Harvester Crane Key Parameters: Optimization in European Russian Pines

Y.Y. Gerasimov
V.S. Siounev
Petrozavodsk State University
Petrozavodsk, Russia

ABSTRACT

The purpose of this study is to find out the effect of using the multiobjective simulation technique for logging technology and machinery optimal design. This topic was identified as important to support forest machinery designers in providing them with the necessary knowledge for carrying out the first drafts without a pilot machinery model. The method is applied to pines growing in the Russian North-West region.

Keywords: *simulation, multiobjective decision-making, system approach, pine stand, logging, thinning, design.*

INTRODUCTION

The history of logging machine development in Russia has mostly been in relation to clear-cut purposes. The development of the machines for thinning has usually been done on the basis of machines for clearcutting. Therefore we have displayed the perceptible lack of agreement between logging and silviculture since the timber industry in European Russia faced intermediate technology on a large scale. There are two defined directions of the problem's decision:

1. The creation of new logging technologies in conformity with existent logging machinery provides less negative effect on the environment.
2. New machinery design meets the requirements of both silviculture and logging.

In Russia the first direction received wider development. Our researchers proposed many different logging technology schemes using Russian felling, felling-bunching, and felling-skidding machines. We are definitely progressing in that direction, but such a direction has no way out. Russian machinery becomes powerful, heavy, and correspondingly dangerous to the environment when used in intermediate technology.

We shall not find a suitable scheme because a designer disregards the system approach. It is expressed as optimization of key machinery parameters without ecological and silvicultural criteria. Therefore, we consider the second direction preferable as it has the best chance for success.

However, this direction did not strongly attract designers' attention, because it required great joint efforts from forestry, logging, and machinery construction institutes. Progress has been made to the point that compact, inexpensive computers with expanded outputs are available to ordinary designers for carrying out the first drafts. The problem needs a new look at the design ideology of forest technology and machinery from the viewpoint of computerisation [6].

We see the first step in realizing the problem of optimizing harvester crane design as a function of stand-related and mechanical constraints.

METHOD AND CRITERIA SELECTION

Optimization of harvester crane key parameters requires the mathematical formalization of the interrelation of machine and the forest. Many stochastic parameters, such as the distance between stops and the diameters, locations, and height of trees on the cutting area, etc., characterize the functioning of our system. In such a case it is difficult to create a comprehensive analytical stochastic model and to obtain resulting analytical functions. Therefore, simulation lies at the basis of our investigation.

Although simulation is now common in forest technology and machinery investigation, it is not clear that it plays the most effective role in the design process. During the past 30 years, forest science has sufficiently wide applied simulation techniques. Many scientific research schools have simulation and optimization ideas, particularly included for Forest Engineering, into their studies.

One stochastic model [4] simulates a thinning harvester operation for the second degree regression surface (f) construction on the experimental

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The authors are, respectively, Professor and Associate Professor, Forest Engineering Faculty.

design theory base:

$$Y = f(\text{Density, Outreach, Distance})$$

where

Y = a performance criterion,
Density = stand density,
Outreach = maximum crane outreach,
Distance = distance between stops.

Tree accessibility, harvester output per hour, average cycle time per tree cutting, and average cutting area per hour are regarded as performance criteria.

A simulation model [9] exists for the harvester output (Output) increasing:

$$Output = Output(a) \rightarrow max$$

which allows to ensure the forestry rules (fr) simultaneously:

$$fr1(a) \trianglelefteq g1,$$
$$fr2(a) \trianglelefteq g2,$$
$$\ldots\ldots\ldots\ldots ,$$
$$frn(a) \trianglelefteq gn.$$

where

a = vector of factors influencing output,
$g_1 \ldots g_k$ = forestry rules limitation.

Analogous simulation models have been published in Russia [1,7], in the USA [8, 10], in Canada [11], in Sweden [3], in Finland [2], etc.

Although much work has been done so far, more studies are required for the better investigation of logging machinery optimal design. Their analysis reveals some shortcomings:

(i) **One-objective character.** If we raise, for instance, the harvester output or reduce cost, the value of other performance criteria (tree damage, inaccessibility, etc.) can decrease.

(ii) **Empirical data use.** We cannot apply these models to a new design stage.

(iii) **Stand damage is not theoretically estimated.** Most researchers use an experimental method.

(iv) **Spatial patterns of trees use Poisson probability distribution.** Young stands grow naturally in groups, but it is not clear how strong they can influence the optimal harvester crane parameters.

The distinctive feature of our process consists of the multiobjective problem at the design stage of the study. The model can improve harvester output (W_{output}), stand damage (W_{damage}), cutting trees' inaccessibility ($W_{inaccess}$), quality control of the thinning regime (W_{qualit}) and machine mass (W_{mass}) with the flexibility inherent in imprecise nature-industrial variations:

$$W_{output}(u,v) \rightarrow max,$$
$$W_{damage}(u,v) \rightarrow min,$$
$$W_{inaccess}(u,v) \rightarrow min,$$
$$W_{qualit}(u,v) \rightarrow max,$$
$$W_{mass}(u,v) \rightarrow min,$$

where

u = vector of controllable factors (designer strategies) influencing W_{output}, W_{damage}, $W_{inaccess}$, and W_{mass} criteria,
v = vector of uncontrollable factors (nature strategies) influencing performance criteria.

