannusten riippuvuus poistuman arvosta ja leimikon tiheydestä.

Volume, cu.m./ha Kuutiomäärä, m ³ /ha	Value of removals, Fmk/cu.m. — Poistuman arvo, mk/m ³												
	29	30	31	32	33	34	35	36	37	38	39	40	41
	Costs, Fmk/cu.m. — Kustannukset, mk/m ³												
	Year 1969 — Vuosi 1969												
50	7.42	7.05	6.77	6.54	6.36	6.18	6.04	5.86	5.60	5.35	5.12	4.89	4.69
70	7.15	6.78	6.50	6.27	6.09	5.91	5.77	5.67	5.47	5.22	4.99	4.76	4.56
90 +	7.01	6.64	6.36	6.13	5.95	5.77	5.63	5.49	5.23	4.98	4.75	4.52	4.32
	Year 1979 — Vuosi 1979												
50	9.81	9.10	8.42	7.93	7.50	7.12	6.82	6.53	6.25	5.98	5.75	5.52	5.32
70	9.21	8.50	7.82	7.33	6.90	6.52	6.22	5.93	5.65	5.38	5.15	4.92	4.72
90 +	8.81	8.10	7.42	6.93	6.50	6.12	5.82	5.53	5.25	4.98	4.75	4.52	4.32

cent annually. In older stands, the opportunities available for mechanisation are better, and the rise in costs is not so great as 4 per

cent; in the most favourable cases, the costs will remain at the present level. The logging costs for 1979 are given in tables 1 and 2.

3. PREPARATION AND PRESENTATION OF THE CUTTING PROGRAMS

A number of series, describing the undisturbed growth of the stands, were prepared on the basis of the information included in the preceding section. Development of the volume of the stand in accordance with these growth series is given in figure 2. There are from 8 to 10 alternative growing stock levels at different ages. Every fifth year, it is possible to thin or to clear cut the stand. Thinning implies moving downward to a series

which corresponds to a lower level of growing stock, and clear cutting moving downward to level 11.

The value and cost figures given in the previous section enable calculation of the net income yielded by each alternative cut. When clear cutting is involved, the net present value of the future income from the land area, or the soil value, is added to the harvesting revenue. The figures given by KILKKI

Figure 2. Possibilities for development of the volume of the forest stand.

Kuva 2. Metsikön kuutiomäärän kehitysvaihtoehdot.

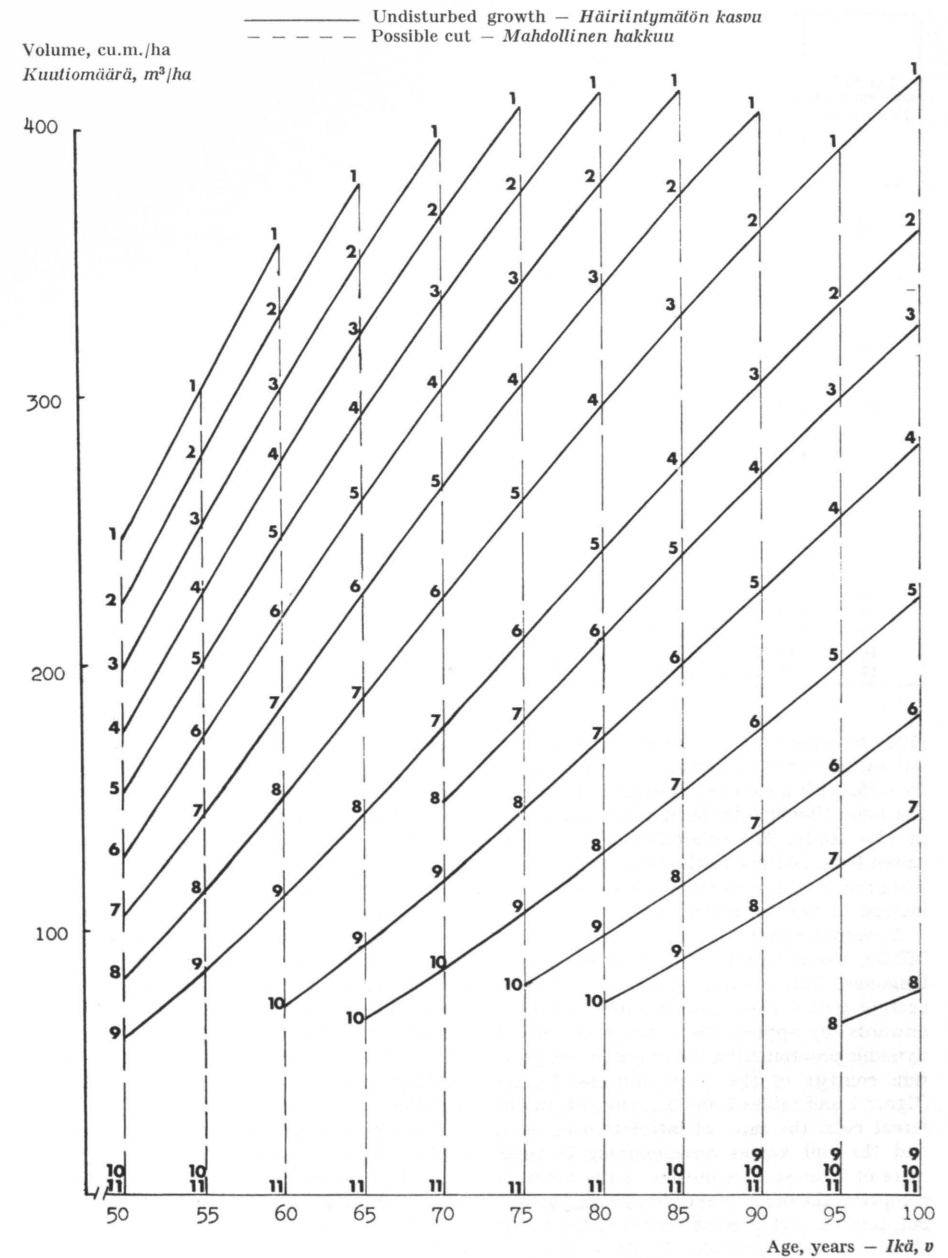


Table 3. Optimum cutting program matrices. Instructions are given in the text.
Taulukko 3. Metsikön optimihakkuuohjelmia kuvaavat matriisit. Matriisien käyttöohje tekstissä.

