THINNING REGIME OPTIMIZATION IN EUROPEAN RUSSIAN PINES

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ABSTRACT

One part of the procedure for improvement of machinery performance criteria is a multi-objective algorithm for thinning regime optimization. A "relative centre mass" method is used as its basis with relative unit harvesting cost and total and/or merchantable (intermediate and final) cutting volume criteria. The problem of optimum density over time for even-aged, one-species stands is formulated as a nonlinear programming task. The number of cuttings, the intensity of the thinning, and the thinning intervals are defined simultaneously using a "random search" algorithm. The method is applied to pine stands growing in the Russian North-West region.

Keywords: *multi-objective decision-making, stand productivity, harvesting cost, system approach, pine stand, random search.*

INTRODUCTION

The share of thinnings in the total volume of the harvest is continually growing in Russia, especially in European Russia. This is associated with a decline in the potential size of the final harvest. During the last 30 years, intensive forest exploitation by clear-cutting methods has led to a drain of raw wood. This situation can be changed by speeding up the development of intermediate cutting methods. If Russian forest engineering starts to advance to this direction, it will need a new philosophy of machinery design.

Mechanized thinning techniques involve bringing machines into the forest quite often. This can lead to a negative impact on nature and increases harvesting costs. Therefore, on the one hand, a forest mechanical engineer should design machinery that is not only more productive, reliable, light, and inexpensive, but also more suitable for intermediate cutting methods; this means predicting residual tree damages, cutting tree accessibility, etc. On the other hand, thinking about a timber yield increasing, a forest manager should plan a thinning regime that is as economical and adaptable for mechanization as possible. Consequently, the decision-making problem of mechanized thinning is rather comprehensive and calls for a systematic approach. Here we can divide the universal problem into several cooperative tasks. Every local task may be solved with the help of uncomplicated computational model on the base of simulation, optimization, and operations research techniques.

The procedure for the improvement of intermediate technology and machinery performance criteria is presented in Figure 1. The aim of the present paper is to describe the highest level of hierarchy -- the thinning regime optimization. It is a very important part of our study [5,6], because a designed machine, and particularly its harvesting crane equipment, must be adapted to future operational conditions.

PROBLEM SPECIFICATION AND REVIEW

Most researchers of decision-making in thinning optimization usually use profitability as the complex criterion of efficiency in the following forms: the profit for the whole rotation time [11], the internal rate of return, or discounted profit [3,8,13]. Economical criteria give a very useful estimate for conducting forestry, but these objective functions may be used only in a stable economic situation. Nowadays, the Russian economy is turning into a market economy. The inflation of the Russian currency does not allow it to define a standard liquidation value and stumpage value for timber. That is why some researchers [10] recommend using the volumetric objective function, which is the total volume, or the merchantable volume. However, the top priority in forestry is not only to increase the wood yield when possible, but to make it economical within the limits of different forestry constraints. For instance, in accordance with the forestry rules of Russia, the minimum relative density of the coniferous stand after thinning must be not less than 0.7, and of hardwood not less than 0.6. Considering that