DECISION-MAKING ALGORITHM

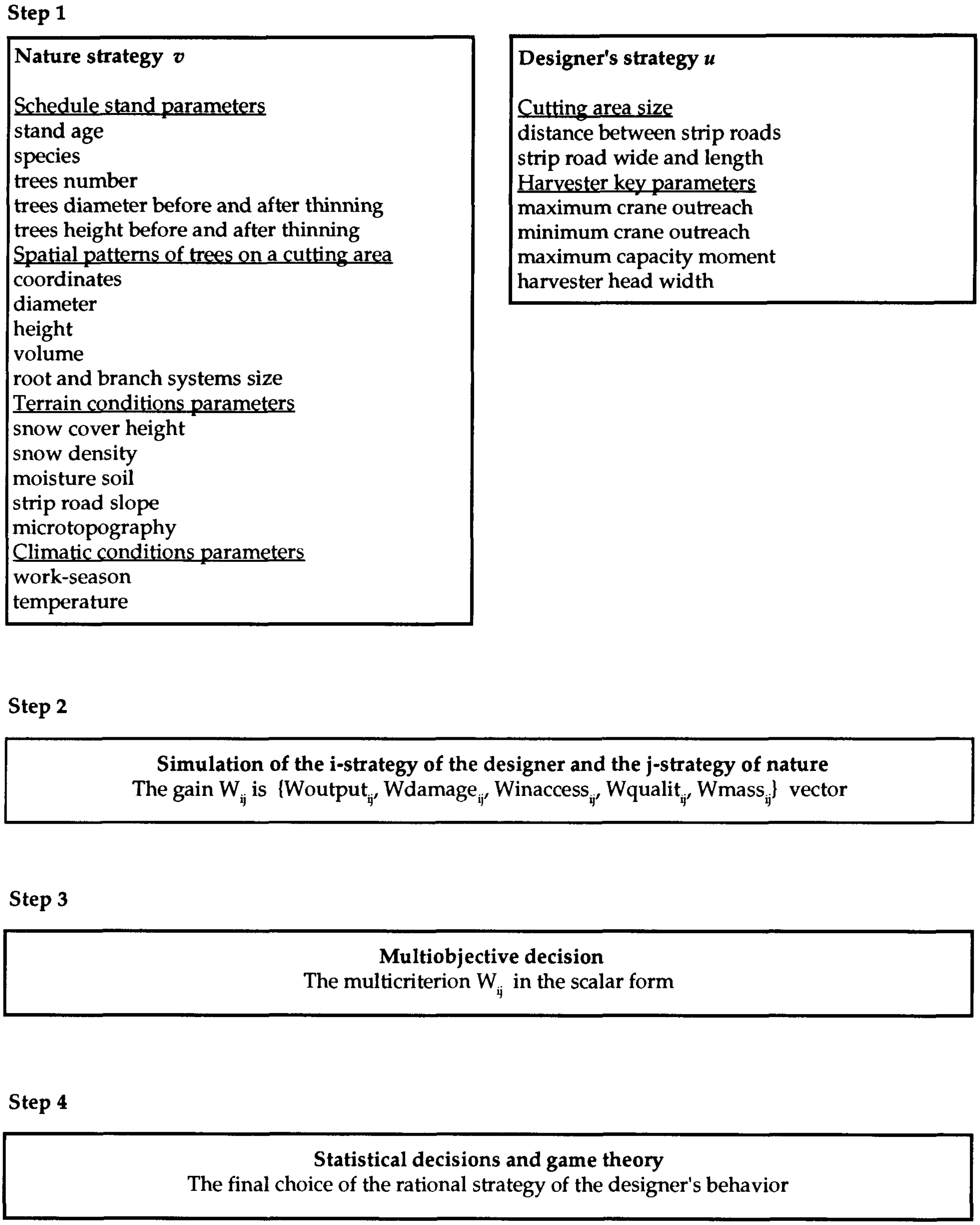
The decision-making algorithm at a preliminary design stage consists of the following steps (Figure 1).

1. The first step uses game theory and statistical decision methods to form the nature strategy v and designer's strategy u vectors. The parameters are listed in Figure 1.

   The nature strategies v are schedule parameters, spatial patterns of trees on a cutting area, terrain conditions, and climatic conditions.

   The designer's strategies u are cutting area size and harvester crane key parameters.

2. The game matrix is considered next where the gain W_{ij} is a vector of the criterion parameters $\{W_{outputij}, W_{damageij}, W_{inaccessij}, W_{qualitij}, W_{massij}\}$, received at the simulation of the i-strategy of the designer and the j-strategy of nature.