Level of growing stock Puuston taso	Logging costs in 1969 — Vuoden 1969 korjuukustannukset																					
	Rate of interest 2 per cent Korko 2 %										Rate of interest 4 per cent Korko 4 %											
	Age, years — Ikä, v																					
	50	55	60	65	70	75	80	85	90	95	100	50	55	60	65	70	75	80	85	90	95	100
	Thinning from below — Alaharvennus																					
1	4	5	7	7	7	6	7	6	6	6	11	5	8	9	9	9	9	9	11	11	11	11
2	2	6	7	6	6	6	7	6	6	11	11	5	8	8	9	9	9	9	11	11	11	11
3	3	6	7	6	7	6	7	6	5	11	11	7	8	8	9	9	9	9	8	11	11	11
4	4	4	6	6	7	6	7	6	5	11	11	4	8	8	9	9	9	9	11	11	11	11
5	5	5	7	6	6	6	7	6	6	11	11	5	8	8	9	9	9	9	11	11	11	11
6	6	6	5	5	7	5	7	7	5	11	11	6	8	8	9	8	9	9	11	11	11	11
7	7	7	6	6	6	6	6	6	11	11	7	7	9	9	9	9	9	11	11	11	11	
8	8	8	7	7	7	7	7	7	11	11	8	8	7	9	9	9	9	11	11	11	11	
9	9	9	8	9	8	8	8	8	11	11	9	9	8	9	8	8	8	8	11	11	11	
10	11	11	9	10	9	9	9	11	11	11	11	11	9	10	9	9	9	11	11	11		
11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11		
	Thinning from above — Yläharvennus																					
1	1	1	3	5	4	5	6	5	11	11	11	5	6	7	7	8	9	11	11	11	11	
2	2	2	4	5	4	5	6	5	3	11	11	6	6	7	7	8	9	11	11	11	11	
3	3	3	2	5	4	5	6	5	4	11	11	3	6	7	7	8	9	11	11	11	11	
4	4	4	3	5	5	5	6	5	3	11	11	4	7	7	7	8	9	11	11	11	11	
5	5	5	4	4	4	4	4	4	5	11	5	5	7	7	8	9	8	11	11	11		
6	6	6	5	5	5	5	5	5	6	11	6	6	8	9	8	9	8	11	11	11		
7	7	7	6	6	6	6	6	6	7	11	7	7	8	9	9	8	11	11	11			
8	8	8	7	7	7	7	7	7	11	11	8	8	7	7	7	9	7	11	11			
9	9	9	8	9	8	8	8	8	11	11	9	9	8	9	8	8	8	11	11			
10	11	11	9	10	9	9	9	11	11	11	11	11	9	10	9	9	9	11	11			
11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11			

Cont. Jatk.

(1968 b) were used as the basis for the soil values. However, the figures were multiplied by 1.75, with a view to inflating the figures to the same timber price level as that employed in this study. The reforestation costs were raised from 50 Fmk in the previous study to 400 Fmk here because planting is used today instead of natural regeneration.

A computer program was prepared for IBM 360/50, using FORTRAN IV programming language. This program finds the optimum cutting policy from each possible situation onwards, by application of the principles of dynamic programming. The input for the program consists of the value and cost figures (figure 1 and tables 1 and 2), removals in different cuts, the rates of interest to be used, and the soil values corresponding to these rates of interest. The output of the program comprises the net revenues from each possible cut, and the net present values of the forest stands in each possible situation. Thus, a

stand at a certain stage of development may have several values, dependent upon the course of action chosen for the next step. According to the principles of dynamic programming, the greatest of these values is selected as the basis in calculating the value of the stand five years earlier.

The most important part of the output of the computer program consists of matrices, of which the elements express the optimum cutting programs in all possible situations. The optimum cutting programs are calculated altogether for 30 possible combinations of the variables of which the influence upon cutting programs was to be analysed. The variables are as follows:

1. Logging costs (costs in 1969, predicted costs in 1979, and changing costs).
2. Thinning pattern (thinning from above and thinning from below).
3. Rate of interest (1, 2, 3, 4, and 5 per cent).

Table 3. Cont.
Taulukko 3. Jatk.

Level of growing stock Puuston taso	Logging costs in 1979 — Vuoden 1979 korjuukustannukset																				
	Rate of interest 2 per cent Korko 2 %										Rate of interest 4 per cent Korko 4 %										
	Age, years — Ikä, v.																				
	50	55	60	65	70	75	80	85	90	95	100	50	55	60	65	70	75	80	85	90	95
	Thinning from below — Alaharvennus																				
1	4	5	4	7	6	11	11	11	11	11	11	5	8	11	11	11	11	11	11	11	11
2	5	6	7	6	6	7	11	11	11	11	11	6	8	8	11	11	11	11	11	11	11
3	3	7	7	6	6	7	11	11	11	11	11	3	8	8	11	11	11	11	11	11	11
4	4	4	6	6	6	7	6	11	11	11	11	4	8	8	11	11	11	11	11	11	11
5	5	5	7	7	6	7	7	6	4	11	11	5	8	8	9	11	11	11	11	11	11
6	6	6	5	5	5	5	5	5	5	11	11	6	6	8	9	11	11	11	11	11	11
7	7	7	6	6	6	6	6	6	6	11	11	7	7	9	9	9	11	11	11	11	11
8	8	8	7	7	7	7	7	7	7	11	11	8	8	7	7	7	7	7	11	11	11
9	9	9	8	9	8	8	8	8	8	11	11	9	9	8	9	8	8	8	8	11	11
10	11	11	9	10	9	9	9	11	11	11	11	11	11	9	10	9	9	9	11	11	
11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	
	Thinning from above — Yläharvennus																				
1	1	1	4	4	4	4	5	11	11	11	11	1	5	7	11	11	11	11	11	11	
2	2	2	1	4	4	4	5	4	11	11	11	2	6	7	7	11	11	11	11	11	
3	3	3	2	2	5	4	5	4	2	11	11	3	6	7	7	11	11	11	11	11	
4	4	4	3	3	3	5	5	3	3	11	11	4	4	7	7	11	11	11	11	11	
5	5	5	4	4	4	4	4	4	5	11	5	5	7	7	8	11	11	11	11		
6	6	6	5	5	5	5	5	5	6	11	6	6	8	7	8	11	11	11	11		
7	7	7	6	6	6	6	6	6	7	11	7	7	6	9	6	6	11	11	11		
8	8	8	7	7	7	7	7	7	7	11	11	8	8	7	7	7	7	7	11	11	
9	9	9	8	9	8	8	8	8	8	11	11	9	9	8	9	8	8	8	11	11	
10	11	11	9	10	9	9	9	11	11	11	11	11	11	9	10	9	9	9	11	11	
11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11		