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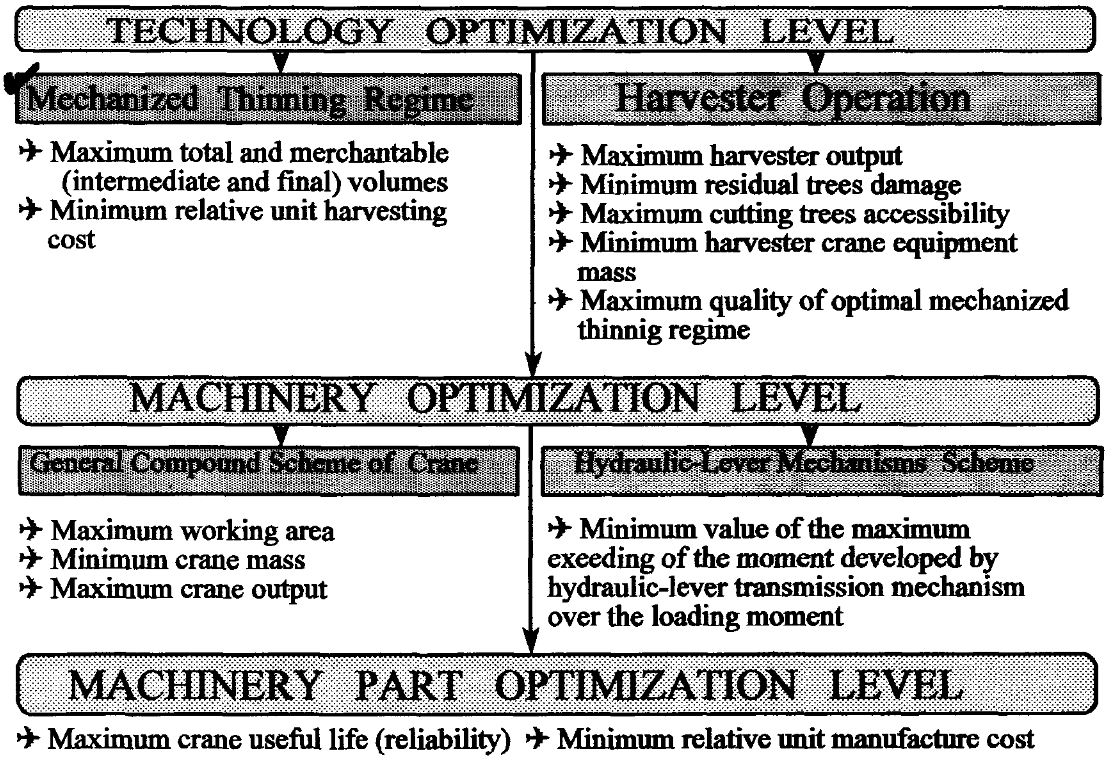

Figure 1. Forest machinery crane optimal design hierarchy.

mechanized thinning has a harvesting cost that is two to three times higher than the final clear-cutting, a multi-objective problem is present.

Let the vector of criteria $\{W_j\}$ represent the following three objective values, which are free from a currency inflation:

W^l = total volume, m^3/ha;
W^d = merchantable volume, m^3/ha;
$W^\$$ = relative unit harvesting cost.

W^l and W^d may be calculated by summing up the final volume (Vf) and the intermediate volume (Vt) over the whole rotation time. The objective function may be expressed as:

$$W^l = Vf^l + \sum_{i=1}^{n-1} Vt_i^l \qquad (1)$$

and

$$W^d = Vf^d + \sum_{i=1}^{n-1} Vt_i^{\,d} \qquad (2)$$

where: n = number of cuttings;
l = symbol for total volume;
d = symbol for merchantable volume.

$W^\$$ is a ratio of total harvesting cost over the final harvesting cost. The objective function $W^\$$ may be expressed as:

$$W^\$ = 1 + \frac{\sum_{i=1}^{n-1} Vt^\$_i}{Vf^\$} \qquad (3)$$

where: $Vf^\$$ = unit final felling cost, \$/m^3;
$Vt^\$_i$ = unit thinning cost, \$/m^3.

For a multi-objective decision-making task we recommend using the "relative centre mass" method, which has received quite wide use in forest engineering applications [2].

Let the extreme values be defined in consecutive order for each criterion W_j that corresponds to the points with coordinates $\{x_{1j}^*, x_{2j}^*,..., x_{nj}^*\}$ in the decision variable space. Single-objective optimization does not include methodological problems. We can use one programming method. The dynamic programming is widely used for thinning regime optimization [1,3,12]. Some researchers apply the nonlinear programming [4,9,10].

The idea of "relative centre mass" of the point (m_j) is as follows:

$$m_j = \frac{\sum_j W_j\left(x_{1_j}^*, x_{2_j}^*, ..., x_{k_j}^*\right)}{W_j\left(x_{1_j}^*, x_{2_j}^*, ..., x_{k_j}^*\right)} \tag{4}$$

where: $W_j(x_{1j}^*, x_{2j}^*,..., x_{kj}^*)$ = the value of the objective function j.