Step 1

Nature strategy *v*

Schedule stand parameters
stand age
species
trees number
trees diameter before and after thinning
trees height before and after thinning
Spatial patterns of trees on a cutting area
coordinates
diameter
height
volume
root and branch systems size
Terrain conditions parameters
snow cover height
snow density
moisture soil
strip road slope
microtopography
Climatic conditions parameters
work-season
temperature

Designer's strategy *u*

Cutting area size
distance between strip roads
strip road wide and length
Harvester key parameters
maximum crane outreach
minimum crane outreach
maximum capacity moment
harvester head width

Step 2

Simulation of the i-strategy of the designer and the j-strategy of nature
The gain W_{ij} is $\{Woutput_{ij}, Wdamage_{ij}, Winaccess_{ij}, Wqualit_{ij}, Wmass_{ij}\}$ vector

Step 3

Multiobjective decision
The multicriterion W_{ij} in the scalar form

Step 4

Statistical decisions and game theory
The final choice of the rational strategy of the designer's behavior

Figure 1. Flow-chart of study.

3. The third step involves a multiobjective decision regarding the multicriterion W_{ij} in the scalar form.

4. Finally, the statistical decisions and game theory. We choose the rational strategy of the designer's behaviour.

SIMULATION MODEL STRUCTURE

The structure of the simulation model is presented in Figure 2.

The elements of vector v are formed in the following blocks:

(i) *Thinning regime* = schedule parameters [6],
(ii) *Horizontal structure* and *Vertical structure* = spatial patterns of trees on a cutting area [5],
(iii) *Terrain* = terrain condition parameters [5],
(iv) *Climate* = climatic condition parameters [5].

The *Project* block includes the vector u: cutting area sizes and harvester key parameters.

The *Process* block is created from the formalized logging technology description base, and links all blocks and decision-making.

The performance criteria are calculated in the *Damage, Output, Inaccessibility, Quality,* and *Mass* blocks, after which the multiobjective criterion is derived from *Multiobjective performance criterion* block.

Let us show how the simulation model works on a typical thinning conducted by a flange-type felling-skidding machine using the log-length method as shown in the *Process* block (Figure 2).

Cutting is conducted in the left-hand sector. If a strip road was not cut before, then a clear-cutting is made in the direction of travel within the cutting

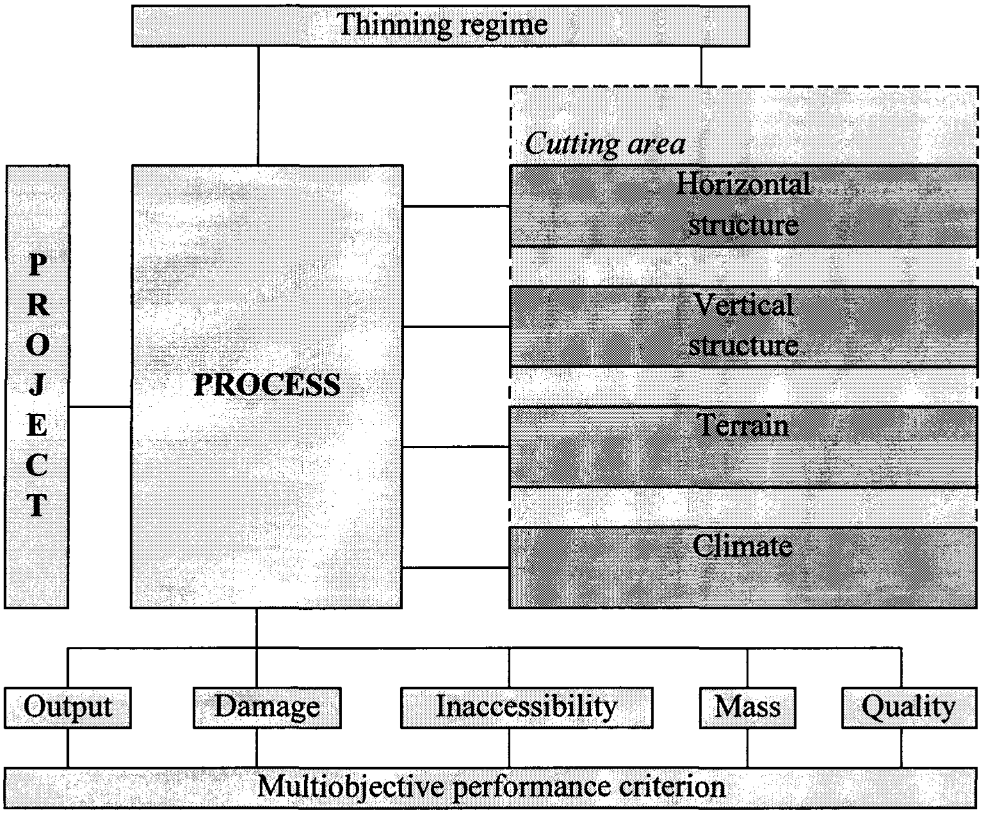


Figure 2. Simulation model structure.

strip. The machine moves from one stop to another, the coordinates of which are determined by the location of the planted cutting tree, on the one hand, and the weights, maximal moment, and outreach of the crane, on the other hand. A tree is termed inaccessible in the following cases. A capacity moment of a tree exceeds the crane maximum capacity moment. A harvester head cannot reach the cutting tree because of trees standing in the way. When the hauling volume reaches the timber capacity, the felling-skidding machine moves to the landing, unloads, and comes back to a new stop. The cycle is then repeated.