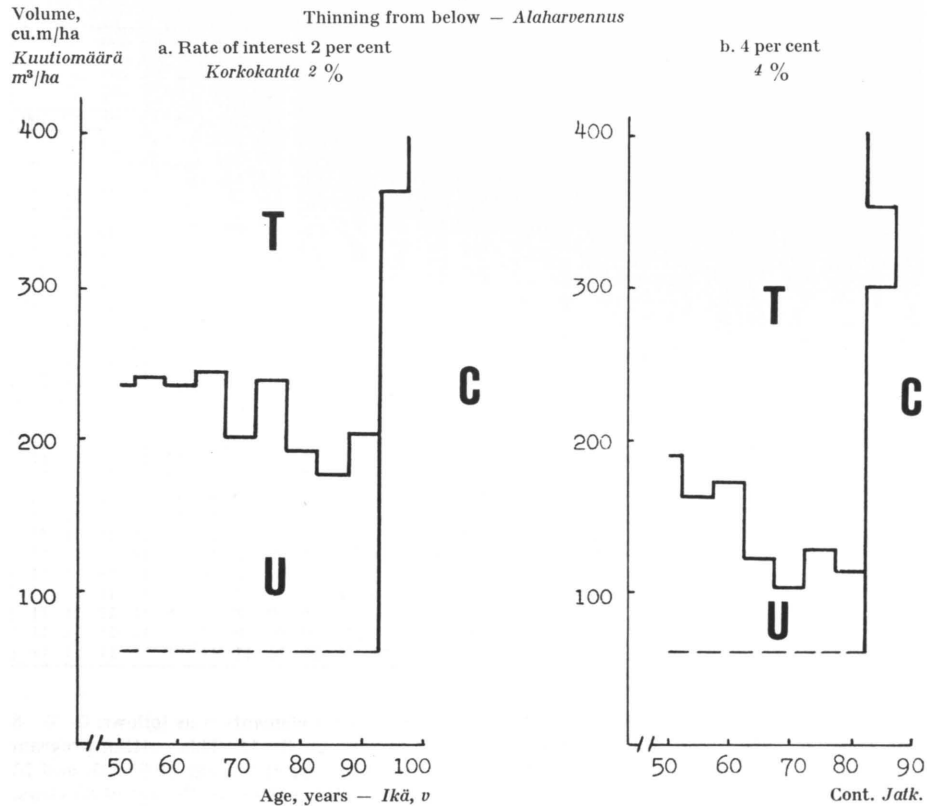
Examples of the cutting policy matrices are given in table 3. The growing stock levels are expressed by the numbers given in figure 2. A matrix element corresponding to a certain age and volume level expresses the volume level reached in five years if the optimal policy is followed. At this age a fresh matrix element is found, to show how the optimum policy continues. Element 11 indicates clear cutting.

To illustrate the use of the matrices in determination of the optimum cutting programs, two examples are taken. In both examples, the costs in 1969, thinning from below, and a rate of interest of 4 per cent are applied. First, it is assumed that the age of the stand is 50 years, and the volume is 129 cu.m./ha, which corresponds to volume level 6. The optimum cutting program expressed

by the matrix elements is as follows: 6—6—8—7—9—8—9—8—11. This cutting program implies thinning at the age of 55, 65, and 75 years and clear cutting at the age of 85 years. Development of the growing stock in conformity with this cutting program is given in figure 5 a.

In the second example, it is assumed that the age of the stand is 60 years, and the volume 185 cu.m./ha, which corresponds to volume level 7 at this age. The optimum cutting program is then as follows: 7—9—9—8—9—8—11. This program implies thinnings at the age of 60 and 75 years, and clear cutting at the age of 85 years. This cutting program meets that put forward in the previous example at the age of 65 years, and subsequently the two cutting programs are identical.

Figure 3. Limits between undisturbed growth (U), thinning (T), and clear cutting (C). 1969 logging costs.
 Kuva 3. Häiriintymättömän kasvun (U), harvennushakkuun (T) ja paljaasihakkuun (C) väliset rajat.
 Vuoden 1969 korjuukustannukset.



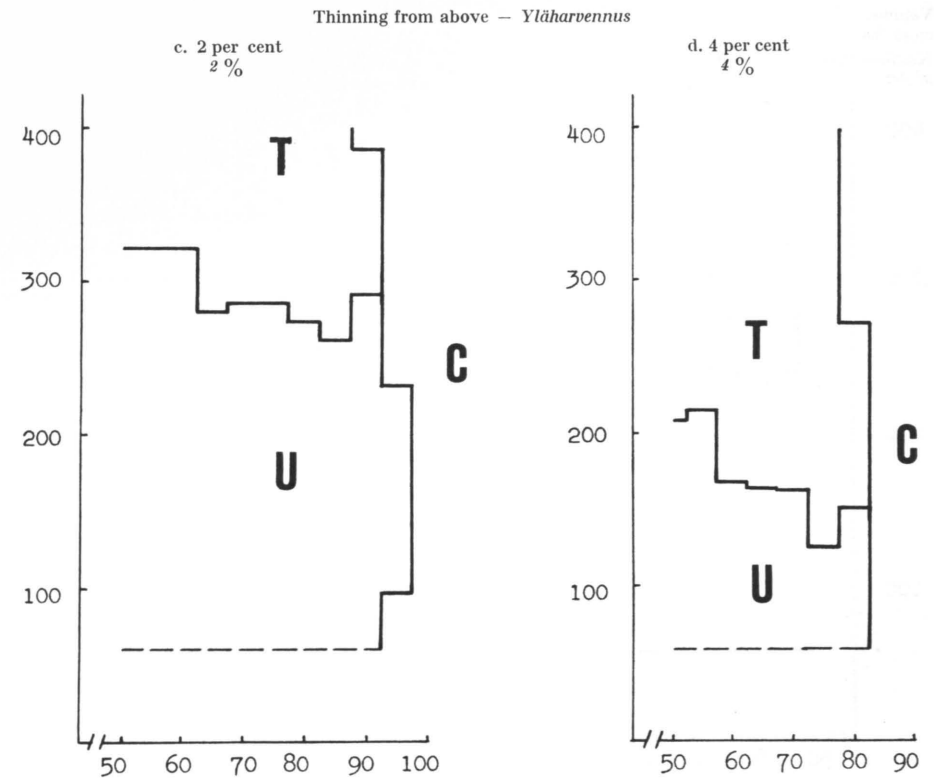
4. FACTORS AFFECTING THE OPTIMUM CUTTING PROGRAM

The limits between the stands to be thinned, clear cut, and left for future growth are presented in figures 3 and 4; these are based upon figure 2 and the matrices given in table 3. These figures do not indicate the amount of removal in the case of thinning. Figure 2 and the matrices in table 3 furnish an answer to this question. However, it must be noticed that the treatment limits are based upon the assumption that there may be a cut every fifth year, if necessary.