Let us consider that the compromise decision corresponds to the collection of the decision variables with the "relative centre mass" coordinates:

$$x_i^{**} = \frac{\sum_j m_j x_{i_j}^*}{\sum_j m_j} \tag{5}$$

This is the weighted average value of the decision variables x_i^{**}, where the weight for the j-th variable is the reciprocal of the objective functions. In our case, the vector of decision variables $\{x_{ij}\}$ represents the thinning regime. It consists of:

n = number of cuttings;
t_i = thinning age, i=1,...,n-1;
t_n = final felling age;
Pr_i = decrease of relative stand density, i=1,...,n-1.

ALGORITHM

Decision-Making Procedure

Let the decision-making procedure be described by the flow chart (Figure 2).

First, a single-objective optimization for the Wl criterion is organized with the help of a "random search" method. The vector $\{n^*_l, t^*l_i, Pr^*_{li}\}$ describes the optimal thinning regime, which corresponds to the maximal value of the total volume.

In the second place, the analogous process is made for the merchantable volume objectiven function W^d using formula (2).

Further, clearly, minimum value of the relative unit harvesting cost criterion $W^\$$ corresponds to the regime without thinnings.

Next, our steps depend on the extreme regimes by W^1 and W^d. If they are the same, then the W^1 and W^d criteria do not compete and one, for instance W^d, may be excluded.

Finally, the multi-objective decision-making is defined by formulas (4 - 5). Beforehand the criteria's values for every combination extreme thinning regimes are calculated using a simulation of stand development and the function of a ratio between final and intermediate harvesting cost [7].

Single-Objective Optimization Procedure

Let the random search process be organized as follows:

1. Set the number of cuttings n, the age t_i and the degree p_i for each felling using Monte Carlo method;

2. Calculate the intermediate volume Vt and final volume Vf using simulation of stand development;

3. Calculate the volume W^1 or W^d using formulas (1) or (2).

4. Repeat steps (1) - (3) as many times k as it is necessary for precision. We recommend using the following formula:

$$k = t_{student} \cdot \frac{\sigma}{\varepsilon^2} \tag{6}$$

where: $t_{student}$ = Student's distribution parameter;
σ = mean square deviation;
ε = confidence interval.

5. Choose the maximum criterion value.
6. Decrease the designing variable space (for n, t_i, and p_i) and repeat steps (1) - (5). If the precision of the decision is enough, then stop. The optimum thinning regime is fixed.