When we imitate a felling-bunching machine operation by the log-length method or a harvester by the shortwood method, the skidding is excluded.

To calculate the inaccessibility criterion $W_{inaccess}$ we accumulate the information on the quantity of inaccessible trees; and at the simulation's end we scale to pure number by means of

$$W_{inaccess} = N_{inaccess} / N_{cut}$$

where

$N_{inaccess}$ = number of inaccessible trees per ha because of interfering trees and insufficient crane capacity,
N_{cut} = appointed number of cutting trees per ha under the optimum thinning regime.

To calculate the damage criterion W_{damage} we accumulate the information on essential damages, and at the simulation's end we scale to pure number by means of

$$W_{damage} = N_{damage} / N_{rem}$$

where

N_{damage} = number of trees per ha with damaged stems or root systems,
N_{rem} = number of remaining trees per ha under the optimum thinning regime.

To calculate the output criterion W_{output}, the capacity and empty travel of a harvester head and a base (only for a felling-skidding machine) are summarized separately. At the simulation's end a total distance of all cycles corresponds to the volume of trees processed and results in a pure number.

To calculate the performance criterion of the optimum regime fulfilment W_{qualit} we accumulate information about the difference between the following volumes. On the one hand, we take cutting and left stems during modelling on a computer. On the other hand, we take scheduled logging volume on cutting and remaining parts under the optimum thinning regime. At the end of the experiment the difference results in a pure number by means of

$$W_{qualit} = V_{cut}/M_{cut} - 1 + V_{rem}/M_{rem} - 1$$

where

V_{cut} = logging volume at modelling, m^3/ha,
V_{rem} = remaining volume (without the account of damaged trees) after thinning at modelling, m^3/ha,
M_{cut} = scheduled logging volume, m^3/ha,
M_{rem} = scheduled remaining volume after thinning, m^3/ha.

To calculate the mass criterion W_{mass} we accumulate the information on the difference between the following moments. First, we consider a maximum required crane moment for trees on the cutting area during simulation M_{tree}. Second, we think about designed maximum net-moment M_{max}. At the end of the experiment the difference results in pure number by means of:

$$W_{mass} = M_{tree} / M_{max} - 1$$

As all criteria have pure numbers the multicriterion can be constructed by a uniform optimization principle:

$$W = W_{damage} + W_{inaccess} + W_{output} + W_{qualit} + W_{mass}.$$

Except for the further key parameters values, the simulation model forms the data bank on the loading mode for future designs.

A similar model can be constructed by use of a machine on a clear-cut. It is enough to generate small trees on a cutting area, to define a damage criterion W_{damage}.

APPLICATION AND RESULTS

Step 1. Strategies' description

The logging simulation model was tested for a felling-bunching machine, dealing with European Russian pines under the optimum regimes, as submitted in the previous study [6].

The cutting schedule of the 3d site class pines with the relative densities 1.0, 0.9, and 0.8 were considered as the nature strategy vector v.

The thinning regimes comprised the following data:

For the first thinning:
Stand age - 30 years,
Height - 11.4 m,
Cutting tree diameter - 6.4 cm,
Remaining trees diameter - 9.4 cm,
Cutting stand volume - 23 m^3/ha,
Remaining stand volume - 55 m^3/ha,
Cutting trees number - 2245 trees/ha,
Remaining trees number -2291 trees/ha.

For the second thinning:
Stand age - 60 years,
Height - 18.1 m,
Cutting tree diameter - 13.7 cm,
Remaining trees diameter - 20.3 cm,
Cutting stand volume - 38 m^3/ha,
Remaining stand volume - 150 m^3/ha,
Cutting trees number - 356 trees/ha,
Remaining trees number -586 trees/ha.

For the third thinning:
Stand age - 80 years,
Height - 20.7 m,
Cutting tree diameter - 18.5 cm,
Remaining trees diameter - 27.7 cm,
Cutting stand volume - 51 m^3/ha,
Remaining stand volume - 206 m^3/ha,
Cutting trees number - 255 trees/ha,
Remaining trees number - 206 trees/ha.

The key harvester parameters the distance between strip roads (DBSR), the maximum crane outreach and its capacity moment were considered as designer's strategy u.

The strip road had a length of 100 m, and a width of 3.5 m. The net moment of a crane varied in a range 20 to 70 kHm, the maximum outreach of a crane varied from 7 to 14 m, cutting strip width changed from 14 to 28 m, and the track of a base tractor had a length 2 m.

The influences of a group location degree (GLD) of a horizontal stand structure, the distance between strip roads, and crane outreach on parameters of performance were investigated. The resulting dependencies are shown in figures 3 to 5.

Step 2. Performance simulation results

Group location degree influence

The most sensitive criterion of GLD (the first thinning, Figure 4) is W_{qualit}, which characterizes a deviation from the optimum thinning regime. For the generation of the GLD of the stand we use the special algorithm [11]. The values of the GLD depend on the irregularity of tree distribution on a cutting area. The GLD for old stands (the Poisson distribution) is 0.5, for young stands, 0.6 to 0.7. The GLD is precisely displayed on small distances between strip roads (up to 20 m). The other parameters of performance, except W_{damage}, change as the values W_{mass} and W_{output} increase and $W_{inaccess}$ decreases. However, influence of a GLD is not strong, especially when the distance between strip roads is great.