There are some special features in figures 3 and 4 which must be discussed before a more detailed analysis is begun. Except in the case of thinning from below, and applica-

tion of the logging costs in 1969, stands with high volumes are to be clear cut earlier than their more open counterparts. This phenomenon is quite easy to explain. The value growth percentage in stands of high volume is so low that undisturbed growth is no longer profitable. Nevertheless, thinning would stimulate the growth of the remaining growing stock, but this is unprofitable, since then a large proportion of the growing stock should be removed at costs appreciably higher than those of clear cutting. Consequently, thinning may be profitable if the removal is not very high. The proportion of the high cost thinning removal is then rela-

Figure 3. Cont.
 Kuva 3. Jatk.



tively small in comparison with the growing stock left for final cut.

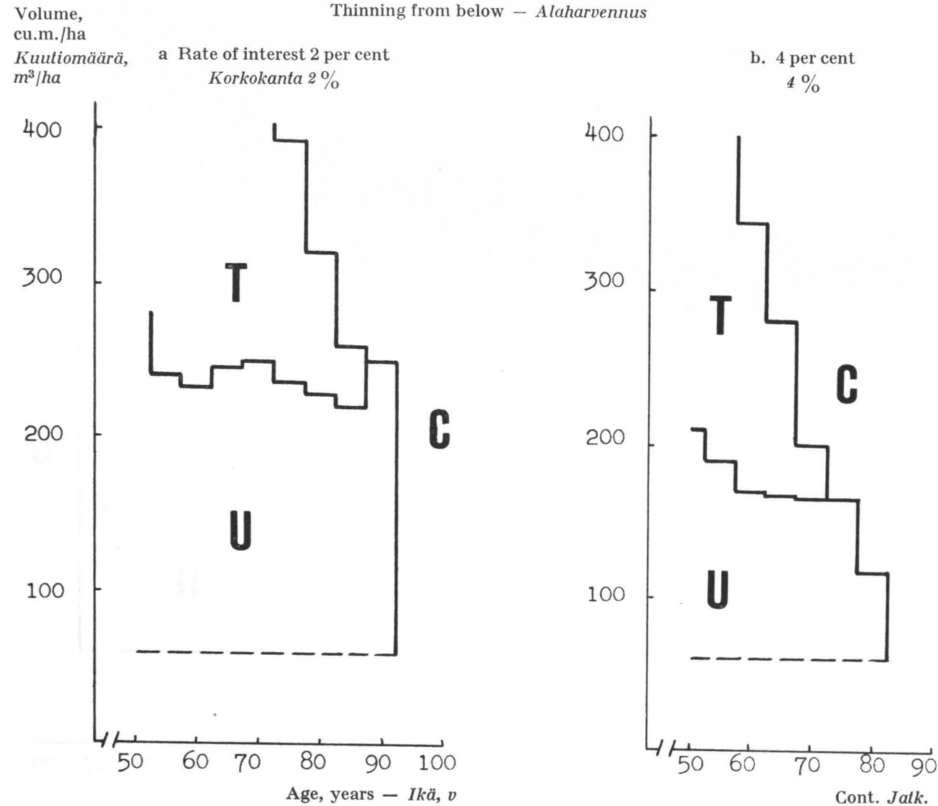
When rates of interest other than 2 and 4 per cent were employed, cases were found in which stands were to be clear cut by reason of too little thinning removal. The stand was then too dense for undisturbed growth, but too open for profitable thinning.

When the logging costs in 1969, and thinning from below are used, thinning seems to be profitable, even 5 years before clear cutting. There are in fact two cases in which a stand is thinned, even though a stand similar to this one should after this thinning be clear cut. Technically, these peculiarities are attributable to there being only one cutting operation possible every fifth year; consequently it is impracticable to clear cut

a stand that has just been thinned. Basically, the reasons for the phenomenon derive from the assumption made in regard to the linear relationship between the unit value and the volume of the growing stock (see p. 00). Evidently, this assumption is not quite realistic. Another reason may lie in the illogical nature of the wage tables.

When 2 per cent interest is applied, the limit between the stands to be grown further, and the stands to be clear cut, is 10–15 years higher than that with a rate of interest of 4 per cent. Generally, it seems that when thinning from below is applied, the difference is 10 years, and with thinning from above, 15 years. The difference may be even higher in the case of thinning from above, as the rotation may exceed 100 years when 2 per

Figure 4. Limits between undisturbed growth (U), thinning (T), and clear cutting (C). 1979 logging costs. Kuva 4. Häiriintymättömän kasvun (U), harvennushakkuun (T) ja paljaasihakkuun (C) väliset rajat. Vuoden 1979 korjuukustannukset.



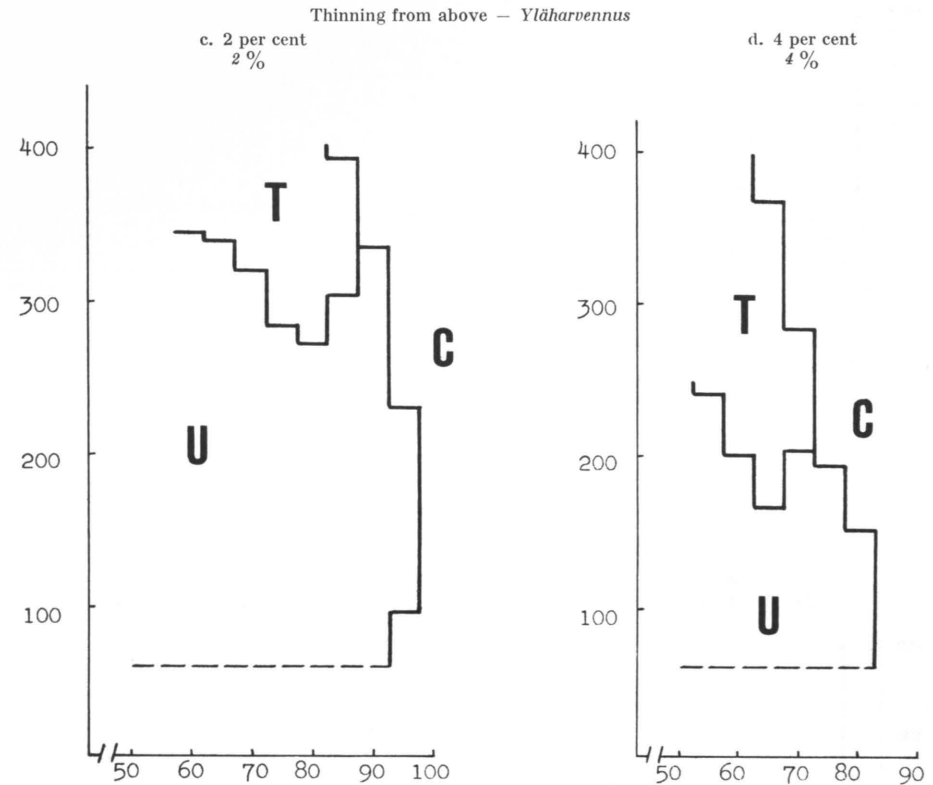
cent interest is applied. However, this assumption could not be confirmed, since 100 years was technically the maximum rotation. Consequently, the limit between the stands to be thinned, and those to be left for future growth, is 60–100 cu.m./ha higher with a rate of interest of 2 per cent applied. The difference is generally greater in the stands thinned from above than those thinned from below.