Stand Development Procedure

The mensurational parameters of the harvested

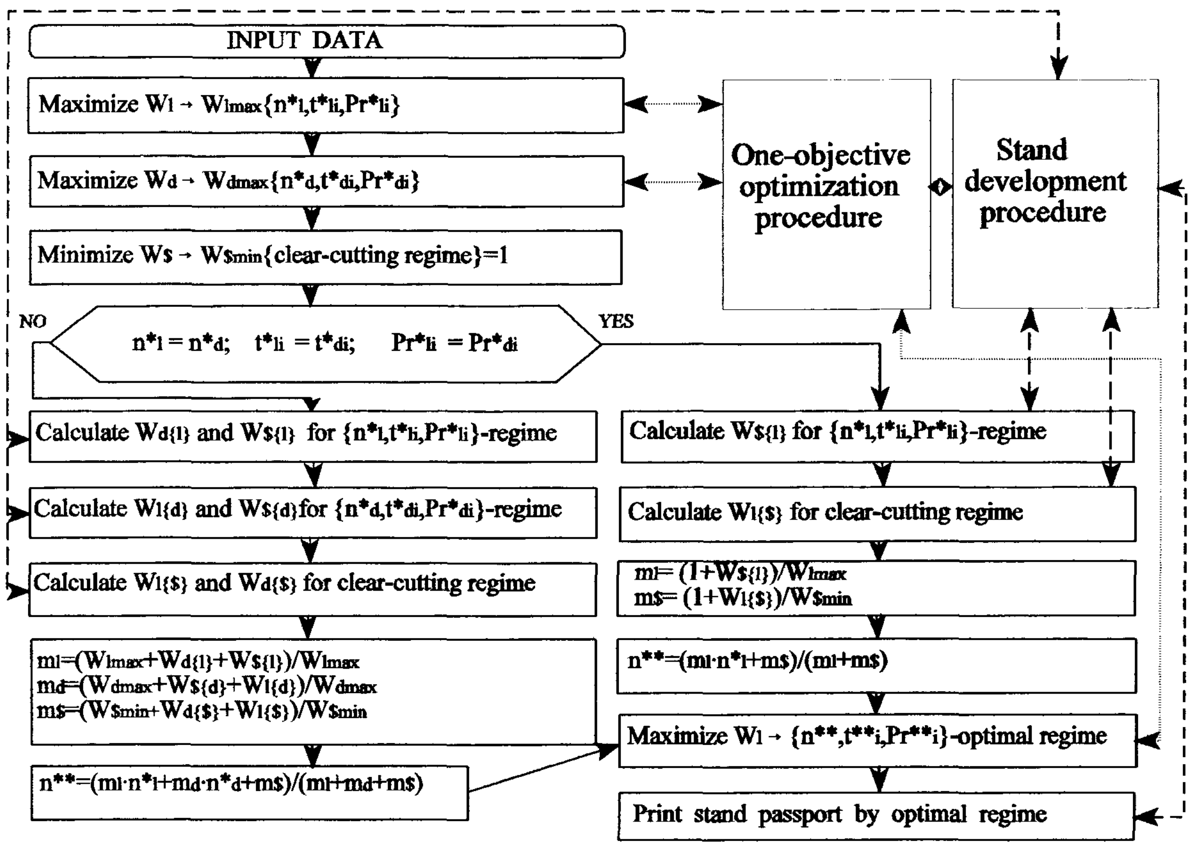

Figure 2. Decision-making procedure.

trees may be calculated in the following way. According to the thinning types the number of the harvested trees (Nb, trees/ha) is

$$Nb = 0.01 \cdot N \cdot n(Pv) \quad (7)$$

where: N = number of standing trees before thinning, trees/ha;
Pv = proportion of volume of outturn with the thinning, %;
n(Pv) = proportion of trees of outturn with the thinning, %.

According to the thinning types, the mean diameter of the harvested trees Db is

$$Db = D \cdot d(Pv) \quad (8)$$

where: D = mean diameter of the standing trees before thinning, cm;
d(Pv) = proportion of diameter of outturn with the thinning, %.

The basal area of the harvested part of the stand (Gb, m^2/ha) is

$$Gb = \frac{\pi \cdot Db^2 \cdot Nb}{4000} \quad (9)$$

The mean tree volume of the harvested part of the stand Vb is

$$Vb = \frac{Mb}{Nb} \quad (10)$$

where: Mb = volume of outturn.

The mensurational parameters of the growing stand after thinning may be calculated in the following way. The sum of the basal area of the remaining part of the stand (Go) is

$$Go = Gp - Gb \quad (11)$$

where: Gp = sum of basal area before the thinning.

The growing stock after the thinning (Mo) is

$$Mo = Mp - Mb \quad (12)$$

where: Mp = growing stock before the thinning.

The density of the stand after thinning (Po) is

$$Po = \frac{Mo}{M1} \quad (13)$$

where: M1 = the normal growing stock from the regional growth and yield tables.

The number of the growing trees after the thinning (No, trees/ha) is

$$No = Np - Nb \quad (14)$$

The mean diameter of the stand after the thinning (Do, cm) is

$$Do = \sqrt{\frac{Go \cdot 4000}{\pi \cdot No}} \quad (15)$$

Formulas (6) - (14) permit simulation of the harvested trees and provide mensurational parameters of the remaining part of the stand after thinning.