For example, the value $W_{inaccess}$ increases by 22% at a change in GLD from 0.5 (Figure 3c) up to 0.7 (Figure 3a) for a DBSR of 14 m, and only by 2% for a DBSR of 28 m. As a whole, the influence of a stand group structure at the first thinning on multicriterion W is not important because the results are not in error by more than 6%.

Distance between strip roads influence

The damage criterion W_{damage} is the most stable for DBSR (Figures 3 to 5). The value of the inaccessibility criterion $W_{inaccess}$ tends to deteriorate with DBSR growth and does not depend on the amount of serial thinning. Such a tendency is weakly expressed at the second and third thinnings (up to 15% on a considered range of DBSR change).

The output criterion W_{output} at the first thinning does not change very much, especially at a DBSR of more than 18 m. At the second and the third thinnings, fulfilment decreases with DBSR growth (up to 30% on a considered range).

W_{mass} has large and quickly decreasing values at the first thinning, connected with a restriction on tree quantity in a harvester head (in considered case 3, Figure 3c). At the second thinning, fulfilment reaches its minimum at 20 m DBSR. At the third thinning at 24 m (figures 4 and 5) and at a further increase of DBSR, the value W_{mass} is sharply increased because of insufficient net and capacity moment.

The behaviour of a performance criterion of a scheduled thinning regime W_{qualit} fulfilment is mostly unpredictable. For the first thinning it is expressed as a minimum in a range of 20 to 22 m (Figure 3c). It is probably connected with two opposite tendencies. On the one hand, we have a negative effect from the necessity of clear cutting on the strip road, smoothed with a DBSR increase. On the other hand, it causes an increase in the number of inaccessible trees to process, and, therefore, a deviation from the given thinning regime. In subsequent thinnings the second factor appears more essential and the values of W_{qualit} increase.

The multicriterion W in all cases (Figures 3 to 5) has a weakly expressed minimum in a range of 18 to 20 m.

Maximum crane outreach influence

Figures 6 and 7 explain the incremental influence of maximum crane outreach at fixed DBSR on the performance criteria. The first drawing corresponds to the first thinning at 20 m DBSR, the second to the second thinning at the same DBSR. The DBSR values were chosen by proceeding from the multicriterion value under a condition of conformity of the maximum crane outreach to DBSR (Figures 3 to 5). From submitted data it is evidently visible that the excess of maximum crane outreach over DBSR does not render an essential influence on all parameters of performance, including the multicriterion W (deviation on a given range is only 4%).

Step 3. Synthesis matrix

The synthesis matrix is shown in Table 1. We note that the obviously irrational strategies of the designer were previously excepted from the matrix.

Step 4. Decision-making

We have an optimum point with the performance multicriterion value of W=1.9. The point corresponds to the first thinning (opposite party strategy) and maximum crane outreach of 10 m, distance between strip roads of 20 m, and crane capacity moment of 35 kHm (optimum strategy of the operating party).

Table 1. Synthesis matrix.

Designer's strategy		*Nature's strategy*		
Outreach	Moment	Thinning number		
m	kHm	1	2	3
8	35	1.98	1.22	1.48
9	35	1.93	1.17	1.55
10	35	1.91	1.15	1.72
11	35	1.93	1.22	1.80
12	35	1.97	1.24	1.91
13	35	2.05	1.28	2.04
8	40	2.00	1.31	1.35
9	40	1.95	1.26	1.36
10	40	1.92	1.21	1.55
11	40	1.93	1.23	1.64
12	40	1.99	1.24	1.74
13	40	2.06	1.30	1.88
8	50	2.02	1.44	1.18
9	50	1.96	1.43	1.23
10	50	1.95	1.35	1.32
11	50	1.97	1.41	1.39
12	50	2.02	1.38	1.46
13	50	2.09	1.38	1.63
8	65	2.03	1.56	1.23
9	65	1.98	1.51	1.13
10	65	1.94	1.51	1.17
11	65	1.97	1.54	1.19
12	65	2.03	1.56	1.25
13	65	2.11	1.55	1.34

Simultaneously the given inflection point corresponds to the optimum strategy of the second thinning with a performance multicriterion value of W=1.15. However, optimum decision for the last thinning corresponds to the crane outreach of 9 m and the capacity moment of 65 kHm.

Thus, synthesis matrix analysis and figures 3 to 7, submitted earlier, evidently show that the development of harvester crane equipment should be separated for the first two thinnings, and for the last thinning used with the key parameters mentioned above.