As an example of how the different logging costs, the starting level of growing stock, and the different cutting patterns influence the cutting program, a study is made of the optimum cutting programs for today's 50-year-old stands. Three logging cost possibilities are employed. First, it is assumed that

the costs remain unchanged at the level for the year 1969. In the second alternative, the costs are initially at the 1969 level, change in ten years to the 1979 level, and remain at that level subsequently. The third alternative implies that the costs permanently remain at the level for the year 1979.

The cutting programs corresponding to these three possible logging costs are given in figures 5 and 6. The figures indicate that there are only a few differences in the cutting programs when the cost possibilities 1 and 3 are used. However, the rotation is 5–10 years shorter when the costs for the year 1979 are employed, and the densities are a little higher; and higher density is just the reason for shorter rotations. The densities are also

Figure 4. Cont. Kuva 4. Jatk.



somewhat higher when thinning from above is applied, instead of thinning from below.

Cost possibility 2 differs clearly from both of the previous possibilities which imply constant costs. Heavy thinnings are made at the age of 50 or 55 years. As a result, no thinnings are effected at the age of 60 years. This phenomenon has a natural explanation. When the logging costs are at the 1979 level, the thinning costs are appreciably higher than in 1969. Consequently, thinnings are made, if possible, before the 1979 costs have taken effect.

Figures 5 and 6 indicate that differences in the starting volumes are noticeable for some tens of years in the future, and even as far as the end of the rotation. This depends upon

the correlation between the thinning removal and logging costs (see tables 1 and 2). In figure 5 a, for example, it is observable that a 50-year-old stand with volume 246 cu.m./ha is thinned to a level of 152 cu.m./ha. If there are 199 cu.m./ha in a stand of the same age, the volume after thinning is 129 cu.m./ha. The example indicates that the density of the growing stock may vary with quite wide limits, without great losses in revenue. Against this, large losses are attributable to high logging costs if a stated optimum density is followed strictly.

Calculations were made also for comparison of the profitability of thinning from below and thinning from above. Then net present-values of the 50-year-old stands were com-

Volume,
cu.m./ha
Kuutiomäärä,
m³/ha

a. Logging costs in 1969
Vuoden 1969 korjuukustannukset

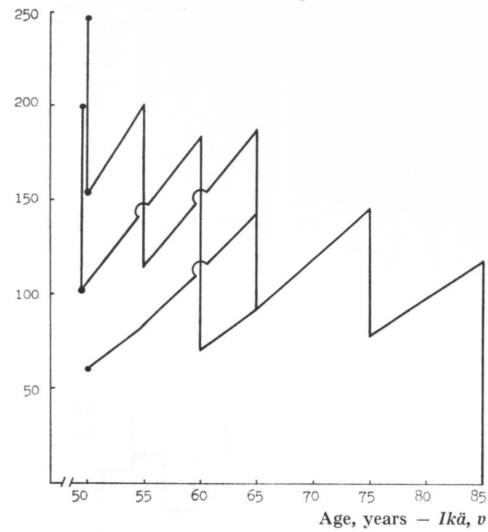
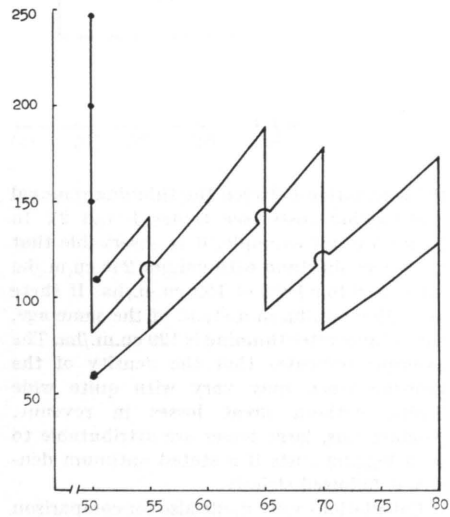


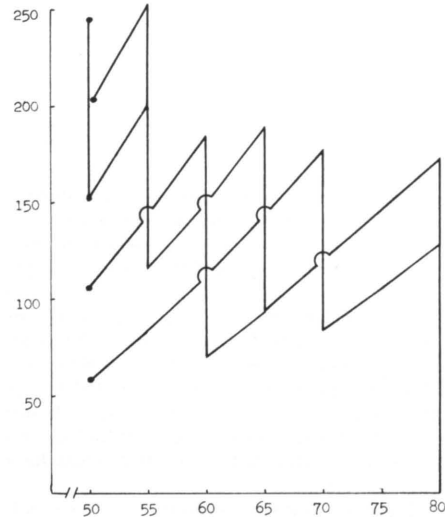
Figure 5. Optimum cutting programs for today's 50-year-old stands. Rate of interest 4 per cent. Thinning from below.