The restoration of the standing stock after the thinning may be predicted by the method [10] based on the conformity to natural laws of the current increment of the stock. It defines the relative density every five to ten years at every step of the prediction of the stand stock restoration:

$$M(T+t) = M(T) + t \cdot Zm \quad (16)$$

where: M(T+t) = restoring stock of the stand after thinning at the age of T+t years, m^3/ha;
M(T) = growing stock of the stand at the age of T, m^3/ha;
Zm = mean periodical current increment of the growing stock, m^3/ha;

for coniferous forest

$$Zm = e^{a0 + a1 \cdot InT + a2 \cdot InH + a3 \cdot InT \cdot InH + a4 \cdot In^2T} \cdot p0.784 \quad (17)$$

for hardwood forest

$$Zm = e^{a0 + a1 \cdot InT + a2 \cdot InH + a3 \cdot InT \cdot InH + a4 \cdot In^2T} \cdot p0.732 \quad (18)$$

where: H = mean height, m;
P = relative density.

The restoring relative density of the stand in t (10 or 5) years is

$$P(T+t)=\frac{M(T+t)}{M1(T+t)} \qquad (19)$$

where: M1(T+t) - stock of the closed stand at the age of T+t,m^3/ha.

The dynamics of the mensurational parameters R(T+t) (mean height, mean diameter, mean density) may be expressed in the following form:

$$R(T+t)=R(T)\cdot e^{y1+y2} \qquad (20)$$

$$y1=b1\cdot 1nC+b2\cdot 1nT\cdot 1nC+b3\cdot 1NH(T)\cdot 1nC \quad (21)$$

$$y2=b4\cdot 1nD(T)+b5\cdot 1nN(T)\cdot 1nC+b6\cdot 1n^2C \quad (22)$$

where: C = 1+t/T;
H(T) = mean height of the growing stand, m;
D(T) = mean diameter of the growing stand, cm;
N(T) = stand density, trees/ha.

$$N=\sqrt{\frac{1000}{0.866\cdot L(T)}} \qquad (23)$$

where: L = mean distance between trees, m.

Formulas (15) - (23) allow one to predict the changes of the mensurational parameters to the next thinning or to the final felling.

APPLICATION

We applied the algorithm for pine stands of the Russian North-West region. The stands are characterized by the 3rd site class and 1.0 (normal), 0.9, and 0.8 relative densities. The first thinning age varies from 20 to 80 years, the final felling age is 100 years. The basic characteristics of normal stand in 20 years are:

mean diameter	=	6.1 cm;
mean height	=	4.9 m;
mean volume	=	0.008 m^3;
mean number of stems	=	6057 trees/ha;
mean stock	=	46 m^3/ha.

Step 1. The single-objective optimization of the total volume. Figure 3 displays the maximum total volume as a function of the first thinning age and the number of thinnings. Figures 3-A and 3-B describe the optimum relations for the high density stands (1.0 and 0.9 relative density), Figure 3-C shows the relations for the middle density stand (0.8 relative density).

Step 2. The single-objective optimization of the merchantable volume. Also, above described thinning regimes provide the maximum merchantable volume. Therefore W^1 and W^d criteria do not compete and W^d is excluded.

Step 3. The single-objective optimization of the relative unit harvesting cost. On the other hand, above recommended regimes had the maximum relative unit harvesting cost of timber $W^{\$}$=1.8...2.1 because it is necessary to carry out nine cuttings. Clearly, that clear-cutting technology ensures the minimum harvesting cost $W^{\$}$=1. However, this regime reduces the stand productivity by 35% for high densities and by 25% for middle density.

Therefore, the problem needs the compromise searching for two criteria -- W^1 and $W^{\$}$.

Step 4. The multi-objective optimization. The formula (4) allows one to calculate "conditional centre mass" values for the total volume (m_w) and for the relative unit harvesting cost ($m_{\$}$):

$m_w^{1.0}$ = 2.44; $m_w^{0.9}$ = 2.47; $m_w^{0.8}$ = 2.50;
$m_{\$}^{1.0}$ = 3.32; $m_{\$}^{0.9}$ = 3.41; $m_{\$}^{0.8}$ = 3.49.

where: 1.0, 0.9 and 0.8=relative stand densities.

The optimum compromise value of the number of thinnings and the final felling (n^{**}) and according to (n^{**}) the optimum first thinning age (t_1^{**}) found by formula (5) and Figure 4. For the relative stand density 1.0, they are n^{**}= 4; t_1^{**}= 30. The optimum thinning regime is presented in Figure 4-A. For the relative stand density 0.9 they are n^{**}= 4; t_1^{**}= 40. The optimum thinning regime is presented in Figure 4-B. For the relative stand density 0.8 they are n^{**}= 4; t_1^{**}= 50. The optimum thinning regime is presented in Figure 4-C.