The Russian felling-bunching machine LP-54 (maximum outreach 10.5 m, capacity moment 52.5 kHm) is the closest to the recommended crane char-

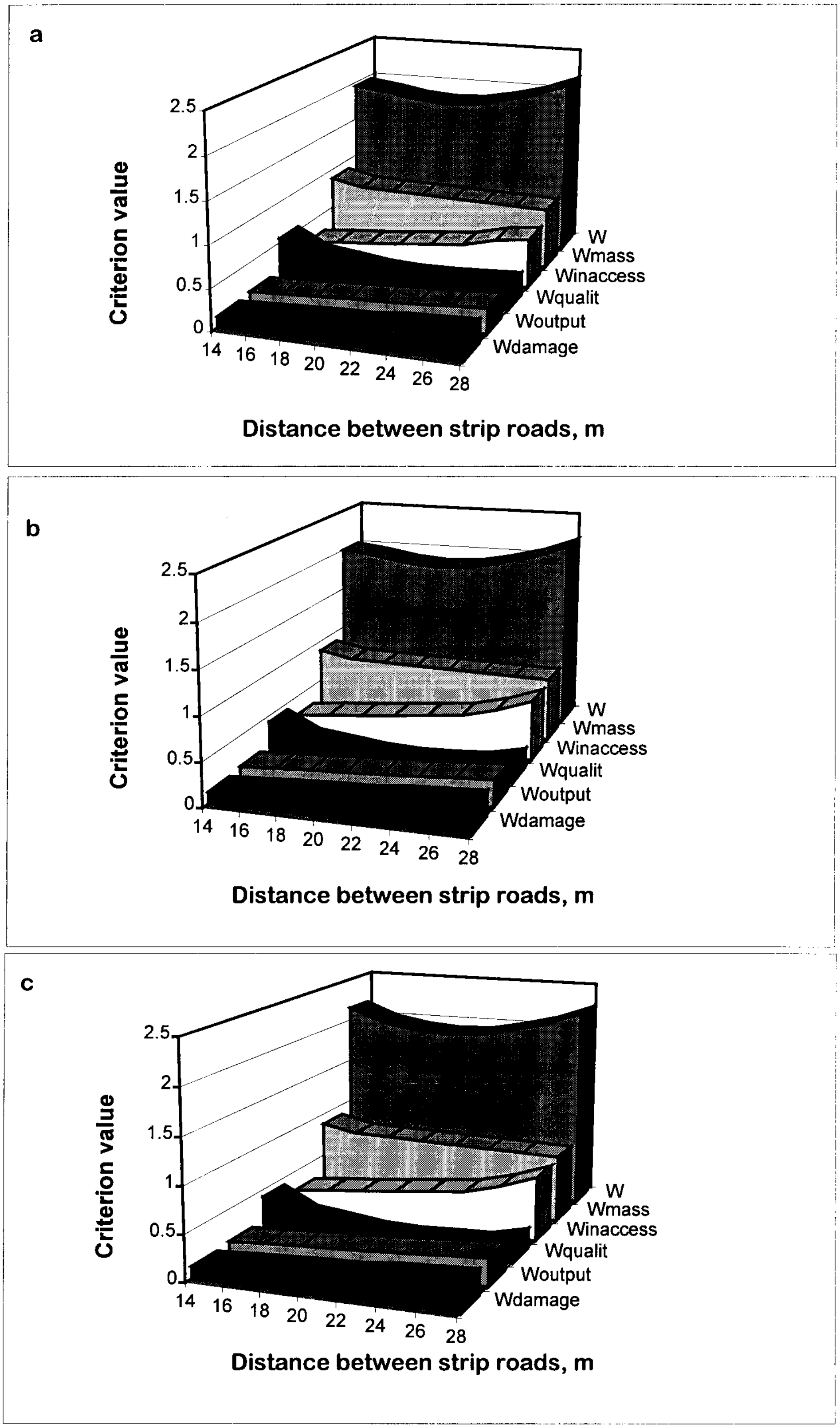


Figure 3. Group location degree (GLD) influence by the first thinning: a - GLD = 0.7; b - GLD = 0.6; c - GLD = 0.5.

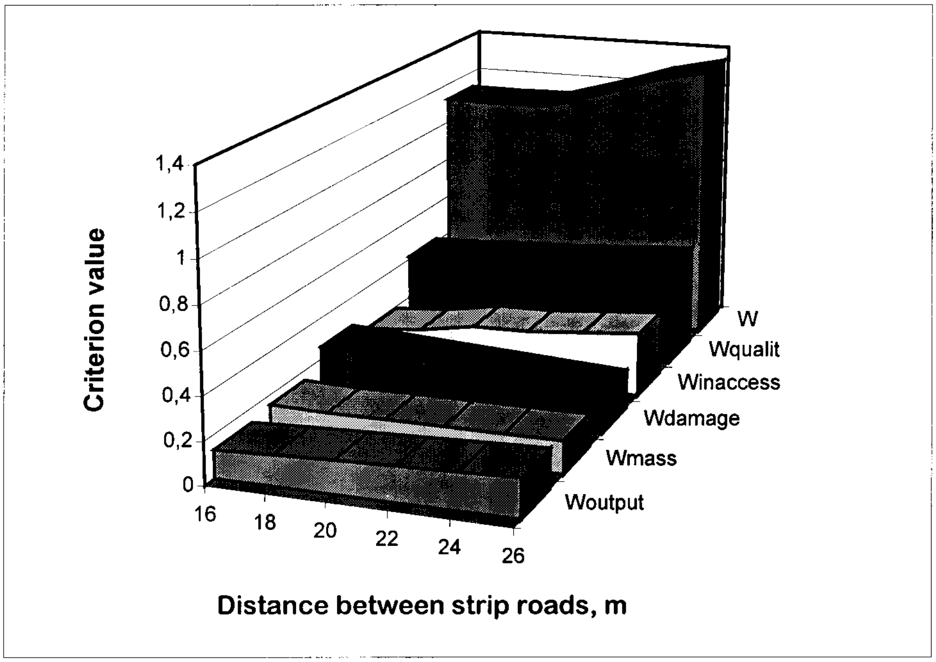


Figure 4. Distance between strip roads (DBSR) influence by the second thinning.