Kuva 5. Optimihakkuuohjelmat tällä hetkellä 50-vuotiaille metsiköille. Korkokanta 4 %. Alaharvennus.

b. Changing logging costs
Muuttuvat korjuukustannukset



c. Logging costs in year 1979.
Vuoden 1979 korjuukustannukset



volume,
cu.m./ha
kuutiomäärä,
m³/ha

a. Logging costs in 1969.
Vuoden 1969 korjuukustannukset

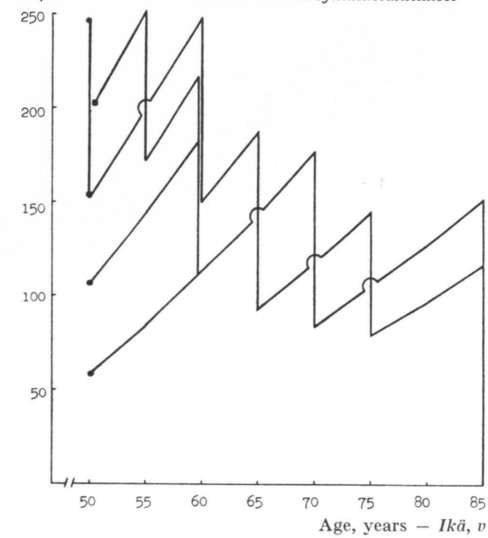
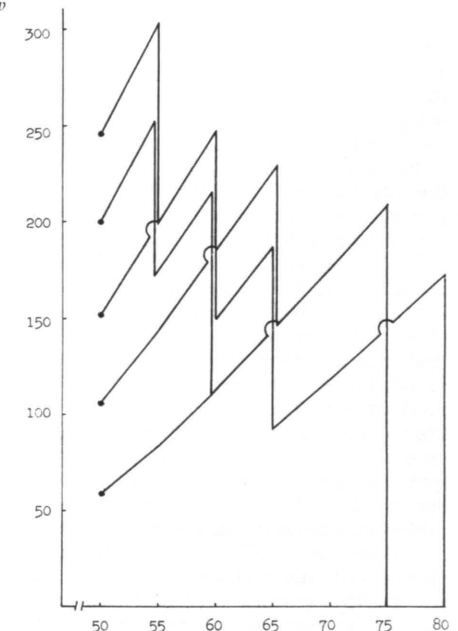
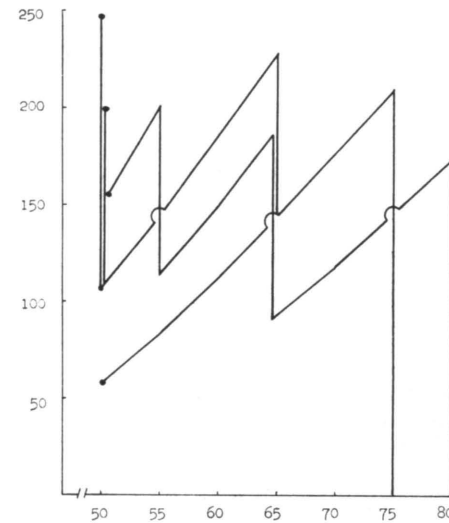


Figure 6. Optimum cutting programs for today's 50-year-old stands. Rate of interest 4 per cent. Thinning from above.

Kuva 6. Optimihakkuuohjelmat tällä hetkellä 50-vuotiaille metsiköille. Korkokanta 4 %. Yläharvennus.

c. Logging costs in year 1979.
Vuoden 1979 korjuukustannukset.

b. Changing logging costs
Muuttuvat korjuukustannukset



pared. These values were standardised before comparison by dividing them by the harvesting values of the 50-year-old stands. In each case, it was noticed that thinning from above yielded a higher net present-value than did thinning from below. The differences varied from 2 to 12 per cent. The smallest differences occurred when the logging costs were in respect of 1969, a rate of interest of 5 per cent was applied and the starting volume was high. The largest differences were apparent when the 1979 cost level, a rate of interest

5. LOSSES IN REVENUE IF THE OPTIMUM CUTTING PROGRAM IS NOT FOLLOWED

In addition to the information on the optimum cutting programs, it is important to know which economic losses are attributable to non-optimal programs. To illustrate these losses, some figures for their expression have been calculated and listed in table 4. Logging costs in the year 1969, thinning from below, and a rate of interest of 4 per cent have been applied. Calculations have been made for 50-, 70-, and 90-year-old stands. The figures in table 4 indicate the extent to which the net present-value of the future revenue from the stand is reduced if the optimum policy is not followed. The figures relate only to the losses generated during the first 5 year period. If a non-optimal policy is continued for a longer period, the losses naturally rise.

In 50-year-old stands, the major losses result from clear cutting. The maximum loss is 919 Fmk. The volume of the stand is then about 150 cu.m./ha. If there is more or less timber in the stand, the losses are not quite so substantial, but clear cutting is still the most unprofitable alternative. Naturally, if the volume falls very low, the stand must be clear cut. However, even 60 cu.m./ha is quite an adequate volume to justify growing the stand. Undisturbed growth is the most profitable alternative in stands consisting of less than 190 cu.m./ha, and thinning in stands with more timber. In the densest stand with a growing stock of 246 cu.m./ha, the most vigorous possible thinning, with the removal of 187 cu.m./ha, is slightly more profitable than undisturbed growth. However, both of these alternatives result in losses

of 1 per cent, and a relatively low starting volume were involved.

Differences in the net present-values between the stands thinned from below and from above do not prove the superiority of thinning from above. Nevertheless, they indicate that the stands thinned from below should grow better than stands thinned from above, if thinning from below is to be justified. It is also probable that trends in logging costs favour increasing thinning from above in the future.

exceeding 100 Fmk, on comparison with the most profitable thinning. The thinning removal would then be 94 cu.m./ha.

Over-density of 70-year-old stands results in greatest losses. The most profitable alternative, in most cases, is a heavy thinning. The growing stock after thinning then consists of about 86 cu.m./ha. If, for example, there are 267 cu.m./ha, undisturbed growth of the stand for 5 years results in a loss of 355 Fmk, compared with a loss of 191 Fmk if the stand is clear cut. Clear cutting results in the greatest losses if the stand is so open that no thinning is required during the rest of the rotation.

In 90-year-old stands, reforestation is clearly the best alternative. If for some reason the stands cannot be reforested, it pays to thin them heavily. Here, 106 cu.m./ha was the lowest growing stock that could be attained within the series used, and evidently it would have been profitable to thin the stands even more if reforestation had been impracticable.

If a stand is clear cut and not reforested immediately, there will be losses in interest which increase for as long as the soil remains unplanted; this is on the assumption that the net present-value of the future income from the soil is positive. In this study, the soil value has been taken to be 400 Fmk, as the rate of interest is 4 per cent. If the land is left without planting after clear cutting, a loss of 71 Fmk will be sustained during the first 5 year period. The longer the area remains bare, the larger the losses will be.

Table 4. Losses in revenue if the optimum cutting program is not followed, Fmk/ha. Logging costs in year 1969. Thinning from below. Rate of interest 4 per cent.