A

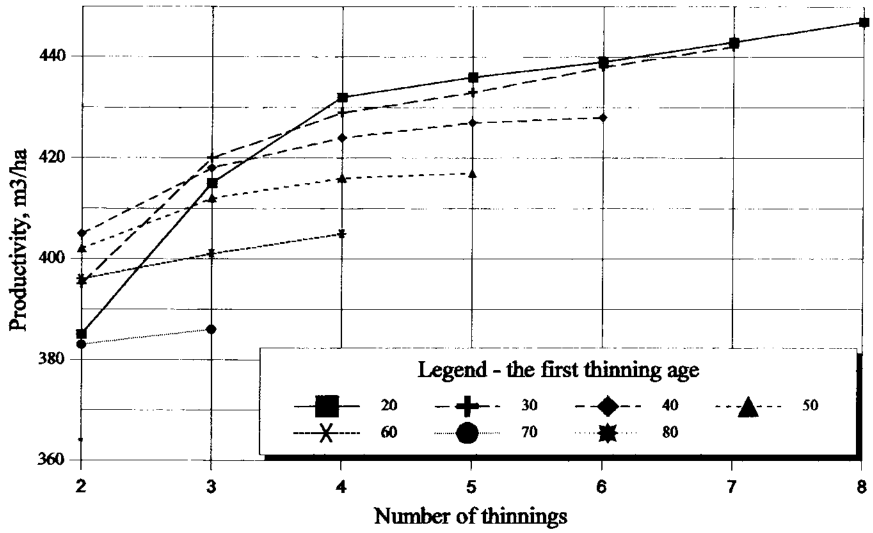

Figure 3-A

B

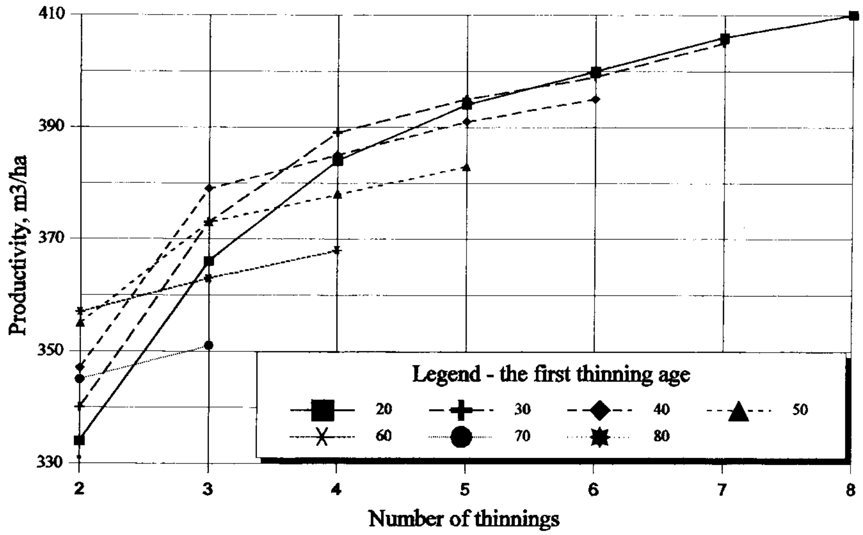

Figure 3-B

C

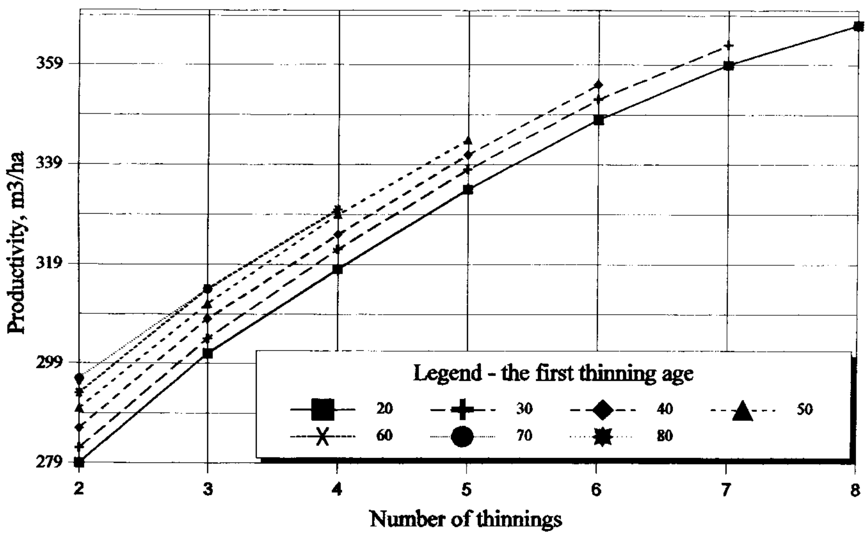

Figure 3-C

Figure 3. Maximum total volume of pine stand (the 3rd site class; the final felling age is 100 years).