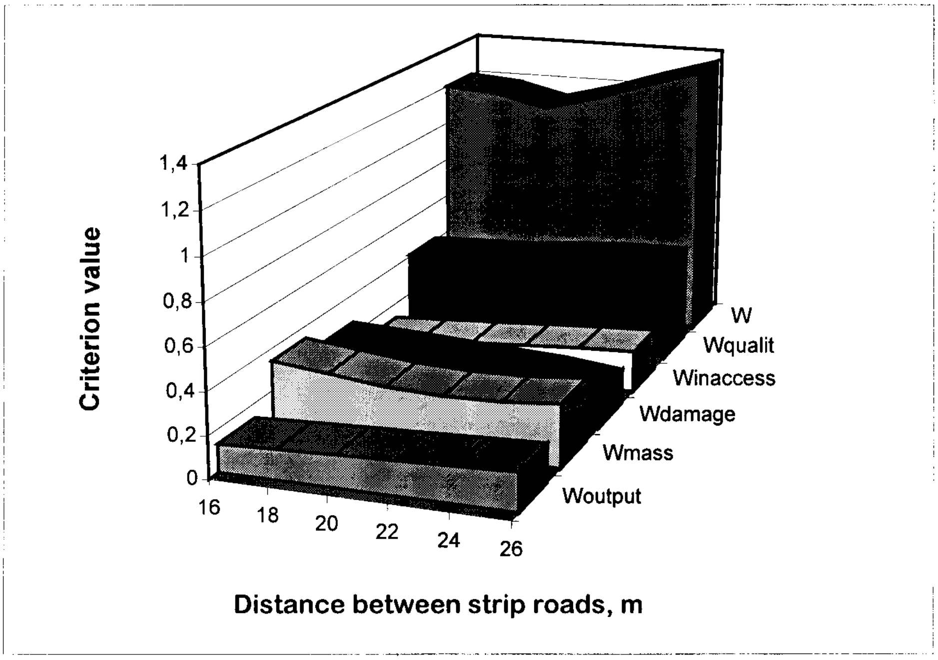


Figure 5. Distance between strip roads (DBSR) influence by the third thinning.

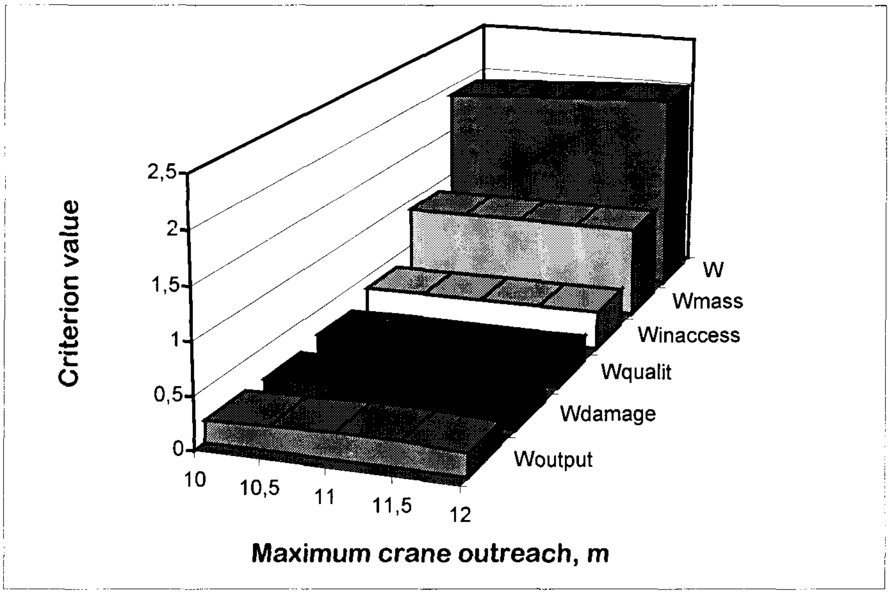


Figure 6. Maximum crane outreach influence at the fixed DBSR by the first thinning.