Taulukko 4. Tuottotappiot optimihakkuohjelmasta poikettaessa, mk/ha. Vuoden 1969 korjuukustannukset. Alaharvennus. Korkokanta 4 %.

Level of growing stock in the beginning of 5 year period <i>Puuston taso 5-vuotiskauden alussa</i>	Level of growing stock at the end of 5 year period — <i>Puuston taso 5-vuotiskauden lopussa</i>										
	1	2	3	4	5	6	7	8	9	10	11
	Age 50 years — <i>Ikä 50 v</i>										
1	141	110	50	14	0	14	17	53	131	—	860
2	—	73	58	24	0	2	6	42	120	—	877
3	—	—	22	30	7	7	0	36	114	—	887
4	—	—	—	0	21	22	13	39	117	—	900
5	—	—	—	—	0	45	38	61	131	—	919
6	—	—	—	—	—	0	37	63	133	—	911
7	—	—	—	—	—	—	0	71	144	—	909
8	—	—	—	—	—	—	—	0	117	—	875
9	—	—	—	—	—	—	—	—	0	—	804
10	—	—	—	—	—	—	—	—	—	—	—
11	—	—	—	—	—	—	—	—	—	—	—
Age 70 years — <i>Ikä 70 v</i>											
1	782	673	559	423	259	112	48	9	0	—	175
2	738	666	539	388	239	101	57	7	0	—	177
3	—	618	528	377	230	96	39	4	0	—	182
4	—	—	489	386	230	92	35	2	0	—	188
5	—	—	—	355	243	88	33	0	0	—	191
6	—	—	—	—	215	107	37	0	0	—	193
7	—	—	—	—	—	83	59	18	0	—	193
8	—	—	—	—	—	—	15	11	0	—	180
9	—	—	—	—	—	—	—	0	26	—	195
10	—	—	—	—	—	—	—	—	0	—	197
11	—	—	—	—	—	—	—	—	—	—	—
Age 90 years — <i>Ikä 90 v</i>											
1	1 056	783	624	451	254	134	67	—	—	—	0
2	1 013	783	615	442	245	130	62	—	—	—	0
3	—	792	667	475	274	163	106	—	—	—	0
4	—	—	648	504	288	178	125	—	—	—	0
5	—	—	—	490	322	197	144	—	—	—	0
6	—	—	—	—	298	221	154	—	—	—	0
7	—	—	—	—	—	182	154	—	—	—	0
8	—	—	—	—	—	—	106	—	—	—	0
9	—	—	—	—	—	—	—	—	—	—	—
10	—	—	—	—	—	—	—	—	—	—	—
11	—	—	—	—	—	—	—	—	—	—	—

The maximum loss is 400 Fmk if the area remains bare forever. When a 90-year-old Scotch Pine stand on site VT is involved, clear cutting without reforestation and growing the stand very open seem equal alternatives. The situation changes if the chances of reproduction change during the time that reforestation is deferred.

Previous calculations have indicated that situations may occur in old stands where

clear cutting is certainly the most profitable alternative, even though immediate reforestation is impossible. Old stands often represent such high exploitation values that their undisturbed growth results in far larger losses than if the relatively cheap land area is left idle.

Examples indicate that largest losses do not always result from wrong rotation but from wrong density. As a rule, the largest

losses are incurred by over-density. Consequently, major losses are often caused when the stand is clear cut by reason of its low density. As the calculations show, the stand may be very open, and is still economically very profitable if grown forward. According to the calculations presented in this work, even 60–80 cu.m./ha well justifies growing of the stand.

Previous calculations are just examples. If the rate of interest falls, the costs of thinning increase, or thinning from above is employed, the optimum densities increase. Losses owing to over-density diminish, and losses

resulting from too low density increase. However, it should be observed that only two cases were found in which the stand was to be clear cut as a consequence of its too low density (see table 3). On the contrary, if the logging costs change as predicted, over-density will today result in losses that appreciably exceed those contained in table 4.

The loss figures in table 4 are applicable to several purposes. They assist in making a choice of which of the alternative cutting concentrations yields the least total losses. The loss figures are also applicable in estimation of the losses caused by forest damage.

6. DISCUSSION

The greatest difficulty encountered in a study of this type is that of acquiring reliable data. The growth and yield figures used in this study cannot be considered very reliable. Only a few characteristics of growing stock have been used to describe its growth and structure. It is possible that another growth function would lead to different results. The cost figures applied here can be regarded as rather reliable, at least as far as the year 1969 is concerned. However, there are some evident inaccuracies in the wage tables for that year. If these were corrected, thinning costs would rise somewhat.

In view of the simplifications made in presenting the problem, several factors other than those taken into account in this study exercise an influence upon the cutting programs. First, it must be noted that the cutting program for a forest stand must be synchronised with the planned cut for the whole forest undertaking. However, this study is limited to providing information on the cutting sequence within the allowable cut.

Natural thinning in forests suggests shorter thinning intervals and lower levels of growing stock than those given in this paper. A temporary reduction in growth intensity, and possible damages in the forest resulting from heavy thinnings also favour lighter thinnings and shorter thinning intervals than those presented here. However, some factors

exert just the opposite influence. In practical forestry, it is not always feasible to give each stand the chance of cutting every fifth year. The cutting cycle is often 10, and even 20 years, and thus thinnings should sometimes be much heavier than those suggested in this study. Moreover, the rotation varies, depending upon the cutting cycle.

The road building costs are probably higher in real forests than those applied in this study, if short thinning intervals are used. This is because with slight thinnings annual harvests should be distributed in stands over a wide area. Here, it was assumed that no cost is involved in moving from one stand to another.

To shed more light on these questions, further studies are needed. It must then be noted that dynamic programming may be no longer an adequate tool. In particular, questions concerning the growth and structure of the stands require more experimental work in the forests. However, the results of this study may provide some advice on how to design thinning experiments.

This work has also raised many other questions which need to be resolved in further studies. Cutting programs for young stands, and the lowest acceptable level of growing stock, are still to be studied, and cutting programs in the form of the matrices in table 3 should be prepared for other sites and tree species.

7. SUMMARY

The purpose of this study has been that of determining the optimum cutting programs for forest stands by the application of dynamic programming. Calculations have been made for even-aged Scotch Pine stands in Southern Finland; the age of the stands varied from 50 to 100 years. Three logging cost levels, thinning from below and from above, and rates of interest of 1, 2, 3, 4, and 5 per cent have been applied. Both optimum routes and the economic results of different cutting programs have been analysed. The main results are:

1. The higher the rate of interest is, the lower the density remains, and shorter the rotation is.

2. The starting level of the growing stock may influence the treatment of the stand for tens of years.

3. If the logging costs change, so that harvesting small wood becomes relatively more expensive in the future than it is now, the density of growing stock will increase. How-

ever, heavy thinnings today are recommendable, to avoid expensive thinnings in the future.