A

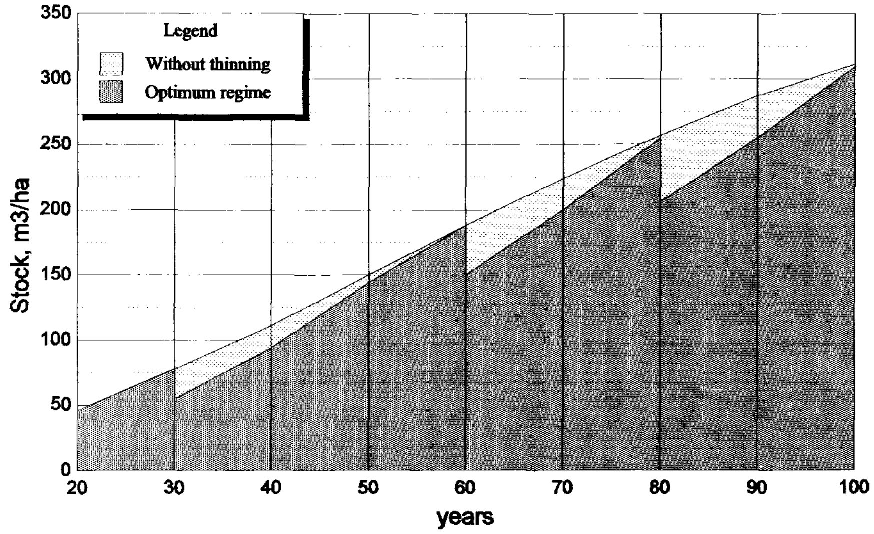

Figure 4-A

B

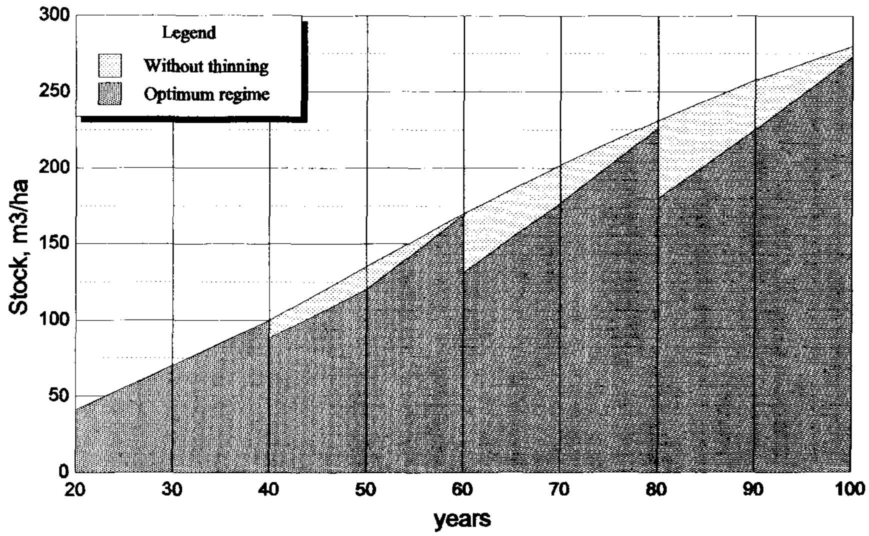

Figure 4-B

C

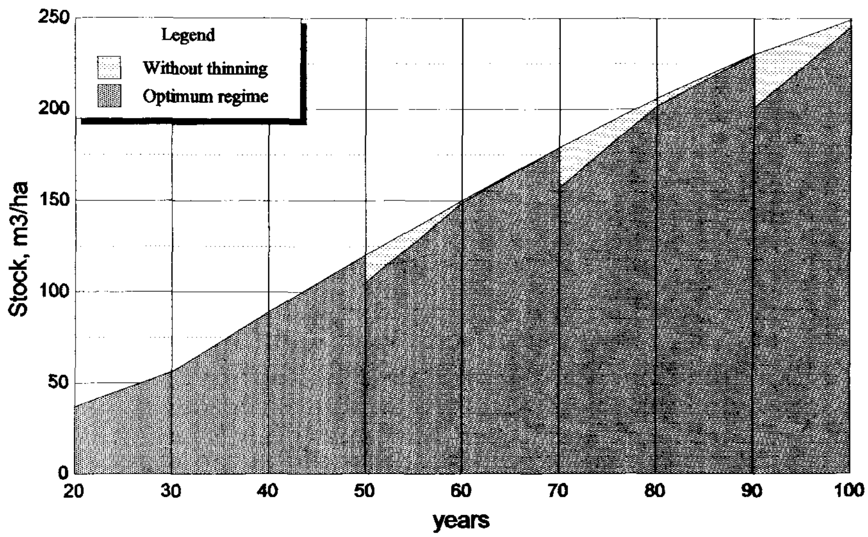

Figure 4-C

Figure 4. Optimum thinning regimes.

CONCLUSIONS AND RECOMMENDATIONS

An optimum thinning regime may be successfully found with the help of the multi-objective decision-making algorithm by the "reliable centre mass" and "random search" methods. We recommend using the following criteria: relative unit harvesting cost and the total and/or merchantable (intermediate and final) volumes. The problem of optimum density over time for even-aged, one-species stands formulate as a nonlinear programming task. The number of thinnings, the degrees of thinning, and thinning interval are the decision variables.

The application of the single-objective algorithm for high-density pine stands of the Russian North-West displays that the first thinning should start as early as possible for the maximization of total volume. This tendency is right with four to eight thinnings (Figures 3-A and 3-B). If we make two or three cuttings then it is necessary to perform the thirst thinning in 40-60 years.

However, the application of the multi-objective algorithm points to the expediency of making 3 thinnings. The first thinning age varied from 30 to 40 years depending on the stand density (Figures 4-A and 4-B). The optimal thinning regimes allow one to increase the stand productivity by 35% and to reduce the relative unit harvesting cost by 12%. Here we compare the productivity values with traditional clear-cutting technology and the harvesting cost values with the traditional Russian thinning schedule.

For the middle density stand (Figure 3-C) our recommendations by the single-objective algorithm differ from the high density stands and have a more definite character, which may be expressed as:

$$t_1=100-10\cdot(n-1)$$

where: t_1 = first thinning age;
$n-1$ = number of thinnings.

We can see that the maximum total volume is obtained independently of the stand density. The optimum regimes by the total volume contain the first thinning in 20 years and the 10 years' interval between cuttings. The stand productivity is expected to increase up 40%.

For the middle-density stand (Figure 4-C) the recommended regime by the multi-objective algorithm raises the productivity by 27% and decreases the harvesting cost on 26%.

The present procedure of forest machinery optimal design supports forest engineers in providing them with the knowledge for designing the intermediate cutting technology and machinery. In our case, the basic stand characteristics before and after cuttings by optimum thinning regimes are used for harvester operations simulation (Figure 2). It allows to optimize the key parameters of technology and machinery.

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The English language script has been edited for clarity, and in doing so we hope that the scientific content has, in no way, been comprimised.

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