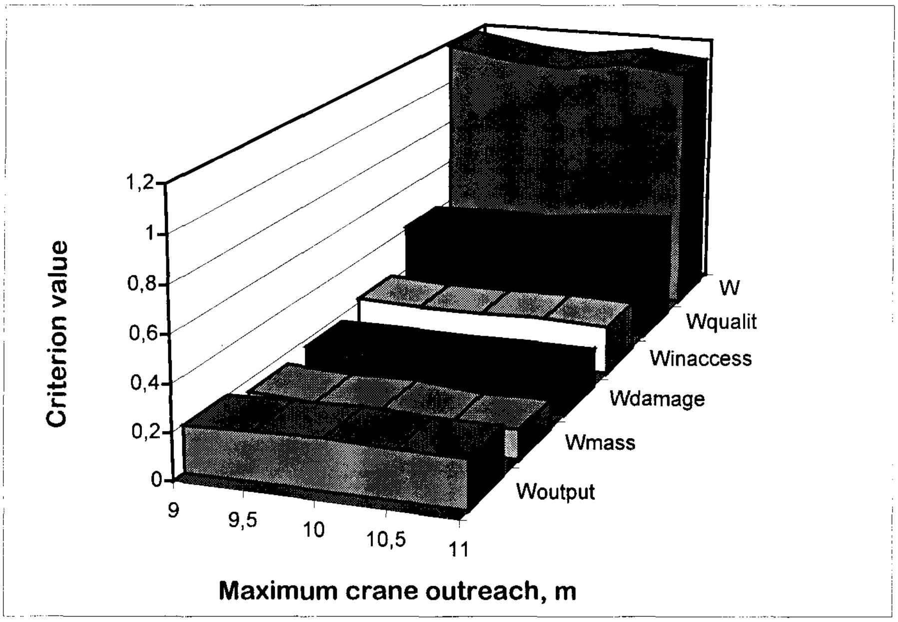


Figure 7. Maximum crane outreach influence at the fixed DBSR by the second thinning.

of LP-54 work and felling-bunching machines with the suggested key crane parameters (for the first and the second thinning the capacity moment of 35 kHm; for the third, 65 kHm at outreach of 10 m) in considered pines under the optimum thinning regime.

The criterion W_{mass}, describing crane consumption of materials, is reduced for the first thinnings by 33% at the invariability of the other performance criteria, and the damage of the remaining stand W_{damage} is reduced by 3%. The inaccessibility of trees to cutting $W_{inaccess}$ is increased by 20%. The parameter W_{mass} is reduced at the constant productivity W_{output} by 6% and the 14% quality of fulfilment of the thinning regime is improved at the last thinning.

From the extensive nomenclature of foreign cranes the following models of firm LOGLIFT are closer to the settlement of key characteristics: for the first two thinnings, F 50 LT 102 (37 kHm, 10.2 m); for the last thinning, F 70 LT 103 (62 kHm, 10.3 m). The values of their key parameters practically coincide with the settlement. At further designing these cranes can be considered as prototypes.

CONCLUSIONS

This topic was identified as important to support forest machinery designers in providing them with the necessary knowledge for carrying out the first drafts without a pilot machinery model. The presented study needs further development in machinery design for other types' of stands (mixed species and ages) and operators' activity influence, because damage to stems and inaccessible trees usually occur from the operator's faulty moves or from unpredictable mechanical reactions after stem severing or processing. Moreover we see that the interesting problem is the use of other multiobjective optimization principles.

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REFERENCES

[1] Andreev, V.N. Optimum design of forest machines with the aid of Markov's chains. Forest, Environment and New Technology in Northern Europe. Joensuu University, Faculty of Forestry 17:95-96.

[2] Asikainen, A. 1995. Discrete-event simulation of mechanized wood harvesting systems. University of Joensuu, Faculty of Forestry, Research Notes 38:1-86.

[3] Axenbom, A. 1990. A simulation model for planning of hay harvesting machinery system and management. Swedish University of Agricultural Sciences, Department of Agricultural Engineering. Report 144.

[4] Boiykov, S.P. and S.N. Sotonin. 1989. Felling-banking machine outputs for thinnings study by simulation. In: Logging and forest transport. Leningrad Forest Technical Academy. Pp.12-16. (in Russian)

[5] Gerasimov, Y.Y. 1994. Multiobjective simulation model of harvester operation for optimal design: study structure and cutting area algorithm. In: Scandinavian Forest Research in Europe: Operational Research. Danish Forest and Landscape Research Institute, Lyngby, Denmark. Pp. 206-219.

[6] Gerasimov, Y.Y. and V.K. Khlustov. 1995. Thinning regime optimization in European Russian Pines. J. of For. Eng. 7(2):7-16.

[7] Grabovskij, A.G. 1992. Timber skidding output increasing by wheel tractor key constructions parameters substation. PhD thesis autoreferat. Leningrad Forest Technical Academy. 18 pp. (in Russian)

[8] Koger, J. 1992. Analyzing timber harvesting systems using STALS-3. For. Prod. J. 42(4):25-30.

[9] Leitas, A.M. and I.K. Ievin'. 1986. Simulation in thinnings study. In. Machinery and equipment for logging and forestry mechanization. Leningrad Forest Technical Academy. Pp. 63-68. (in Russian).

[10] Randhawa, S.U., T.M. Scott and E.D. Olsen. 1992. Timber harvester: a microcomputer-based system for automatic selection of timber harvesting equipment. Appl.Eng.Agric. 8(1): 121-127.

[11] Stuart W.B. Harvesting analysis technique: a computer simulation system for timber harvesting. For. Prod. J. 1981 31(11):45-53.

Editor's Note

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