4. The density of the growing stock should be higher if thinning from above is applied, instead of thinning from below.

5. The growth of the stands thinned from below needs to be greater than the growth of stands thinned from above, to justify thinning from below.

6. Too high a density often results in larger losses in returns than do too low a density or the wrong rotation.

7. Thinnings seem to be profitable even at much higher logging costs than those of today.

8. The maturity of the stand is determined both by the age and the density of the growing stock. The stand may be mature because of great age, because of the high density combined with a relatively high age, or because the growing stock is too low in density.

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SELOSTE:

METSİKÖN OPTIMIHAKKUOHJELMAN MÄÄRITTÄMINEN DYNAAMISEN OHJELMOINNIN AVULLA

Tämän tutkimuksen tarkoituksena on ollut etsiä metsikölle sellainen hakkuuohjelma, jota noudatettaessa metsiköstä saatavien nettotulojen nykyarvo maksimoituu. Tätä ongelmaa on aiemmin pyritty ratkaisemaan hakemalla metsikön kasvuun perusteella optimiäikeys ja optimikiertoaika rajakannattavuusanalyysiä käyttäen. Metsätöiden koneellistuttua on kuitenkin jouduttu suurentamaan pinta-alayksiköllä saatavaa hakkuukertymää. Tällöin on syntynyt yhä kasvava ristiriita puuston kasvun ja korjuun vaatimien metsikön kasvatustapojen välillä. Nykytilanteessa ei perinteellinen rajakannattavuustarkastelu, joka tarjoaa ainoastaan staattisia optimiratkaisuja, olekaan enää riittävä.

Dynaaminen ohjelmointi antaa mahdollisuuden sekä kasvu- että korjuunäkökohtien huomioinnille metsikön hakkuuohjelmaa laadittaessa. Koska dynaaminen ohjelmointi on jo eräissä tämänkaltaisissa tutkimuksissa osoittautunut käyttökelpoiseksi menetelmäksi, päädyttiin sen soveltamiseen myös tässä työssä.

Tarkastelun kohteena ovat olleet 50—100 vuotiaat Etelä-Suomen VT-männiköt. Niille on laskettu vaihtoehtoisia kuutiomäärän kehitystä osoittavia sarjoja (kuva 2). On oletettu, että joka viides vuosi voidaan tehdä joko harvennus- tai paljaaksihakkuu. Harvennushakkuissa on oletettu voitavan noudattaa joko ala- tai yläharvennusta. Hakkuista saatava puutavara on hinnoiteltu kaukokuljetusväylän varrella saatavien hintojen perusteella. Näistä tuloista on vähennetty korjuukustannukset, jotka käsittävät kaato- ja lähikuljetuskustannukset. Korjuukustannuksina on käytetty vuoden 1969 palkkataulukoista saatuja lukuja sekä vuodelle 1979 ennustettuja kustannuslukuja (taulukot 1 ja 2).

Dynaamisen ohjelmoinnin avulla on haettu optimihakkuuohjelma jokaisesta vaihtoehtoisesta metsikön tilasta eteenpäin. Nämä optimihakkuuohjelmat on ilmaistu taulukossa 3 olevien matriisien avulla. Kun tiedetään metsikön ikä ja puuston taso, saadaan taulukosta matriisielementti, joka ilmaisee puuston ikänsä vuoden kuluttua, jos optimihakkuuohjelmaa noudetaan. Lisäksi on laskettu eri hakkuuohjelmien antamat tuotot. Tällöin on laskettu tuotot myös sellaisille

hakkuuohjelmille, jotka poikkeavat optimista ensimmäisellä 5-vuotiskaudella.

Tutkimuksen päätulokset ovat seuraavat:

1. Mitä korkeampaa korkokantaa käytetään sitä harvempaa metsikköä tulee kasvattaa ja sitä lyhyempi on kiertoajan oltava.

2. Puuston alkutaso saattaa vaikuttaa metsikön käsittelyyn kymmenien vuosien ajan.

3. Jos korjuukustannukset muuttuvat siten, että pieniläpimittaisen puun korjuu tulee suhteellisesti kallimmaksi tulevaisuudessa kuin nykyisin, kasvatustiheys nousee. Nykyhetkellä ovat voimakkaat harvennukset kuitenkin suosittavia, jotta kalliista harvennushakkuista säästyttäisiin tulevaisuudessa.

4. Yläharvennusta käytettäessä tulee puuston kasvustiheyden olla suurempi kuin alaharvennusta käytettäessä.

5. Alaharvennuksilla käsitellyn metsikön kasvun tulee olla suurempi kuin yläharvennuksilla käsitellyn, jotta alaharvennus olisi edullisempi harvennustapa.

6. Liian suuri tiheys aiheuttaa usein suurempia taloudellisia tappioita kuin liian alhainen tiheys tai virheellinen kiertoaika.

7. Harvennushakkuut tulevat ilmeisesti olemaan kannattavia vielä nykyistä huomattavasti korkeampien korjuukustannusten vallitessa.

8. Metsikön hakkuukypsyyden määräävät ikä ja tiheys yhdessä. Hakkuukypsyyden aiheuttajia voivat olla joko metsikön korkea ikä tai liiallinen tiheys, joka liittyy suhteellisen korkeaan ikään, tai sitten metsikön alipuustoisuus.

Saatuja tuloksia tarkasteltaessa on pidettävä mielessä eräitä varauksia. Ensinnäkin tulokset ovat sovellettavissa suoraan vain sellaisille VT-männiköille, joiden kasvu likimain seuraa annettua kasvuyhtälöä. Toinen merkittävä oletamus on se, että metsikön aiempi käsittely ei vaikuta kasvuun nykyhetkellä. Tämä oletamus, on johtanut ilmeisesti aivan liian voimakkaisiin harvennushakkuisiin eräissä tapauksissa. Todellisuudessa tällaiset hakkuut eivät tulisi kysymykseen, koska niiden seurauksena olisivat monenlaiset metsätuhot. Vielä on muistettava, että kysymyksessä ovat yksityisille metsiköille laaditut hakkuuohjelmat, jotka käytännössä on nivellettävä metsälän kokonaisuohjelmaan.

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